THE IMPACT OF ICELANDIC VOLCANIC ERUPTIONS UPON THE ANCIENT SETTLEMENT AND ENVIRONMENT OF NORTHERN AND WESTERN BRITAIN.

VOLUME 1.

John Patrick Grattan.

This work is submitted in fulfilment of the requirements for a Doctor of Philosophy in the Faculty of Pure Science at the University of Sheffield.

This work was supported by Historic Scotland and
The Science and Engineering Research Council.

Acknowledgements:

I must acknowledge the help and support of many people; Patrick Ashmore at **Historic Scotland** for supporting this project. John Barber of the **A.O.C.** for mooting the impact of volcanic eruptions in Scotland, and his logistical support. Paul Buckland and John Sadler, for discussing this and associated topics, and for confirming my first tephra identifications. Richard Tipping for guiding me around the Strath of Kildonan, and Paul Robbins for help with the core extraction. Alex Woolf, for bringing St. Columba to my attention. Brian Pyatt, for suggesting the application of EDMA to the study of Palaeoenvironments. Brian Leakey for patiently training me to use the microprobe at Plymouth. The 1991-1992 intake of M.Sc. students at Sheffield, for working in a very cold and wet Borve Bog. The students of the University of Plymouth, for being interested and searching archives in their home towns. Anne Kelly for inventing a simple method of tephra extraction. The University of Plymouth, for having faith in me and giving me a chance. Professor David Gilbertson for his example and his constant support and encouragement.

Contents.

Figures . Volume 2.

Page

Forethought.

This thesis will explore the impact of volcanic eruptions upon the environment and peoples of northern Britain. Before a detailed investigation of the theoretical and practical considerations of this question, consider the following account, which is taken from "The life of St. Columba", written in the Seventh Century A.D:

> "While the Saint was living in the island of Io ... he saw a heavy rain cloud that had risen from the sea to the north, on a clear day. Watching it as it rose, the saint said to one of his monks ... 'This cloud will be very hurtful to men and beasts; and on this day it will quickly move across and in the evening drop pestiferous rain upon Ireland ... from the stream that is called Ailbine to Ath cliath (Dublin) and it will cause severe and festering sores to form on human bodies and on the udders of animals. Men and cattle who suffer from them, afflicted with that poisonous disease will be sick, even to death'. Following the saint's instruction ... Silnan arrived with the Lord's help, at the place aforesaid; and found the people of that district ... devastated by the pestiferous rain falling upon them from the cloud"

[*Adomnan's Life of Columba.* From the translation by Anderson & Anderson 1961]

Does the above account describe the impact of an Icelandic volcanic eruption upon the people of Ireland? This study will investigate that possibility.

Introduction.

This thesis is an exploration of the potential impact of volcanic eruptions on the ancient settlement and environment of Northern Britain, in particular the environmental changes which may have occurred as a result of the eruption of the Icelandic volcano Hekla in the Second millennium B.C.

Along the Strath of Kildonan in Caithness lie upwards of 2000 hut circles [Barclay *et al.* 1985], which the archaeologists of Historic Scotland believe were abandoned in a relatively short period of time, at approximately 1150 B.C. The abandonment of the Strath is a stark illustration of the abandonment of marginal lands which has been noted in many areas of the British Isles. Marginal lands are here considered to be those which lie at an altitude, or a latitude which discourages or prevents intensive agricultural exploitation. Field surveys have shown that there was a widespread abandonment of settlement in the late Second Millenium B.C. in northern Scotland [Barclay *et al.*, 1985; Hunt 1987; J. Barber *pers comm*]; as well as other marginal areas of the United Kingdom [Annable 1987; Burgess 1980, 1985; Fleming 1985; Gates 1983; Halliday 1982; Jobey 1980, 1981, 1983 Smith *et al.* 1981]. Traditional explanations for such changes in settlement pattern emphasise the consequences of a climatic transition in progress during this period, from Sub-Boreal to Sub-Atlantic climatic conditions [Frenzel 1966; Godwin 1975].

The abandonment of mediaeval upland settlement in the Lammermuir hills of Scotland, in the face of a gradually worsening climate [Parry 1975] is a useful analogue for the response of Bronze Age peoples to a similar deterioration in climate. However, while a gradual deterioration of climate may have played the key role in causing the abandonment of marginal lands across the British Isles, the apparent suddenness of the Late Bronze Age settlement abandonment in northern Scotland, has led to speculation that an "external trigger mechanism" may have accelerated the process. Prior to 1989 speculation as to the nature of the "external forcing mechanism" focused primarily on disease. Burgess [1985] argued plausibly that an event such as the "Black Death" may have occurred in the British Bronze Age, and led to the contraction of settlement. Other, equally plausible explanations, again advanced by Burgess [1985], proposed economic or social collapse as alternative hypotheses. In 1988 Baillie and others noted the coincidence of extremely narrow growth increments in Irish bog-oaks and acidity peaks in the Greenland ice-cores which were taken to indicate volcanic activity [Hammer 1977, 1984; Hammer *et al.* 1980, 1981, 1987, 1988]. This coincidence led to the suggestion that an Icelandic volcanic eruption, and a subsequent severe climatic deterioration was the trigger mechanism for the sudden abandonment of land in northern Scotland [Burgess 1989; Keys 1988]. The discovery, in Scottish peat bogs, of tephra from Icelandic volcanic eruptions of the Late Second Millenium B.C. [Dugmore 1989], focused further attention on the environmental forcing associated with such events. It is this hypothesis that this work examines.

The value of volcanic tephra horizons as isochrones has long been recognised and the use of them in palaeoenvironmental studies has been advocated by Buckland *et al.* [1981] but the use of tephra horizons in this context, has to date, been sadly lacking in critical analysis. There is a danger that any historical or environmental change may be ascribed to a convenient volcanic eruption. As Renfrew [1979 p.582] notes:

> "... it is necessary to recognise and discount the common tendency among archaeologists and historians to assume a causal link between the distant and widely separated events of which they may have knowledge. An eruption here, a destruction there, a plague somewhere else - all are to easily linked in hasty surmise"

To this might be added a further caveat:

> the need to avoid the assumption that the external forcing mechanism identified was of sufficient magnitude to bring about the environmental change observed.

These themes are pursued throughout this work.

Is it possible that eruptions of Icelandic volcanoes might have been an initial agent of change responsible for the abandonment of settlement along the Strath of Kildonan and elsewhere in the Scottish Highlands? At present there are two broad categories of volcanically-induced impact which might have induced the abandonment of these settlements:

1. Climatic fluctuation associated with volcanic eruptions.

2. The impact of volcanic emissions on down-wind ecosystems.

Both hypotheses are investigated in detail. In Chapter One the evidence that volcanic eruptions may cause environmental deterioration is investigated. Volcanic eruptions are detected and presented as "stress" exhibited in certain tree-ring chronologies during and after eruption years. It is suggested in this thesis that while some trees may experience stress during eruption years, many do not. Those that do state stress were growing in marginal locations. It is reasoned that it is necessary to establish in what ways a tree's environment may be considered marginal, before one can speculate as to the nature of any external forcing mechanism.

In Chapter Two the mechanisms by which volcanic eruptions are held able to cause a deterioration in climate are reviewed in detail. The different indices by which the scale of a volcanic eruption is judged are analysed, and it is suggested that the Hekla eruptions of the Second Millenium B.C. were not of exceptional magnitude. The degree of temperature reduction in the wake of modern eruptions is studied and the modelled and observed scale of temperature response to volcanic eruptions is seen to fall far below the degree necessary to cause drastic environmental change. Indeed it is noted that in many cases this is minimal, falling well within the standard deviation of normal temperature fluctuation. The implications of this, for models which propose an exceptional human response to an unexceptional temperature reduction in the wake of a volcanic eruption are considered.

In Chapter Three the possibility that the slight reductions in temperature may trigger severe disruption to atmospheric circulation patterns is considered. It is shown that many of the studies which advocate this hypothesis are based on poor records of both eruption frequency, and of the frequency of the climatic phenomenon studied. In several cases it is pointed out that precursors of the meteorological event occurred several months **before** the volcanic event held to be the cause or trigger. It is concluded that it is unsafe to assume that a significant shift in atmospheric circulation patterns will follow a major volcanic eruption.

Having examined the theory by which volcanic eruptions may cause climate change, this dissertation examines two volcanic events which are held to have caused major climate change are studied.

Chapter Four examines the eruption of the Indonesian volcano Tambora, and its association with the "year without a summer" 1816. This major southern hemisphere eruption is studied because it is necessary to consider whether such an event, occurring in prehistory, may disrupt climate sufficiently to bring about the abandonment of territory in northern Scotland. It is shown that temperature trends had been deteriorating for several years prior to 1816, and that social, economic and climatic trends together were responsible for the perception of 1816 as a "crisis" year.

The climatic impact of a major northern hemisphere eruption, that of the eruption in Iceland of the Laki fissure is 1783, is considered in Chapter Five. This eruption is associated, in Europe, with a cool summer and a harsh winter. The conventionally accepted perception of the climatic impact of this eruption is largely based on the personal observations of Benjamin Franklin, who was in Paris in 1783. Extensive documentary evidence is presented which demonstrates that in many parts of Europe climatic conditions were distinctly different to Franklin's observation. The climatic impact of this eruption is considered and a new model, by which volcanic eruptions may cause warming, rather than cooling is proposed.

It is shown that events on the scale of the Laki fissure and Tambora eruptions, do not provide unequivocal evidence of a severe climatic deterioration. In the light of this review, the ability of the much smaller eruptions of the Icelandic volcano Hekla to cause severe climatic deterioration, and hence prompt the abandonment of settlement in Scotland are called into question.

Having considered the climatic impact of volcanic eruptions in detail, the impact of volcanic emissions on downwind ecosystems in north west Europe is investigated in Chapter 6. The existence of a mechanism by which volatile volcanic gases and aerosols may be transported across large distances is demonstrated, and the Laki fissure eruption is again used as an analogue for prehistoric volcanic events. Considerable documentary research, presented here for the first time, proves that severe "acid damage" occurred across a wide area of Europe in 1783. The palaeoenvironmental implications of this event are discussed, and it is proposed that the impact of acid volatiles, on sensitive ecosystems, may be a more effective agent of environmental change than minimal temperature fluctuations.

An alternative mechanism is presented, which emphasises the severe and discriminatory impacts of the acid volatile emissions from Icelandic volcanic eruptions. Documentary research carried out in the course of this project has identified severe crop damage across eastern England and Western Europe, in the summer of 1783, which was probably caused by the deposition of acid volatiles emitted by the Laki fissure eruption in Iceland. The present understanding of these impacts is then reviewed, and used as a basis for presenting a tephra related mechanism of environmental change which is predicted to have had a very selective and discriminatory impact upon specific environments in northern and western Britain.

This hypothesis is examined by a study of the geochemical history of sediments retrieved from a range of lake and mire sediments in the Highlands and Islands of Scotland, and the degree of the geochemical response to tephra deposition is investigated.

The geochemical study involves the application of Energy Dispersive X-ray Micro Analysis [EDMA] to the investigation of palaeoenvironmental change. A significant part of this work involves exploring the limitations and advantages of this technique, and developing a theoretical framework upon which models of environmental change may be constructed.

A pilot study was conducted and the results of this analysis are presented and discussed. The research strategies were reformulated in the light of this research and fresh cores retrieved from lacustrine and mire environments in the Highlands and islands of Scotland. The results of these analyses are presented in the relevant chapters and in the discussion which closes this work.

Chapter one.
Dendro-chronological indications of volcanic activity.

Summary of Chapter.

This chapter deals with the principle biological indicator for volcanically induced environmental change tree-rings. The subject is dealt with at several levels. The significance of the Irish bog-oak chronology and the correlation between narrow growth rings and acid peaks in the Greenland ice-cores is considered. To aid in the interpretation of the Irish evidence, tree-ring studies in general are considered and alternative hypotheses to volcanic eruptions are presented. Dendro climatic data gathered on a regional scale is analysed for any evidence for volcanic forcing of climate. In Europe it can be seen that there is no association between bad years indicated by the dendrochronology and known volcanic activity. In North America a dendrochronological response to volcanic activity is noted, but the evidence is ambiguous. Far from presenting a picture of general climatic deterioration the North American tree-ring records show that some regions benefit from the climatic disturbances indicated in others. Several American studies are considered in detail and it is noted that while there appears to be a plausible correlation between each study and known volcanic activity, there is little agreement between different studies. Finally the Irish chronology is reinterpreted in the light of this discussion and it is suggested that climatic stress need not be the only volcanic mechanism responsible for the narrow tree-rings in Ireland.

Introduction.

The physiological response of trees to environmental stress is recorded in their annual growth increment. Studies of ring-width [Lamarche 1984, 1974; Baillie 1988], ring-colour [Filion *et al*, 1986], isotopic ratio [Epstein & Krishnamurthy 1990], damaged annual rings [LaMarche *et al*, 1984] and late and early-wood density [Briffa et al 1988, 1990; Conkey 1986; Graumlich & Brubaker 1986; Scuderi 1990], allow the reconstruction of the macro and micro environmental influences on a tree's location. The longevity of particular tree species, the survival of others in fossil form and their wide latitudinal and geographical distribution, permits the reconstruction of climatic change [LaMarche 1974; Fritts *et al.* 1979, 1981] and allows an assessment of the climatic significance of individual eruptions.

Tree-ring response to environmental forcing is often used in an attempt to reconstruct the environmental impact of volcanic eruptions [LaMarche & Hirschboek 1984; Lough & Fritts 1987], and to improve eruption chronologies based on incomplete data [Scuderi 1990]. Historical sources decrease in both number and quality prior to 1500 AD, and for obvious reasons are concentrated in the Mediterranean [Stothers & Rampino 1983 a & b; Sullivan 1988] and China [Pang *et al.* 1988; Xiangding & Xuhzi 1991; De'er 1991] the use of dendrochronology may counter this regional and temporal bias. Acidity peaks in the Greenland ice core might be thought to record significant eruptions [Hammer *et al.* 1980] and provide a chronology which is independent of location and personal observation, but the proximity of Iceland and the Alaskan and Aleutian ranges to the Greenland ice sheet may have introduced an obvious bias in favour of such eruption sources. The position of the Jet Stream and circum-Polar vortex over north west U.S. and Canada and frequently over Iceland may add to this selection in favour of eruptions in Iceland, Alaska and the north western Rocky mountains. Rather than measure the injection of climatically significant levels of acid gases into the stratosphere [Baldwin *et al.* 1976 Pollack *et al.* 1976], favourable tropospheric winds may inevitably lead to the overestimation of the acid output of northern hemisphere volcanic eruptions; while that of low latitude or southern hemisphere eruptions may be under estimated. The physiological response of trees to climatic change generated by a volcanic eruption may allow us to remove one part the geographical bias from both the historical and the ice-core records by broadening the basis of the study.

Most dendrochronologies are in broad agreement and trace the general trends of northern hemisphere climatic change of the past 500 years, in particular a sudden cooling in the early 1800s and a steady warming since the mid nineteenth century [Briffa *et al.* 1988, 1990; Fritts *et al.* 1979; Jacoby *et al.* 1985, 1988, 1989]. Such broad reconstructions of climatic change emphasise the macro-scale changes in environment at the cost of local micro-scale reconstructions [Yadav 1993; Yamaguchi 1993]. It is the local environment, however, which conditions the responsiveness of the tree to environmental forcing. If a tree-ring response were shown to be related to a volcanic eruption, should we assume then that evidence for environmental stress in a tree-ring record reflects volcanic influences at the **macro** rather than the **micro** scale? I shall show that many studies fail to identify volcanically induced climatic change, and that there is little correlation or coherence between those which claim to. This chapter will demonstrate the need for caution in the construction of environmental models based on the interpretation of tree-ring records, and question the common assumption that some tree-ring stress previously correlated with volcanic eruptions is indicative of severe widespread climate change.

Volcanism, tree-ring records and Northern Britain.

The principal evidence for an environmental deterioration in Northern Britain in response to volcanic eruptions, comes from a study of tree-ring width minima recorded in trees growing in northern Ireland. Using deciduous oaks, *Quercus petraea* and *Quercus robur*, from Ireland, northern and southern Germany and northern England, Pilcher *et al.* [1984] were able to develop a 7272 year tree-ring Chronology for western Europe. This chronology securely dated the incidence of decade length periods of particularly narrow tree-rings in Irish bog oaks [Baillie & Munro 1988]. These were then associated with the record of volcanically induced acid peaks in the Greenland ice cores [Baillie 1988, 1989 a & b, 1991 a & b; Baillie & Munro 1988; Hammer 1977, 1984; Hammer *et al.* 1980, 1981] [Table 1.1]. As a result the suggestion was made that volcanic eruptions were able to cause significant climate change in Britain and Ireland [Baillie 1988, 1989, 1991].

IRISH OAK. RING-WIDTH MINIMA.	GREENLAND ICE CORE ACIDITY.
4370 BC	4400 ± 100 BC
3195 BC	3250 ± 80 BC
1628 BC	1645 ± 20 BC
1159 BC	1120 ± 50 BC
207 BC	210 ± 30 BC
540 AD	516 ± 4 AD.

Table 1.1. Correlations between ring-width minima in Irish Bog oaks acidity peaks in the Greenland ice core. After Baillie and Munro 1988 and Hammer *et al.* 1980.

The Irish tree-ring chronology is unique in that the narrow rings persist over decadal length periods. This is in direct contrast to the narrow or damaged rings noted elsewhere [Discussed below], which are predominantly single year events. The long term stress indicated in the Irish tree-ring record led to speculation [Baillie 1988, 1989 A & B; Keys 1988; Burgess 1989; J.Barber *pers comm.*] that volcanically induced environmental stress in northern Europe may be more severe than suggested by current research, and may persist over decades rather than the few years that most other research suggests [See Chapters 2 & 3]. Disruption of northern hemisphere atmospheric circulation over Britain in the wake of a major eruption it was hypothesised might have brought about colder and wetter conditions in the first summer following an eruption [Kelly & Sear 1984], but there is no known mechanism by which a single volcanic eruption may severely modify climate for a period of up to twenty years.

Table 1.2.

Irish Oak Ring width Minima	**Associated Phenomena.**
1159 BC.	The Hekla 3 eruption. Greenland acidity peak, 1120 ± 50 BC. Abandonment of the Strath Of Kildonan. Late 12th Century BC. Movement of the "Sea People" *Ca.* 1200 BC. Fall of Mycenae. *Ca.* 1200 BC. Plague in Ireland 1180 - 1131 BC. Hittites leave Anatolian Plateau. 13th Century BC. Libyan peoples migrate towards Egypt. *Ca.* 1200 BC. Catastrophic flooding in Hungary. *Ca.* 1200 BC. Rise in level of the Caspian Sea. *Ca.* 1200 BC. Wide tree rings in Turkey. 1159 BC Deepening of lakes in Turkey. 1200 - 1100 BC. Lowered snowline in Norway. *Ca.* 1200 BC. Crop failure in China.
207 BC.	Unknown eruption. Greenland acidity peak. 210 ± 30 BC. Irish murrain of cattle. 210 - 200 BC. Stars invisible in China. 208 BC. Chinese famines. 207 -204 BC. Chinese dynastic change. 202 BC. Frost ring event. 206 BC.
540 AD.	Unknown eruption. Greenland acidity peak. 516 ± 4 AD. European Mystery Cloud. 536 AD. Chinese atmospheric disturbance 540 AD.

Table 1.2. Phenomena associated with Irish ring-width minima. Data from Baillie 1988, 1989; Burgess 1989; Bryson & Goodman 1980; Kuniholm 1990; Pang *et al.* 1987, 1988, 1989; Stothers & Rampino 1983 a & b; Warner 1990

A review of historic and environmental phenomena in years which the Irish tree-ring record suggests environmental stress may serve to illustrate the scale of environmental disruption which, it has been argued by various researchers, were caused by the eruptions of volcanoes [Table 1.2]. The Hekla 3 eruption, in particular, appears to have had a wide geographical impact. Is it possible that a volcanic eruption on this scale could be the agent for narrow tree-rings in Ireland, land abandonment in Scotland, raised sea levels, lowered snowlines, the near collapse of Mediterranean civilisations and crop failure in China; as suggested by Baillie [1989 a & b], Bryson and Goodman [1980], Burgess [1989], Kuniholm [1990], Pang *et al.* [1988, 1989], Stothers and Rampino [1989 a & b] Warner [1990]? This question will be addressed below by reference to the tree-ring response to far larger eruptions.

Is the framework of dating and correlation between eruption and tree-ring chronologies "tight enough" to allow such associations to be made? Alternative forcing mechanisms must be considered, but frequently are not. For instance a sunspot minima greater than that associated with the Little Ice Age occurred in the three centuries before Hekla 3 erupted [Eddy 1977, 1992]. Many of the historical and environmental phenomena associated with the eruption of the volcano could have been generated by such an event. There is a danger that any historical or environmental change may be ascribed to a convenient volcanic eruption. As Renfrew [1979 p. 582] notes;

"...it is necessary to recognise and discount the common tendency among archaeologists and historians to assume a causal link between the distant and widely separated events of which they may have knowledge. An eruption here, a destruction there, a plague somewhere else - all are to easily linked in hasty surmise..."

Are the correlations between the Irish ring-width minima and Greenland ice-core acidity fortuitous, or do they genuinely record a severe climatic deterioration caused by a volcanic eruption? Are there alternative hypotheses which may account for the narrow tree-rings? Can the mechanisms by which a volcanic eruption triggered a tree-ring response be reconstructed? Do such reconstructions have a measurable significance at the macro- or micro-scale? Do eruptions on the scale suggested by the ice-core acidity evidence affect environments across wide areas? A study of research into tree-ring response to climate change, and of work which attempts to link a physiological response in trees to volcanic eruptions may answer these questions.

Tree-ring studies.

Environmental conditions at any location will control the response of a tree to environmental stress generated by external forcing. The most sensitive tree-ring chronologies are those from trees which are growing at their physiological limits, which in practise means growth at the altitudinal or latitudinal tree-line. Temperature in the short growing season is the primary limitation on tree growth in such locations. But while many tree-ring chronologies are in accord, in recording yearly and decadal temperature cycles [Jacoby *et al.* 1989], there are others where ecological stresses particular to a location obscure this signal [Graumlich & Brubaker 1986; Jacoby *et al.* 1988a]. Trees growing in marginal locations respond to their environment in an integrated manner. Therefore soil conditions, soil temperature, soil moisture, air temperature, precipitation, aspect, slope and direct solar radiation all play a role in conditioning a tree's sensitivity to environmental stress. Cambial division may occur in a growing season as short as six weeks, but photosynthesis, root extension and other processes, such as nutrient cycling in the soil, take place through a much longer season. A tree's response to environmental stress may therefore be either buffered or enhanced due to environmental conditions in previous years and a significant time lag response may be introduced [Jacoby & Ulan 1982; Lough & Fritts 1987].

Environmental conditions specific to each tree's location may enhance or limit the response to a volcanic eruption. As a result little correlation exists between chronologies which attempt to reconstruct episodes of particular stress, such as may occur in response to volcanic eruptions [LaMarche & Hirschboek 1984; Conkey 1986; Scuderi 1990], and between chronologies which record other extreme environmental phenomena such as drought [Cook *et al.* 1992]. Local conditions may also introduce a time-lag response of up to five years to an episode of environmental stress [Lough & Fritts 1987]. In such cases the correlation of a tree's response to volcanic activity becomes problematic; especially given the estimates of background volcanic activity suggested by McClelland *et al.* [1989], that at least 400 eruptions >VEI 5 and 2835 > VEI 4 should have occurred in the past 4000 years.

The particular environmental conditions which allow the classification of a tree's location as marginal must be identified, since the environmental factors which condition a tree's response may not be solely in response to climate. Was it possible that the stress recorded in the Irish Oak trees was in response to forcing mechanisms not related to climate change?

Tree-rings, volcanic eruptions and climate forcing? Alternative hypotheses.

Not all climatic forcing can be traced to mechanisms operating within the earth's ocean, atmosphere, cryosphere system. Anderson [1992] suggested that an association existed between tree response, surface winds and the Maunder sunspot cycle; while Kullman [1992] suggested the earth-sun geometry as another mechanism controlling tree-line conditions. Caution must be used when advancing the suggestion that volcanic eruptions are the sole or primary mechanism responsible for climate change.

Sunspot minima are linked to periods of diminished solar output and climatic extremes, the Little Ice Age occurred during one such episode, the "Maunder Minimum" [Eddy 1977, 1992]. Meko [1992] reported a clear relationship between dendrochronological indications of drought conditions in the Great Plains of North America and sunspot minima. D'Arrigo and Jacoby [1992] found that dendrochronological indications of cooling in northern North America coincided with the timing of the Maunder sunspot minima in the seventeenth Century AD and in the mid 1800s. Graybill and Shiyatov [1992] also noted that growth minima in the northern Soviet Union coincided with the Maunder sunspot minimum.

Not all occurrence of ring-width minima can be related to climatic change. Jacoby *et al.* [1988b] noted the strong correlation between narrow tree ring and earthquake occurrence along the San Andreas fault in California. Yadav and Kulieshius [1992] also noted the occurrence of narrow tree-rings in response to earthquakes in Kazakhstan, Central Asia.

Following the eruption of the Alaskan volcano Katmai in 1912, Griggs [1922] noted that the response of trees growing in the area of the eruption was widely different. Trees growing on a bog experienced an enhancement of their environment and recorded improved growth. The deposition of quantities of tephra improved the hydrology and the nutrient status of the bog. Trees growing nearby but rooted in a mineral soil experienced stress and recorded 1912 as a poor year!

Denton and Karlén [1977] noted that many fossil trees found in alluvium and glacial moraine in the White River valley and Skolai Pass in Yukon Territory, had been killed by the direct impact of tephra from relatively proximal Alaskan volcanoes. Surviving trees may have recorded the stress of these episodes with a narrow tree-ring. Yamaguchi [1983, 1993] observed that the eruption frequency of Mt. St. Helens in Washington State, was recorded by narrow tree-rings in proximal and down wind trees; a response generated by tectonic disturbance and tephra fall. Likewise Yadav [1992, 1993] noted tree-ring indications of the eruption frequency of Kamchatka in Siberia which were linked to tectonic disturbance and tephra fall rather than climatic change.

Reduced growth increments may also be induced by stress generated by atmospheric pollution [Peterson *et al.* 1991]. Cobb *et al.* [1968] noted that following damage by photochemical oxidants, the ponderosa pine, *Pinus ponderosa*, was severely infested by the bark beetle *Coleoptera scolytidae*. While acknowledging that climatic deterioration is are the most probable cause of narrow or damaged tree-rings, the studies outlined above illustrate that climatic change may not be the single critical factor. The emissions from a volcanic eruption are capable of a direct impact on downwind flora and ecosystems. This possibility should be taken into account when interpreting the Irish record.

There may also be a degree of auto-correlation between periods of poor weather, reduced growth increments and volcanic eruptions. The suggestion has been made [Pyle 1989; Rampino *et al.* 1979] that climatic change may itself cause volcanic eruptions. Rising or falling sea levels may affect slope stability [McGuire 1992] as may tectonic pressures when glaciers and ice-sheets advance or retreat [Danny Harvey 1988].

Decline as a naturally occurring phenomenon in forests must also be considered. Sinclair [1964, 1966] highlighted several instances of the catastrophic reduction in specific tree species in north America unrelated to climate, volcanism, pollution, people or infestation. He speculated that a natural cycle of growth and decline may occur within specific tree species in a forest environment.

Care must be exercised in the interpretation of Dendrochronological records lest an assumption of volcanic forcing of the plant is made in the absence of supporting evidence.

Northern Hemisphere Climate Change: A Clear Volcanic Signal?

1. EUROPE.

Briffa *et al.* [1990], reconstructed Fennoscandian summer temperatures for the past 1400 years, based on raw mean ring widths and the maximum latewood density of conifers from the Torneträsk region of northern Sweden. Growing at high latitudes this record is sensitive to climate change and is worth considering in detail.

Positive.			Negative.	
Anomaly (°C)	Year		Anomaly (°C)	Year
		Individual Summers		
2.07	1761		-1.65	1139
2.05	1831		-1.58	1109
1.99	1703		-1.57	961
1.71	1937		-1.53	800
		Twenty year means		
0.78	1158-1177		-0.93	1127-1146
0.79	1748-1767		-0.73	795-814
0.67	749-768		-0.65	1601-1620
0.52	1087-1106		-0.55	848-867
0.49	1551-1570		-0.53	1344-1363
		Fifty Year means		
0.35	1152-1201		-0.58	1108-1157
0.34	1403-1452		-0.42	1576-1625
0.33	1750-1799		-0.34	780-814
0.29	719-768		-0.31	1867-1916
0.27	926-1011		-0.23	1345-1394

Table 1.3 Largest temperature anomalies and trends in Fennoscandia. From Briffa *et al.* 1990.

It is clear that none of the worst individual summers in Fennoscandia correlate with acid peaks in the Greenland ice core [Hammer *et al.* 1980; 1981]. Equally neither the worst twenty years nor the worst fifty years in their reconstruction can be linked to known volcanic activity. To imply a volcanic agency for these events therefore is doubtful. Summer temperatures can be seen to vary on an decadal time scale [Figure 1.1]. Attempts to link volcanic activity to these trends given the probable background levels of activity [McClelland *et al.* 1989], would be dubious. There is no record in this work that the Laki fissure eruption in 1783, nor to the Tambora eruption in 1815 had any significant impact on climate. The acidity trace of both eruptions are several orders of magnitude greater than the eruptions associated with the severe Irish ring-width minima [Hammer 1977, 1984; Hammer *et al.* 1980,1981] yet they appear to have had no impact on marginal trees in Fennoscandia. Is the Irish tree-ring record more sensitive to climatic change than those of Scandinavia or were other external forcing mechanisms involved in Ireland?

Working over a shorter time scale, 1750-1850, Briffa *et al.* [1988] reconstructed summer temperature patterns for Europe. Thirty seven long chronologies were used from southern Spain and Greece in the south to Finland and Norway in the north [Figure 1.2]. This work identified several years where significant departure from the mean occurred [Table 1.4].

UNITED KINGDOM.		SCANDINAVIA.		CENTRAL EUROPE.	
-	+	-	+	-	+
			1761		
		1772			
1782		1782			
		1790			
1799					
		1812			
				1814	
1816				1816	
1829			1829		
			1831		
		1838			
			1852		
1860					
		1864			
		1867			
			1868.		

Table 1.4. Years with a departure greater than 1 °C from the 1951-1970 mean. After Briffa *et al.* 1988.

None of the significant temperature departures in Table 4 are associated with an acidity peak in the Greenland ice core. For example 1782 is recorded as a poor year in the U.K. and in Scandinavia, and this was a year of crop failure in Britain, but a significant volcanic eruption is not recorded for this year. A European climatic deterioration in response to the eruption of the Laki fissure in 1783 is not recorded, a conclusion supported by Hughes *et al.* [1984]. The eruption of the Laki fissure, in 1783, is associated with a cool summer in Europe [Franklin 1784]. But Schove [1954] noted that in the Finnish tree-ring record the summer of 1783 was recorded by extremely narrow rings, caused by extremely high temperatures and drought rather than by cool wet conditions. Current research [Briffa & Schweingruber 1992] indicates that the summer of 1783 was warmer than the 1951-1970 mean, and of critical importance, theoretical computer based models of climatic response to volcanic eruptions do not currently suggest that warming should follow a major northern hemisphere eruption. Documentary research undertaken in the course of this thesis has identified a volcanic component to this warming which is discussed in detail in Chapters 5 and 6, below.

The work of Schove [1950, 1954] similarly fails to indicate a significantly narrow tree-ring for 1816 but confirms the conclusions of Briffa *et al.* [1988], Briffa and Schweingruber [1992], and Graybill and Shiyatov [1992], that 1810 saw the beginning of a short cool period in Europe. The tree-ring evidence suggests that Europe experienced cold conditions between 1810-1817 and 1832-1838 and slight warming between 1819-1828 and 1868-1875, but with these exceptions similar conditions were rarely found across maritime and continental Europe. The poor correlation across Europe between incidences of extreme departure from the mean in any particular year encourages extreme caution in assuming that the Irish tree-ring minima indicate Europe-wide, or even global climatic change.

This study of European temperature reconstructions illustrates the dangers of assigning ring-width minima to the influence of conveniently dated volcanic eruptions. None of the minima in Tables 1.3 and 1.4 are caused by a volcanic eruption, and the most climatically significant eruptions of the Holocene failed to trigger a narrow ring in Europe. Departures from the temperature norm of up to 2°C are recorded, well beyond estimates for the degree of temperature change caused by the eruptions of Tambora and Laki [Sigurdsson 1990]. Given this, attempts to prove climatic stress from the correlation of narrow tree-rings and volcanic activity must be viewed with suspicion.

2. North America.

A study of North American dendroclimatic studies, in particular of studies which record climatic extremes or which claim to record environmental forcing caused by distant volcanic eruptions further aids the interpretation of the Irish ring-width minima.

The response of trees to environmental supposedly forcing induced by volcanic eruptions is conditioned by the environmental factors specific to each location. Climatic cycles progress with or without the influence of volcanic eruptions, and many North American chronologies present a broadly similar picture of cooling in the early 1800s, and warming from the mid 1800s [D'Arrigo & Jacoby 1992; Jacoby *et al.* 1985, 1988; LaMarche & Stockton 1974, LaMarche *et al.* 1984]. In continental locations such records of climatic conditions are widely replicated. Villalba's [1990] reconstruction of climate in northern Patagonia also indicates a cold period in the early 1800s, and warming since 1850. Some Chronologies however, display a marked absence of trend [Conkey 1986; Graumlich & Brubaker 1986; Jacoby *et al.* 1988]. Local environmental factors obviously dominate the tree ring response to external forcing at these locations. It is from within the variation in these records that the influence of volcanic eruptions must be detected.

The correlation of volcanic eruptions with anomalous North American tree-rings was first noted by Giddings [1941], and Oswalt [1957]. They observed that Alaskan White spruce trees *Picea glauca*, growing at the limits of their environmental tolerance, experienced physiological stress, expressed by narrow tree rings, associated with poor latewood growth, in the year 1783. This was the year of the major eruptions of the Laki fissure in Iceland, and of Asama Yama in Japan. The occurrence of this ring was sporadic in the tree-line spruce of the Copper and Kuskokwim Rivers, and common in the Yukon River spruce in Alaska. The sporadic occurrence of the narrow ring in 1783 confirms the importance of local environmental factors in conditioning a tree's response to environmental stress associated with an eruption. Growth for 1783 was unusual in that the trees put on limited latewood, suggesting that the environmental effect was felt towards the end of the growing season. Twentieth century data suggests latewood growth begins in August [Oswalt 1957]. The Laki eruption began on June 8th [Thórarinsson 1969] and continued for eight months and so would, in principle, have been capable of affecting latewood growth.

Oswalt's study demonstrates that both macro and micro-environmental factors may condition the physiological response of a tree to external forcing mechanisms.

Several other studies of tree response to the influence of volcanic eruptions serve to emphasise the importance of micro-environmental factors. The eruption of the Indonesian volcano Tambora in 1815 is widely held to have been responsible for "the year without a summer" in the northern hemisphere in 1816, with particularly severe impacts in North America [See Chapter 4]. This cool summer, if truly exceptional, should be clearly recorded in the North American tree-ring record. If a volcanic eruption of the magnitude of Tambora fails to leave a clear signal in dendrochronological records of climate change, we must begin to doubt the ability of the much smaller eruptions associated with the Irish ring-width minima to do so.

Jacoby *et al.* [1988] found only limited tree-ring evidence for a poor summer in 1816. In a study of three proximal chronologies constructed from white spruce trees, *Picea glauca*, growing at the latitudinal tree-line in northern Quebec [Figure 1.3] two were shown to record a poor year in 1816 while the third did not [Jacoby & Ulan 1982; Jacoby *et al* 1985]. The response of each chronology was conditioned by the geomorphology of the site. Trees sampled at Kuujjuarpik and Richmond Gulf grew in an east-west trending narrow valley, protected from wind but shielded from low angle sunlight. The third record was obtained from the Castle Peninsula, a south facing slope. Trees at Kuujjuarpik and Richmond Gulf recorded distinct stress in 1816 and 1817. However, both sites failed to record the warming trends evident in other records [Jacoby *et al.* [1989]. In contrast the chronology obtained from the south facing Castle peninsula did not record specific cooling in 1816, but indicates a cool period from the early 1800s followed by increased growth over the past 150 years which is in accordance with the trends recorded in most other chronologies [Figure 1.4]. The depletion of solar energy due to the presence of volcanic aerosols in the stratosphere in 1816 may have been insufficient to trigger a physiological response in trees growing outside the ravine but sufficient that trees growing within the ravine experienced stress recorded by narrow rings in 1816 and 1817. This study demonstrates that the geomorphology of the site limited the levels of solar energy reaching the growing trees. It was probably a further reduction in solar energy as a result of a stratospheric aerosol cloud which triggered a tree-ring response to a volcanic eruption. Recovery from the stress recorded in 1816 and 1817 took thirty years. However, the continued cooling suggested by other records may have conditioned this response and recovery coincided with the initiation of a warming trend and it would be unwise to ascribe the stress recorded over a thirty year period to the impact of a single volcanic eruption. To interpret the Irish record we need to identify the environmental conditions which rendered the Irish trees sensitive to external forcing.

The occurrence of "light rings" in the black spruce tree, *Picea mariana*, growing at the tree-line in northern Quebec, was taken to indicate a shortened growing season by Filion *et al*, [1986]. 65 light-rings were identified in the period AD 1308-1982, of which 43 were correlated with volcanic eruptions identified by Simkin *et al*, [1981] with a VEI > 4 [See Chapter 2]. Light-rings occurred in 1784 and in 1816 and 1817 which suggests that the eruption of the Laki fissure and Tambora may be recorded by this tree-ring study. The occurrence of light-rings in 1816 and 1817 mirrors the record from Kuujjuarpik, also from northern Quebec [Jacoby *et al.* 1988a]. However, as with other tree-ring records the occurrence of this diagnostic feature is sporadic and not all the trees sampled marked eruption years with light-rings. The correlations established by Filion are problematic in that the index of volcanic effectiveness used, the VEI, is a poor measure of the acid output of an eruption. The volume of acids emitted in an eruption is the primary measure of its ability to act as a climatic forcing agent [See Chapter 2 for a detailed review of this process]. The incomplete nature of eruption records makes the simple correlation of a narrow tree-ring with a volcanic eruption an insufficient indication that one may have caused the other. The mechanisms by which an eruption may have had an impact at any tree-ring site must be established before any attempt at association is made or accepted.

Three proximal tree-ring records in Maine north eastern U.S.A. also fail to record a consistent response to a major volcanic eruption. Conkey [1986] investigated the response of the red spruce tree, *Picea rubens*, at three sites along the mountains of Maine in the north eastern United States, to the eruption of Tambora [Figure 1.5]. All three sites were above 900m elevation, representative of the highest stands of red spruce in the region and therefore sensitive to environmental forcing. There was little evidence to support the assertion of the researchers

Stommel and Stommel [1979] that the summer temperatures in 1816 were unique. Reconstructions based on the tree-ring record from Traveler Mt. suggested that the spring of 1816 was one of the coldest in the series, but reconstructions based on records from Elephant Mt. failed to indicate that the spring of 1816 as exceptional. In contrast, the spring of 1808 was recorded as severe at Elephant Mt. but was not recorded as exceptional at Traveler Mt., no suggestion exists that this narrow ring occurred in response to a volcanic eruption. Correlation exists between all three records in the 1830s, 1860s, 1870s, and 1880s, but again there is no suggestion that this is in response to volcanic forcing. This study again confirms that volcanic forcing of climate is insufficient to generate a response in all trees at marginal locations, and that severe ring-width minima may occur in years in which there is no evidence for a significant volcanic eruption. Macro-climatic factors are shown here, as elsewhere, to be an insufficient explanation for all variation in tree-ring response to environmental forcing. Should we therefore assume a consistent, severe and long lived climatic impact in Ireland in the wake of major volcanic eruptions?

Graumlich and Brubaker [1986] reconstructed annual temperatures for Longmire, Washington, by studying the growth of mountain hemlock [*Tsuga mertensiana*] and subalpine larch [*Larix lyallis*] growing at or near the timberline of the Cascade Mountain Range. These chronologies had a positive response to summer temperature and a negative response to spring snow depth. The temperature trends indicated by this record are in accord with other proxy records in Washington state such as the fluctuations of the Mt. Rainier glacier [Burbank 1981, 1982] but are not in good agreement with the reconstructed temperature record for other areas of the western United States. Sudden sharp cooling is identified starting in 1800 and ending in 1820. Any tree-ring response to the eruption of the volcano Tambora is obscured by the response of the Longmire chronologies to local environmental conditions. A cooling trend is identified throughout the nineteenth century, in clear contrast to the trends identified in the work of Jacoby *et al.* [1985, 1988] and LaMarche and Stockton [1974] and LaMarche *et al.* [1984].

The examples discussed above highlight the pitfalls involved in assessing the palaeoclimatic impact of any volcanic eruption. Each demonstrates the role and importance of the local environment in conditioning a tree's response to external environmental stress. My conclusion is that the local environment of the tree, the conditions under which it lived and its ability to respond to an external environmental stress must be identified and built into any such study. The correlation of tree-ring stress with volcanic eruptions in the studies above, was largely noted by me as fortuitous, and an unspecified, but typically severe climatic impact was assumed not proven. Correlations between tree-ring minima and volcanic eruptions must specify the mechanism by which the eruption was able to trigger a response in the growing tree. These must be based on correlations with ice-core acidity records [Hammer 1977, 1984; Hammer *et al.* 1980, 1981] or with estimates of volcanic degassing [Devine *et al.* 1984; Palais & Sigurdsson 1989] as these are the only effective measures of the ability of an eruption to force climatic change.

Volcanically induced Circulation anomalies and tree-ring response.

Several studies [below], which have attempted to reconstruct the means by which volcanic eruptions are able to modify climate, can be criticised in terms of the probable efficacy of the "volcanic cause" to produce the observed tree-ring response.

LaMarche and Hirschboek [1984] noted stress in trees, especially the subalpine bristlecone pines [*Pinus longaeva* and *Pinus aristata*] across a wide geographical area from California to Colorado. This stress was caused by frost damage associated with anomalous weather conditions which they correlated with volcanic eruptions. Unlike evidence from Alaska which suggested stress in the latewood stage [Oswalt 1957], LaMarche and Hirschboek found evidence for unseasonably low temperatures both in the latewood growth and in the early spring growing period. Latewood frost damage appears to have occurred at several localities sometimes separated by several hundred kilometres. Seventeen frost rings were counted in the period 2035 BC - 1884 AD of which eleven were correlated with volcanic eruptions with a VEI greater than 3. Based on these correlations the suggestion was made that the occurrence of frost damage could be used to construct a proxy record of climatically effective volcanic eruptions. According to Lamarche and Hirschboek [1984] frost damage could have been caused by a southward shift in the position of the sub-polar low pressure zone in the north Atlantic in the year following a major eruption, as argued by Wexler [1956] and Lamb [1970]. This pattern of circulation would have brought unseasonable cold polar air to the western U.S.A. during the main growing period of the tree. Nevertheless the occurrence of frost ring damage in early growth was not widespread, and with the exception of 1902, appeared to be restricted to one locality for each event. This again suggests the importance of local mitigating or exacerbating micro-climatic factors. The sporadic replication of frost damaged rings within any year does not suggest that harsh conditions were widespread and that local conditions mitigated or exaggerated the response of the tree. Can the occurrence of frost damaged or narrow rings be taken to indicate an unseasonable macro-scale circulation anomaly caused by the influence of a distant volcanic eruption?

Further analysis questions LaMarche and Hirschboek's correlations of tree-ring damage and volcanic activity. Hirschboek's [1979] enhancement of Lamb's [1970] record of volcanic events is used, but while this approach forms an improvement on earlier work, this record of volcanic events is demonstrably incomplete. The increase in volcanic activity since AD 1500 must be the result of an improved record rather than an increase in global volcanism. If the figures for Twentieth century approach the real eruption frequency [Figure 2.1] we must ask the question "can any reliance be placed on correlations between 'recorded' volcanic events and frost damaged rings in the historic and pre-historic period?"

Not all damaged rings were associated with years of volcanic eruptions, nor do all significant volcanic eruptions correlate with a damaged ring! Neither the 1641 eruptions of Awu in Japan and Gunung in Indonesia [Komagatake in Hammer *et al's.* 1980, ice core data], nor the 1783 eruptions of the Laki fissure in Iceland and Asama Yama in Japan, nor the eruption of Tambora in 1815 appear to have caused frost damage. The absence of frost-damage in the wake of the eruptions of the Laki fissure in 1783 and Tambora in 1816 is particularly damning. The acid output and hence the climatic effectiveness of both eruptions was greater than any other of the Holocene [Devine *et al.* 1984].

Some frost rings were linked with eruptions which erupted outside the time-lag response of the tree. A frost ring securely dated to 1626 BC was linked to an eruption with an ice-core acidity peak dated to 1390 ± 50. The "correlations" were further undermined by Parker [1985] who pointed out that some were made using climatically ineffective minor eruptions, such as Vesuvius in 1785, which were unlikely on theoretical grounds to have had a significant climatic impact [See Chapter 2]. LaMarche and Hirschboek [1985] defended their work by pointing out that to be recorded by the tree, the induced low temperature must have occurred in the short growing period, and if the putative causal eruption occurred before or after this time then the tree would not have recorded the event in its ring structure. This argument undermined their earlier reliance on a theoretical displacement of north Atlantic climatic circulation, and ignores the long term impact of a stratospheric aerosol layer on global temperatures and circulation [See Chapter 3]. Their correlations therefore, while interesting, are questionable.

Fritts and Shao [1992] also used dendroclimatic evidence in an attempt to reconstruct North American circulation anomalies, specifically unseasonable storm tracks in Western North America. Correlations between tree-ring anomalies and volcanic events were noted with eruptions in 1816, 1822, 1835, and 1845; but only one event, 1816, was associated with a major acid producing eruption [Hammer *et al.* 1981] This study demonstrates that stress in tree-ring records does not only occur in response to volcanic eruptions and that neither can one be inferred from the other.

Increases in Optical Depth and tree-ring response.

In an attempt to avoid reliance in this context on a "theoretical displacement" of atmospheric circulation pattern, Scuderi [1990] linked a direct physiological response in trees to the presence of volcanic aerosols in the upper atmosphere, similar to that observed by Jacoby *et al.* [1988]. The formation of a stratospheric aerosol layer by the oxidation of acid gases should lead to an increase in optical depth, and hence a decrease in solar "receipts" at the surface, which might be recorded in a tree's annual growth increment. This process is described by Baldwin *et al.* [1976], Mass and Schneider [1977], Self *et al.* [1981], Rampino and Self [1982], Pollack *et al.* [1976], and Deepak and Newell [1982] [See Chapter 2]. By emphasising the direct impact of the presence of volcanic aerosols in the stratosphere on tree growth, Scuderi [1990] felt able to present his data as a proxy record of both the incidence of volcanic eruptions and as a measure of their effectiveness as climatic forcing mechanisms.

Working at three tree-line sites near Mt. Whitney in the Sierra Nevada of California, Scuderi identified narrow rings in the temperature-sensitive subalpine *Pinus balfouriana.* He proposed that the narrow rings were linked to the increase in stratospheric optical depth following volcanic eruptions. He further suggested that the absence of volcanic activity was responsible for periods of increased growth; particularly during the mediaeval climatic optimum AD 1000 - 1250 and 1890 - 1980.

Scuderi observed 53 severe ring width events in the period 500 BC - 600 AD, eight of which correlated with known volcanic eruptions. A further 38 severe ring width events were observed between 600 - 1980 AD, eight of which again correlated with known volcanic eruptions. Contingency analysis of these results, by Scuderi, suggested that the correlations observed between ring-width minima and the incidence of known volcanic eruptions was significant. As a result the suggestion was made that the 75 ring-width minima recorded by Scuderi, for which there was no known eruption, may indicate unknown volcanic eruptions.

The potential to enhance the eruption record, especially given the paucity of the eruption records when compared to the estimates of McClelland *et al*, [1989] that approximately 100 eruptions >VEI 5 occur per 1000 year study period, made Scuderi's study attractive. However, as with the work of LaMarche and Hirschboek [1984] no tree-ring response was associated with the eruptions of Tambora or Laki, the largest acid emitting eruptions of the Holocene and theoretically capable of a major climatic impact. This is an important point. The eruption of Tambora is the only event since 1800 which is held to have **depressed** global mean temperature by > 0.7°C [Post 1977, Stommel & Stommel 1979; Devine *et al.* 1984; Self *et al.* 1984; Stothers 1984; Sigurdsson & Carey 1984; Palais *et al.* 1989; Sigurdsson 1990]. No other eruption has approached this figure, the maximum being a depression of > 0.2 > 0.3°C, which falls within the standard deviation of normal temperature fluctuation [Angell 1990] and which is unlikely to be detected above the background noise in the data. The eruptions of Krakatoa, 1883, and Agung, 1963, are associated with a minimal ring width, but the scale of response was not significant.

The failure of the tree-ring minima studied by Scuderi to record significant volcanic events suggests that the technique is not infallible as a proxy record of volcanic eruptions [Pyle 1992]. Scuderi's suggestion that climatic amelioration may be caused by the absence of volcanic eruptions is also doubtful. Many external forcing mechanisms exist, of which the most important are changes in the level of solar activity. Eddy [1977] presented clear evidence that cyclical changes in solar activity were associated with climatic phenomenon. An increase in solar activity is associated with the mediaeval climatic optimum and a decrease with the Little Ice Age. Scuderi's attempt to explain these events solely by their correlation with volcanic eruptions is therefore dubious.

The use of Scuderi's tree ring chronology, as a proxy record of volcanic eruptions, is further undermined by the lack of correlation between this and the chronologies established by LaMarche and Hirschboek [1984]. Of the forty nine frost-rings, reported by LaMarche and Hirschboek, for the White Mountains and the western Rockies since 50 B.C., only five events correspond with any of the ring-width minima reported by Scuderi. The assumption cannot be made, that each ring-width minima is likely to represent the climatic impact of a volcanic eruption.

Alternative responses? Warming and Cooling.

This review of tree-ring response to volcanic eruptions has largely assumed that climatic cooling follows a volcanic eruption. Schneider however [1983], speculated that volcanically induced circulation anomalies could cause global climatic warming as well as cooling. Does the tree-ring record support this suggestion?

Hoyt and Siquig [1982] suggested that volcanic forcing had a greater influence on the temperatures of continental interiors than maritime regions. Evidence to support this was presented by Lough and Fritts [1987] who showed that, in eruption years, both cooling and warming was recorded by north American tree-rings. Temperature response was found to be conditioned by both the latitude of the eruption and the season and by the location of the tree. Cooling trends were identified in central and eastern US states and warming in western US states. The magnitude and extent of the temperature response varied, with the warming trends in western states most obvious in the winter records and cooling in the east most marked in the summer.

Volcanic eruptions occurring in latitudes >50 degrees north and between 20 degrees north and 10 degrees south generated the clearest response. Eruptions occurring in mid latitudes between 20 and 50 degrees north were observed to have little impact on global air temperature. High latitude eruptions were associated with a warming tendency in central northern states and cooling in south eastern states. Low latitude eruptions generated warming in the Pacific north western states and south western Canada and significant cooling in central and eastern states [Figure 1.6]. Washington State was seen to experience slightly warmer summers, while Philadelphia experienced cooler annual temperatures for up to two years after eruption years. The assumption that the impact of volcanic eruptions is restricted to temperature declines is seen to be unsupported. But the temperature differences were in the order of 0.2°C - 0.8°C. Are temperature departures on this scale likely to trigger land abandonment and the collapse of civilisations associated with the ring-width minima in the Irish Record? In the case of low-latitude eruptions, in particular, since significant warming may clearly occur as well as cooling.

This work is a valuable addition to both tree-ring studies and to the study of the climatic impact of volcanic eruptions. The warming and cooling shown to occur in eruption years, by Lough and Fritts [1987], suggests that cooling should not be the only response modelled, and this possibility should be considered when discussing the Irish record.

Discussion.

The physiological response of trees growing in marginal zones to external influences, will be governed by micro-meteorological and micro-environmental conditions specific to each location and attempts to extrapolate climatic and environmental change on a macro scale from these records must be treated with caution. The correlations between tree-ring chronologies which claim to record the climatic or environmental impact of volcanic eruptions are poor, as are the correlations **between** climatic reconstructions and eruption chronologies based on chronologies obtained from a wider area. Any attempt to extrapolate environmental conditions across a wide area from the physiological response of trees growing at marginal locations must be made with great care. The tree-ring response to major volcanic eruptions is sporadic and often not repeated in proximal chronologies.

Rather than assume a non specific deterioration in climate or solar receipts, a study of the factors which make a tree's location marginal may identify the specific mechanisms by which a volcanic eruption was able to trigger a recorded response. In these locations slight changes to the environment may have the potential to affect tree growth, since their ability to respond to environmental change is severely limited. Hence trees growing in marginal zones may respond to the short term, 2-3 year climatic deterioration associated with climatically effective eruptions, and put on limited growth. Narrow or damaged tree-rings need not be taken to indicate great climatic fluctuation, rather they demonstrate that slight climatic or environmental change has a severe impact in marginal locations. The Irish tree-ring chronology need not then indicate a series of volcanic eruptions and uniquely severe climatic deteriorations.

Irish tree-rings reinterpreted.

Baillie and Munro's [1989] statistical analysis of the correlation between narrow Irish tree-rings and ice-core acidity peaks demonstrated a significant relationship between the two phenomena. Ninety percent of the trees sampled exhibited stress in response to the Hekla 3 eruption. It appears probable that the volcanic eruptions recorded in the ice-cores did affect the environment of the Irish bog-oaks. However, the discussions above suggest that it is unsafe to assume that the environmental change indicated by the Irish tree-ring record was a widespread phenomenon. The range of phenomena and dates associated with the Hekla 3 eruption occupy most of the 12th century BC, and it is unwise to assume that the Hekla eruption was the sole such event in the entire period. Nor was the Hekla 3 eruption of the magnitude which might be expected to generate the global phenomena ascribed to it [Devine *et al.* 1984]. The continuing debate concerning the scale and precise climatic impact of the far larger eruptions of the Laki fissure and Tambora, suggest that care be exercised when ascribing wide ranging and extreme phenomena to the far smaller eruptions recorded by the Irish chronology.

The narrow rings in the Irish chronology need not indicate that poor climate was widespread. The work of Briffa *et al.* [1988] demonstrates that tree growth in the western fringes of Europe is rarely synchronised with tree growth in central and eastern Europe. Similarly Lough and Fritts

[1987] demonstrated that in North America, volcanically-induced circulation anomalies might result in warming as well as cooling in the areas affected. This must be true for Europe and Asia also. Narrow tree-rings in Ireland need not, and probably do not, indicate an episode of cooling across Europe and Asia. An amelioration in Near Eastern Turkish climate is indicated by broad tree-rings in the Turkish record at 1159 BC [Kuniholm 1990].

The environmental stress indicated by the Irish chronology persisted for decades. We must ask therefore "does the Irish chronology record severe and long lived climate change, a time-lagged environmental response to external forcing or an unspecified deterioration in the environment in which the Irish trees survived?" There are no known mechanisms by which a volcanic eruption may alter north Atlantic climatic circulation patterns for up to twenty years. Either the eruptions recorded in the Irish tree-ring chronology, and the Hekla 3 eruption in particular, were more climatically effective than any other known, or there is another mechanism responsible. Many studies indicate that local environmental conditions control the response of a tree to external environmental forcing [Conkey 1986; Graumlich & Brubaker 1986; Jacoby *et al.* 1988].

In what ways can the environment of the Irish trees be interpreted as marginal, and how may a volcanic eruption have intensified this for decadal length periods? The Irish trees exhibit stress which may be interpreted as occurring in response to a persistent environmental deterioration or as a time-lagged environmental response to a single event. Jacoby *et al.* [1988] noted that trees growing in a marginal location in Quebec experienced stress in the years 1816 and 1817, when the aerosols from volcano Tambora may have diminished solar receipts. Recovery from this stress was slow, but difficult to isolate from the general climatic trends established elsewhere. It is therefore difficult if not impossible to isolate evidence for climate change for a single decade in prehistory. Nevertheless the mechanisms by which the Irish chronology was vulnerable to long term stress may be identified. The trees from which the Irish chronology is constructed cannot be considered marginal in respect of either the altitude or the latitude at which they growing. They did, however, grow in a situation which may be considered unique for oak trees, on raised bogs on peat up to seven metres in depth [Pilcher 1992]. There are specific conditions which make a raised bog an unattractive situation for an oak tree to grow. Raised bogs are an acidic environment, with a low pH and a low base status. They also have poor nutrient supply and a low Cation Exchange Capacity and can also be waterlogged [Ashmore *et al.* 1988]. Baillie [1982 p. 200] discussed the narrowness of the Irish tree-rings in respect of German chronologies, and suggested that this was due to the poor levels of nutrient in the Irish peat. The Irish oak trees can be considered likely to exhibit stress in response to their environment throughout their lives, but to exhibit particular stress following some volcanic eruptions. Irish oak trees may then be considered marginal in respect of the acidity of the bog, the nutrient availability and the degree of waterlogging.

Could a volcanically induced climatic change result in a significant increase in rainfall and subsequent waterlogging of the bog? This question will be discussed in detail in Chapter 3, but no significant increase in rainfall has been observed following nineteenth and twentieth century eruptions. If not the local "climate" then we must consider whether the acidity and nutrient status of the bog were vulnerable to volcanic eruptions. Acid rain will reduce the base status and lower the pH of an acid sensitive environment. In a raised bog, the replenishment of bases removed by acid rain may take decades [Mulder *et al.* 1989]. Icelandic volcanic eruptions may produce large volumes of acid gases and aerosols. Tephra from Icelandic eruptions has been found in Northern Ireland [Pilcher & Hall 1992] and Scotland [Dugmore 1989] which demonstrates that eruption clouds may travel from Iceland to northern Britain. Could the Irish tree-ring chronology record episodes of acid deposition and the slow replenishment of leached bases? We must consider the possibility that rather than generate an unspecified and extreme degree of climate change, the volcanic eruptions recorded in the Irish chronology may have had a direct impact on the acid sensitive ecology of Northern Britain and Ireland. Such a model identifies the specific conditions by which the environment of the Irish Oaks may be considered marginal, and the specific mechanisms by which Icelandic volcanic eruptions may have a significant impact on this environment.

Chapter two.

Climatic responses to volcanic eruptions.

Summary of Chapter.

This chapter discusses the theoretical and empirical framework on which much of the debate which associates volcanic eruptions and climate change has been based. Historical records are used to suggest that there is some justification for the assumption that a volcanic eruption may bring about climate change, but the often loose (and convenient) correlation of historical events and volcanic eruptions is challenged. In this chapter The use and construction of various eruption chronologies are considered and it is demonstrated that many of them are inadequate. Alternative records of volcanic activity, in particular ice-core acidity are considered. Measures of a volcanic eruption's ability to effect climate change are discussed. In particular the "Dust Veil Index" [DVI] and "Volcanic Explosivity Index" [VEI] are examined. As an estimate of the potential of an eruption to perturb climate, the DVI is shown to be inadequate in that it over emphasises the importance of dust output and employs a circular argument to establish the relationship between "climatic flux" and eruption magnitude. The degree to which temperatures have responded to Twentieth Century A.D. eruptions is considered and the mechanisms by which a volcanic eruption may perturb climate are discussed. Understanding of the Hekla 3 eruption placed in the context of these issues.

Why have volcanic eruptions been identified as having the potential to effect environmental change? We need to understand the climatic mechanisms by which environmental change may be caused in regions which are distant from the eruption. In particular was the Hekla 3, eruption of the magnitude which could trigger the typical scale of settlement abandonment described by Burgess [1985, 1989] and could it have caused the global and climatic phenomena described by Baillie [1988, 1989 a & b; 1991 a & b] and Pang *et al.* [1987, 1988, 1989]?

Volcanic eruptions and surface cooling.

The assumption that cooling will follow a volcanic eruption is based on observations made by Benjamin Franklin in Paris, in 1783. Franklin described atmospheric and climatic phenomena, which we now know were the result of the Laki fissure eruption in Iceland.

> *"During several of the summer months of the year 1783, when the effect of the sun's rays to heat the earth in these northern regions should have been greatest, there existed a constant fog over all Europe and great part of North America. This fog was of a permanent nature; it was dry, and the rays of the sun seemed to have little effect towards dissipating it, as they easily do a moist fog arising from water. They were indeed rendered so faint in passing through it that when collected in the focus of a burning glass, they would scarce kindle brown paper. Of course, their summer effect in heating the earth was exceedingly diminished.*
>
> *Hence the surface was early frozen.*
>
> *Hence the first snows remained on it unmelted, and received continual additions.*
>
> *Hence the air was more chilled, and the winds more severely cold. Hence perhaps the winter of 1783-4 was more severe, than any that had happened for many years.*
>
> *The cause of this universal fog is not yet ascertained. Whether it was adventitious to this earth...or whether it was the vast quantity of smoke, long continuing to issue during the summer from Hecla in Iceland, and that other volcano which arose from the sea near that island, which smoke might be spread by various winds over the northern part of the world, is yet uncertain. It seems however worth the enquiry, whether other hard winters, recorded in history, were preceded by similar permanent and extended summer fogs."*
>
> [Franklin 1784].

Franklin's observations make it possible to suspect and even detect the impact of other volcanic eruptions in extant historical records.

In 44 B.C., Plutarch described the veiling of the sun's rays

> *"..the obscuration of the sun's rays. For during all that year its orb rose pale and without radiance, while the heat that came down from it was slight and ineffectual, so that the air in its circulation was dark and heavy owing to the feebleness of the warmth that penetrated it, and the fruits imperfect and half ripe, withered away and shrivelled up on account of the coldness of the atmosphere"* [*Plutarch* cited in Stothers & Rampino 1983a].

Not all volcanic eruptions are so clearly identified with atmospheric veiling, but a strong ice-core acidity signal [Herron 1982] suggests that an unknown volcanic eruption was responsible for similar phenomena in the year A.D. 536:

> *"The sun became dim...for nearly the whole year...so that the fruits were killed at an unseasonable time"* [*John Lydus* cited in Stothers & Rampino 1983b, Stothers 1984].

> *"... the sun gave forth its light without brightness, like the moon, during this whole year, and it seemed exceedingly like the sun in eclipse, for the beams it shed were not clear, nor such as it is accustomed to shed"* [*Procopius* cited in Stothers & Rampino 1983b].

> *"... the sun was dark and its darkness lasted for about eighteen months; each day it shone for about four hours, and still this light was only a feeble shadow...the fruits did not ripen and the wine tasted like sour grapes"* [*John of Ephesus*, cited in Stothers 1984].

Similar accounts can be found in Chinese historical annals [Pang *et al.* 1987, 1988, 1989]. One such has been dated to 1600 ± 30 BC, and correlated with narrow tree-rings in the Irish Record [Baillie & Munro 1988], frost-damaged tree-rings in California [LaMarche & Hirschboek 1984], and an acid peak in the Greenland ice-core [Hammer *et al.* 1987].

> *"At the Time of King Chieh the sun was dimmed ... Winter and summer came irregularly ... Frosts in the sixth month ... The five cereals withered ... therefore famine occurred"* [Pang *et al.* 1989]

The common themes in the accounts above are a reduction in the energy of the sun's rays as they reach the earth and a veiling or dimming of the sun. The comments of Franklin in 1784 allow us to suggest that these phenomena indicate the presence, in the atmosphere of volcanic aerosols. It would be easy to assume that similarly cool summers, harsh winters and poor harvests generated the environmental stress indicated by the Irish tree-ring record. A severe, if unspecified, environmental deterioration could then be postulated with some degree of "theoretical confidence" and volcanic influence on settlement abandonment in northern Scotland postulated. But is the dating framework secure enough to allow this interpretation to be suggested with confidence? Are such descriptions firm enough to allow us to construct models of critical environmental change in upland Scotland, in which volcanic eruptions appear to be the only independent variable?

Correlating historic climate records and volcanic eruptions: the need for caution.

The need for caution can be demonstrated by further investigating one of the cases cited above, for which the Chinese "Annals", Irish and American dendrochronological research and ice-core evidence appear to be in agreement in recording the impact of a major volcanic eruption, the eruption of Thera. It was suggested that several lines of evidence, tree-ring width minima and ice-core acidity peaks, have actually recorded the impact of the eruption of the Greek island of Thera, in Minoan times [Hammer *et al.* 1987; Manning 1988]. Pang *et al's.* [1989] estimated date for this event was reached by "counting back" the generations from a "secure date" of 841 BC. To the cynical this gives a sixty year window around 1600 BC within which any convenient volcanic eruption may be "blamed" for the "impacts" detected. It is unrealistic to suggest that only one significant volcanic eruption, that of Thera, occurred within this time frame [McClelland *et al.* 1989]. Vogel *et al.* [1990] and Beget *et al.* [1992] list at least three other major eruptions which took place within this period: Avellino in Italy, Mt. St. Helens in Washington State, and Aniakchak in Alaska. To further disturb the "Theran" argument, the dating of the acid peak in the Greenland ice-core record has been revised from 1390 ± 50 BC [Hammer *et al.* 1980] to 1645 ± 7 BC [Hammer *et al.* 1987]. Subsequently Hammer and others [1988], Cadogan [1988] and Pyle

[1989], suggested that it was unlikely that the eruption of Thera was the culprit for all or any of the phenomena which researchers were attempting to assign to it. A strict interpretation of dates places the ice-core acidity peak outside the time frame suggested by the Chinese Annals. The "absolutely" dated tree-ring records indicate environmental stress in the period 1628-1626 B.C. [LaMarche & Hirschboek 1984; Baillie & Munro 1988], which is at least 10 years after the ice-core acidity peak date, and only just within the sixty year range suggested for the poor summer in China. The desire to link such phenomena and the stretching of the dating frameworks involved is an attractive but questionable practise and one which is discussed in depth by Baillie [1991 a & b].

All such attempts to **link** (and hence infer associations between) historic eruptions and environmental phenomena and human "impacts", rely on the accurate and precise association in time of the two events. The account above suggests that this does not occur for the eruption of Thera. A more general investigation of eruption chronologies constructed since 1970 suggest that such associations are not reliable when based on eruption data gathered earlier than the twentieth Century.

Eruption Chronologies.

The use of eruption chronologies to prove that volcanic eruptions are the major independent variable in the generation of transient but powerful "fluctuations" such as cooler temperatures, damaged tree-rings, disturbed atmospheric circulation patterns, famine and social unrest, remains problematic. The mere association of an eruption and an environmental phenomenon thought worth recording in the past is not proof of a dependent relationship.

> *"There is no question but that the available data suggest an unmistakable coincidence in time between the occurrence of major volcanic eruptions and an accompanying or subsequent minimum in curves of surface temperature. The important question remains whether this represents a causal relationship or a mere coincidence in time"*. [Ellsaessar 1986 p.1184].

A review of four eruption chronologies constructed since 1970 will illustrate the problem [Figures 2.1 & 2.2]. In 1970, Lamb's seminal work on volcanic activity and climate change published an eruption chronology for the years 1500 - 1969. This recorded 380 known eruptions. Ten years later Hirschboek [1980] presented a revised eruption chronology which recorded 4796 eruptions for the same period, a very significant increase on Lamb's figure. Simkin and others [1981] raised this figure to 7664 eruptions and Newhall and Self [1982] further increased the number of known eruptions in this period to 7713.

While the upgrading of eruption chronologies presents a manageable problem the deterioration in the temporal quality of the data is less easily accounted for. The difference between the number of eruptions recorded in the twentieth century and in the sixteenth century can be seen on Figures 2.1 and 2.2 and in Table 2.1. The marked rise in the number of volcanic eruptions recorded in each century is a factor of better reporting rather than a real increase in eruptive activity.

	Lamb 1970.	**Hirschboek 1980.**	**Simkin *et al.* 1981.**	**Newhall & Self 1982.**
1600-1699.	**27.**	**176**	**436**	**270.**
1900-1969.	**57**	**1942**	**3018**	**3480.**

Table 2.1. Recorded eruptions Sixteenth and Twentieth centuries.

The paucity of eruption data in earlier periods is illustrated in Figure 2.1 which shows that 3018 eruptions were recorded between 1900-1969 and 11 were recorded between 1 and 100 AD. [Simkin *et al.* 1981]. The data is also weighted, for obvious reasons, by observations made in Europe [Stothers & Rampino 1983 a & b] and in China [Pang *et al.* 1986, 1987, 1989].

The role and application of the **Volcanic Explosivity Index** [VEI] will be reviewed below but recent work on eruption frequency and scale in the Twentieth century A.D. [McClelland *et al.* 1989], indicate eruption frequencies per 1000 years of 12 000-VEI 1, 12 000-16 000-VEI 2, 4000-5000-VEI 3, 600-VEI 4, 65-VEI 5, 25-VEI 6 and 1-5-VEI 7. This gives a total expected eruption rate of approximately 30 000 per 1000 years. The fact that only 19 eruptions ^{3} VEI 5 are known of [Simkin *et al.* 1981], out of an expected frequency of 100, shows that caution must be used in the application and correlation between eruption chronologies and other "proxy" data.

The poor nature of the data makes any attempt to prove an association between recorded historical eruptions and weather by statistical analysis a doubtful exercise. Equally problematic is any attempt to suggest that **mere association** is sufficient to suggest that one of the few recorded eruptions might be responsible for archaeological, palaeoenvironmental or historical phenomena.

Within the twentieth century A.D., despite improved reporting and recording of eruptions, volcanic events have sometimes gone unrecorded. Simkin *et al.* [1981 p.25 their Figure 5] show that the number of recorded eruptions dropped steeply during the First and Second World Wars. Hoyt [1978] suggested that an unrecorded major eruption in 1928, of Paluweh on the Lesser Sunda Islands, Indonesia, was responsible for the reported atmospheric turbidity and a decrease in Northern Hemisphere summer temperatures of 0.3°C. Sedlaek and others [1983] monitored sulphur concentrations in the stratosphere between 1971-81 and noted several injections of volcanic sulphates into the stratosphere for which **no** eruption had been recorded or reported in the literature.

This analysis shows that the dating framework within which volcanic events and historical or environmental records of climate change are related cannot be regarded as accurate. It is not sufficient to assume a causal relationship between an eruption and an environmental response. Not all eruptions modify climate and it is not sufficient to model an unspecified, but large, volcanic event, and an unspecified, but severe, degree of climate change. To deal with this problem an eruption must be categorised, the size of an eruption must be estimated, and the degree of climatic change expected to follow modelled. Two attempts to do this are the work of Lamb [1970] who constructed a measure known as the **DUST VEIL INDEX**, and Newhall and Self [1982] who constructed the **VOLCANIC EXPLOSIVITY INDEX**.

THE DUST VEIL INDEX.

An attempt to quantify the "climatic effectiveness" of volcanic eruptions was made by Lamb [1970, 1972, 1977], who worked on the principle that the passage of the sun's rays through the atmosphere was primarily inhibited by the volume of dust emitted in an eruption. The climatic effectiveness of any single volcanic eruption could therefore be assessed by an measuring, or estimating, its dust (*i.e.* tephra) output. Lamb's measure of climatic effectiveness was termed the Dust Veil Index [DVI] and has formed the basis for much subsequent work. Focusing on the volume of dust emitted by different eruptions, and using the 1883 eruption of Krakatau as a standard, Lamb constructed a classified chronology of eruptions. The volume of dust emitted in an eruption was correlated with available temperature records, and Lamb's research suggested a positive correlation between low temperatures and a DVI ≥100.

Lamb emphasised the importance of the role played by the fine dust thrown into the stratosphere during an eruption. Lamb further suggested that stratospheric circulation would pass dust from low latitude eruptions around the world whilst dust from high latitude eruptions would remain in the hemisphere of origin. Different climatic impacts were therefore modelled for eruptions which occurred at different latitudes. Several other controlling parameters were suggested, in addition to the latitude of the eruption, which ought to have a key role in causing climate change, these were; the residence time of the dust in the atmosphere, the size of the dust cloud, the maximum departure from average temperature and the greatest depletion of incoming solar radiation.

It is worth exploring the relationships of the parameters used by Lamb in his formulae as these constitute the basis for much later work. The DVI could be calculated in three ways:

$$\mathbf{DVI = 0.97RDmax\ Emax\ tmo.}$$

$$\mathbf{DVI = 52.5tdmax\ Emax\ tmo.}$$

DVI = 4.4qEmax tmo.

Where **RDmax** = the greatest percentage depletion of direct solar radiation shown by the average monthly temperatures for the hemisphere concerned.

Where **Emax** = the greatest proportion of the earth affected by the dust veil. **Emax** = 1 for eruptions between 20° latitude north and south; 0.7 for eruptions between 20° and 35° north and south; 0.5 for eruptions between 35° and 42° north and south; and 0.3 for eruptions occurring above 42° latitude.

Where **TDmax** = the estimated average lowering of temperature for the most affected year over the middle latitudes of the hemisphere affected.

Where **q** = the estimated volume in cubic kilometres of solid matter injected into the atmosphere.

Where **tmo** = the residence time of the dust in the atmosphere.
Lamb considered that those eruptions achieving a DVI of 100 or over were capable of a significant impact on climate.

There are problems with the use of Lamb's indices. Values of **R**, **T**, and **t**, are calculated from observations in mid-latitudes but these are not necessarily where the maximum effect of a low or high latitude eruption would be felt. Calculating the DVI of an eruption based on recorded values of **T** (temperature lowering) could lead to a circular argument. This is because any temperature variation from the norm is directly related to the size of an eruption, and not to any other external forcing factors such as variation in the output of energy from the sun [Eddy 1977, 1992], or fluctuations in the earth's orbit [Kukla 1979]. Problems also lie in the use of an inadequate Eruption Chronology, and in the assignment of a values for **RDmax** (greatest depletion in Solar radiation) and **Emax** (latitudinal dispersal of the dust cloud) from proxy records. Inadequate data exists from which to assign a DVI to eruptions prior to the nineteenth century, or to small eruptions, or where several eruptions were closely spaced. As a result there is a real risk of entering into a circular argument where temperature declines are used to support estimates of the value of **RDmax**, which value is then held as a measure of the degree of eruption magnitude. It is simply not safe to assume that all temperature departures in eruption years are the result of volcanic activity. Estimates of **Emax** fail to take into account the possibility of other phenomena such as dust storms being interpreted as being of volcanic origin. Of Lamb's 250 DVI estimates only 10% were based on measured observations of a decrease in solar radiation or fall in temperature, whilst 48% were based on non-quantitative descriptions of eruptions such as may be gleaned from travellers' accounts and eye witness observations [*cf.* Burton 1875; Nordenskiöld 1876] . Problems also arise in the existence, accuracy and relevance of temperature records. Accurate and precise temperature records do not exist beyond the seventeenth century [Manley 1974] and reliance on other types of observations of climatic severity can be misleading. Baillie [1982 p.248] noted three instances of the "worst winter in living memory" within a five year period in Ireland 1766-71. Temperature series constructed from observations made in a continental interior may not be relevant for conditions on the continental fringe and obviously the opposite must be equally true.

In order to assess the value of the DVI as a tool to be used in reconstructing the climatic impact of prehistoric eruptions, several studies which have linked the DVI to environmental change, will be reviewed below.

Applications of the DVI.

Pursuing Lamb's theme, other workers announced significant negative deviations in surface temperature following the injection of volcanic dust into the stratosphere [Mitchell 1971; Mass & Schneider 1977]. In an early attempt to refine the use of the DVI as a major climatic forcing mechanism, Cronin [1971] investigated the periodicity with which volcanoes had erupted in the mid Twentieth Century A.D. He suggested that the eruption of volcanoes at lower latitudes where the stratosphere is lower, had a greater climatic impact than the eruption of volcanoes at high latitudes, where the stratosphere is higher. Cronin's work was undermined by the use of an inadequate "Eruption Chronology". Several significant twentieth century eruptions A.D. were ignored. In particular eruptions of Alaskan volcanoes (Trident in 1952 and Spurr in 1953), and of Bezymianny on the Kamchatka peninsula, in Siberia in 1956, and the Japanese volcano Tokachidake in 1962, were all absent from his analysis.

Bray [1974] used the DVI in an attempt to correlate volcanic activity and glacier response in the northern and southern hemispheres over the past 40 millennia. In an attempt to prove a monocausal relationship between the two phenomena, this work demonstrates the problems inherent in such an approach. His work was hindered by an inadequate eruption chronology. The response of glaciers to volcanic forcing was inconsistent, in some cases it was synchronous and in others lagged by up to 100 years. Both the accurate dating of volcanic eruptions which occurred up to forty thousand years ago and the estimation of their DVI was problematic. The DVI was inadequate to explain all glacier response and the inconsistent response time suggested further problems with the use of the DVI to account for climate change.

The theme of glacier response to significant DVI events was pursued by Bradley and England [1978]. Between 1947-1963 glaciers in the North American High Arctic experienced a continuous loss of ice at a rate of *circa* 3500 kg/m2/yr. After 1963, this loss fell to 350 kg/m2/yr. They suggested that the DVI of 800 calculated for the 1963 eruption of the Indonesian volcano Mt. Agung, indicated its responsibility for this phenomenon. As with the work of Cronin [above], Bradley and England ignored or were unaware of significant DVI events between 1947-1963. They also assumed a "temperature response" to volcanic eruptions which was not quantified. In fact, in the first year after the eruption of Mt. Agung, a decrease in northern hemisphere temperatures of no more than 0.42°C is reported and temperatures had returned to normal by the third year after the eruption [Hansen *et al.* 1978; Newell 1981a; Rampino & Self 1982]. The 1963 eruption of Mt. Agung is therefore unlikely to have been the sole cause of north American glacier fluctuation and the DVI is shown to be an inadequate measure of volcanic ability to force climate change.

There is obviously a flaw in the deterministic application of the DVI in studies of climatic change. Miles and Gildersleeves [1978] suggested that the problem lay in the reliance on questionably complete eruption chronologies, but it may equally lie in the assumption that volcanic eruptions are the sole or major independent variable capable of generating climate change.

The DVI is seen to be an inadequate measure of the climatic effectiveness of a volcanic eruption. In the case of prehistoric eruptions which may have had an impact on the north British environment, the calculation of a DVI would be largely inaccurate. The "responsible" eruptions are not always clearly identified, and to calculate a probable DVI from a climatic response which itself has been estimated as a result of supposedly related settlement abandonment, or tree-ring stress would lead to a circular argument. It is not sufficient to demonstrate that narrow tree-rings in Ireland apparently correlate with apparently large ash-producing eruptions, which might have caused a climatic deterioration in Northern Britain. The DVI is therefore an inadequate measure for such purposes. Other estimates of magnitude were subsequently developed as a result of some of the failings described above.

The Volcanic Explosivity Index.

An alternative measure of volcanic eruptions was proposed by Newhall and Self [1982] who suggested that it was the volume of dust injected into the stratosphere which determined the climatic effectiveness of an eruption and advanced a Volcanic Explosivity Index [VEI], as a measure of this effect. The VEI depends on an estimation of five parameters of magnitude first suggested by Walker [1980, 1981]. These are:

1. **Magnitude.** Determined from the volume of volcanic ejecta.
2. **Intensity.** Determined by the volume of ejecta per unit time calculated from column height and velocity.
3. **Dispersive power.** Determined from column height.

4. **Violence of the eruption.** Analogous to intensity but meant for instantaneous rather than sustained eruptions.

5. **Destructive potential.** Determined by the extent of devastation, actual or estimated, caused by an eruption.

VEI (km)	CRITERIA DESCRIPTIVE	VOLUME OF EJECTA(m3)	ERUPTION COLUMN HEIGHT
0	non - explosive	<104	<0.1
1	small	104 - 106	0.1 - 1.
2	moderate	106 - 107	1 - 5
3	mod - large	107 - 108	3 - 15
4	large	108 - 109	10 - 25
5	very large	109 - 1010	>25
6	very large	1010 - 1011	>25
7	very large	1011 - 1012	>25
8	very large	>1012	>25

Table 2.2. The Volcanic Explosivity Index.

As with the DVI, estimates of the VEI are necessarily based on estimates of variable quality, but being based on volcanologically-derived data it removes the circularity of argument which was built into the use of RDmax and Emax in estimating the value of the DVI. Based on these factors a Volcanic Explosivity Index was assigned to known eruptions on a scale of 0 - 8 Table 2.2.

Eruptions assigned a VEI ≥4 are those which are estimated to have produced at least 10^8 m3 of ejecta and achieved column heights of 10 - 25 km. These estimates are independent of observations of temperature depression, atmospheric effects, decreases in radiation receipts or by climatic observations in mid-latitudes. As such the estimates of magnitude reached are climatically independent. Attempts to link significant VEI events and climatic change avoid some of the pitfalls which undermined the use of the DVI. Cruz-Renya [1991] subsequently demonstrated that using the VEI, the scale and frequency of volcanic eruptions could be fitted by a Poisson distribution. Thus one eruption of VEI ≥7 and 100 VEI 4 can be expected in a 500 year period if time is viewed as a statistically "normal" sample population.

While the VEI includes estimates for magnitude and stratospheric penetration, a significant degree of climatic forcing associated with volcanic events assigned a VEI ^{3}4 is assumed rather than demonstrated [Hingane *et al.* 1990; Mukherjee *et al.* 1987]. In a critical review of the application of this index to studies of climate change, Bradley [1988] found a statistically-significant temperature anomaly when the 44 known events with a VEI $\geq$4 between 1883 and 1981 were analysed through a "superposed" epoch analysis. However, the observed temperature reduction was small, between 0.05 to 0.1°C, and seen only in the month following the eruption. When the eruptions were divided into three latitudinal zones, no significant temperature departure in either the latitudinal zone, or the northern hemisphere as a whole was observed. Large, but historically-rare events, such as the 1912 eruption of the Alaskan volcano Katmai, assigned a VEI of 5 or more, were correlated with temperature depressions <0.4°C lasting for 2 to 3 months. Temperature responses of this degree seem an unlikely catalyst for long-term environmental change in northern Britain and there appears to be no evidence that any large eruption, of VEI <4 has had a significant effect on low frequency temperature changes.

Eruption chronologies based on personal observations are inevitably weighted by both time and location, hence the vast increase in recorded eruptions in the twentieth century and the dominance of Mediterranean eruptions and Chinese observations in the early historic records. Poor recording and geographic weighting have hindered attempts to isolate "clear volcanic signals" from the background noise of the environmental and historical records.

ICE CORE DATA.

Proxy records of volcanic eruptions constructed from material deposited on the Greenland and Antarctic ice cap have may the potential to identify climatically-significant eruptions with greater reliability and precision. The annual deposition of snow in the Earth's polar regions contains a wide range of atmospheric, climatic and environmental information [Lorius 1990]. The accumulation, in Greenland, of annually deposited snow, over a period of 150 000 years, preserves this information in consecutive dateable layers. Though the precision of the record deteriorates with time as it becomes more difficult to identify annual snow deposition, some the acids and particles emitted by some volcanic eruptions will, with luck, be preserved in each "annual" layer. Prominent acidity peaks or micro-particle concentrations, in ice-cores can be used as reference horizons [Langway *et al.* 1988], and allow an estimate to be made of climatically significant volcanic activity which is not biased in time and space by human "observation".

Acidity.

Acid concentrations within ice cores may be a good source of information on both the occurrence and the intensity of volcanic events. Hammer [1977, 1984] and Hammer and others [1980, 1981] constructed a chronology using acidity concentrations in the Dye 3, Crête and Camp Century ice cores from Greenland. The concentration of these acidity peaks can be used as both an indicator of climatic impact and of global acid fall out. Since it is the volume of acids injected into stratosphere that forces climate change, the acid level in the ice-core offers a means to check the acid output and hence potential climatic impact of historically-famous eruptions, and identify the occurrence of unrecorded events. .

Rather than recording all eruptions, ice-core acidity peaks are best viewed as providing a record of the occurrence of volcanic events which have the potential to affect climate [Sigurdsson 1982]. This removes much confusing noise from the Eruption Chronology and records the occurrence of eruptions which may not have appeared in other records. Several such ice-core acidity peaks appear to correlate with ring-width minima in the Irish record [see Chapter One]. For further information Table 2.3 presents a list of eruptions with significant acid peaks and estimates of their acid fallout in Greenland and on a global scale.

Trends in global volcanism can also be detected and correlated with global temperature trends. Ice-core acidity records [Table 2.3] indicate that the highest rates of volcanic activity since AD 533 occurred in the periods AD 1250-1500 and AD 1550-1700; the initial and culminating phases of the Little Ice Age. Similar work in both Greenland and Antarctica [Dia *et al.* 1991; Legrand & Delmas 1987] allow the ice core acidity record to be refined and the removal of the inevitable latitudinal bias which the proximity to Greenland of the volcanic areas of Iceland, Alaska and Kamchatka has introduced. Both Dia et al. [1991] and Legrand and Delmas [1987] record a major acid peak in 1810, which preceded the massive eruption of the Indonesian volcano Tambora in 1815 and suggest this pre-Tambora event which is absent from eruption chronologies compiled from "personal observations" and historical records, was on the scale of the 1963 Mt. Agung eruption.

Langway and others [1988] present ice core acidity evidence for an unrecorded acid producing event in 1259 AD, which produced an ice-core acidity signal on the scale of that produced by the Laki fissure an Tambora eruptions. The omission of an event of this scale from eruption chronologies derived from other sources illustrates their failings, and demonstrates the futility of using such compilations to assign statistical significance to the correlation of known eruptions and climatic extremes.

Often the magnitude of acid peaks has allowed an estimate to be made of the comparative magnitude of each eruption. Clausen and Hammer [1988] analysed the acid signal of the 1783 eruption of the Laki fissure and the 1815 eruption of Tambora and suggested that global acid emission for each event was over 200 X 10^6 tons. The identification of the acid peaks associated with climatically significant events in relatively recent times will allow an estimation to be made of the climatic effectiveness of the smaller eruptions thought to have had a significant impact on the north British environment in the past.

			Volcanic acid fallout in Greenland. kg km2.	Global acid fallout X106
CRETE.	Location.	Date		
Agung	Indonesia	1963	9	20
Hekla	Iceland	1947	6	5
Katmai	Alaska	1912	37	30
Krakatoa	Indonesia	1883	21	55
Tambora	Indonesia	1815	58	360
Laki	Iceland	1783	116	280
Lanzarote	Canary Isl.	1730-36	36	60
Krafla	Iceland	1724-30	63	55
Unknown	?	1666?		
		}	60	100
Pacaya	Guatemala	1664		
Awu	Indonesia	1641		
Adiksa	Indonesia	1641 }	81	190
Komagatake	Japan	1640		
Unknown	?	1600/01	61	50
Raudubjallar	Iceland	1554	23	20
Unknown	?	1257/58	128	300
Hekla 1	Iceland	1104	51	45
Eldgja	Iceland	934	189	165
Unknown	?	622/23	52	45
Camp Century.	Location	Date BC.		
Unknown	?	50±30	192	120
Unknown	?	210±30	72	45
Unknown	?	260±30	54	35
Hekla 3	Iceland	1120±50	99	60
Thera	Greece	1390±50	98	125
Hekla 4	Iceland	2690±80	96	60
Unknown	?	3150±90	255	160
Mt. Mazama	Usa	4400±110	156	200
Hekla 5	Iceland	5470±130	90	60
Unknown	?	6060±140	119	75
Unknown	?	6230±140	102	65
Unknown	?	7090±160	79	50
Unknown	?	7240±160	124	80
Unknown	?	7500±160	51	35
Unknown	?	7640±170	412	260
Unknown	?	7710±170	69	45
Unknown	?	7810±170	73	45
Unknown	?	7910±170	95	60

Table 2.3 . Magnitude of volcanic events estimated from the annual acidity layers in ice-cores in Greenland. Based on figures retrieved from Hammer *et al.* [1980] and upgraded after Clausen and Hammer [1988] & Langway *et al.* [1988].

Micro-particle content.

As with acid output, so the tephra emitted in volcanic eruptions may be deposited in the annual layers of an ice-core. Betzer *et al.* [1988] discovered the long range transport of mineral particles up to 10 000 km from their source and Ram and Gayley [1991] have discussed the long range transport of volcanic material to the Greenland ice-sheet. Micro particle concentrations in an ice-core may therefore indicate the occurrence of large ash-producing volcanic eruptions.

Several "peaks" in micro particle concentration in an Antarctic ice-core drilled at the Amundsen-Scott South Pole Station [Thompson & Moseley-Thompson 1981] were found to correlate with known volcanic eruptions Krakatoa, Indonesia 1883; Coseguina, Nicaragua in 1835; Tambora, Indonesia in 1815 and Mayon, Luzon in 1766. Examination of particles under a scanning electron microscope [Moseley-Thompson & Thompson 1982] confirmed the volcanic origin of the material. Micro particle concentrations may therefore offer an alternative or complimentary record of eruption history.

Correlating results from Antarctica, Greenland and Devon Island, Danny-Harvey [1988] found that large increases in atmospheric aerosol loading had occurred during the "Late Devesian-Glacial Maximum". The optical depths indicated by the aerosol content of the ice-core were calculated and the results suggested that increases in aerosol content at that time would have lowered the global mean temperature by 2-3 degrees centigrade, a significant contribution to global cooling. Petit *et al.* [1990] also linked the dust record in the Vostok [Antarctic] ice-core, with palaeoclimatic trends in the southern hemisphere, and confirmed the work of Danny-Harvey [1988] that a significant increase in dust loading of the atmosphere occurred in the Late-Glacial cold maximum. However they estimated that the maximum volcanic contribution to the ice-core dust levels was never greater than 20% of the total micro-particle content.

This discussion of the construction and application of Eruption Chronologies has been necessary in order to demonstrate that the simple association of an eruption with environmental phenomena elsewhere is insufficient proof of a causal relationship. Both the DVI and VEI were shown to be inadequate both in terms of the number of eruptions recorded and the criteria measured. Even in the twentieth century eruptions have gone unrecorded. Extreme caution must be exercised in any attempt to link the few eruptions identified in prehistoric times with palaeoenvironmental change.

In order to be considered climatically significant, a volcanic eruption must emit a significant volume of acid volatiles. Even where a temporal association between an eruption and an environmental phenomenon elsewhere is demonstrated, if the eruption was not acid-producing a relationship between the two events cannot be assumed or accepted. Ice-core data provides a partial proxy record by which acid emissions and dust output can, in appropriate circumstances, be reconstructed. The correlation of an acid-producing eruption and environmental phenomena may suggest a link between the two events. A further measure of this relationship may be found in the environmental response of trees to volcanic forcing of climate. The record of stress in the dendrochronological record and acid peaks in the ice-core record may indicate that an historic or prehistoric eruption had an environmental impact elsewhere - but matters may also be more complicated.

Models: Volcanic Eruptions and Climatic Impact.

To evaluate the potential environmental impact of volcanic eruptions on the north British environment, it is necessary to review the mechanisms by which they are held able to modify climate. Many theoretical studies assume that surface cooling will follow the introduction of significant levels of volcanic material into the atmosphere [Handler 1989; Kelly & Sear 1984; Lamb 1970; Mukherjee *et al.* 1987]. It has been suggested that there may be both direct environmental responses to such cooling [Scuderi 1990], as well as disruptions caused in the patterns of atmospheric circulation [Lamb 1970]. Surface cooling may cause environmental stress in specific locations [Pyle 1992], but the disruption of circulation patterns in the lower atmosphere is thought more likely to generate significant terrestrial environmental change [Handler 1989; Kelly & Sear 1984; LaMarche & Hirschboek 1984; Lough & Fritts 1985].

Investigations of the potential of volcanic eruptions to affect climate have concentrated on the disturbance to the net radiation budget of the earth which may follow the introduction of volcanic material into the atmosphere. The net radiation budget of the earth is attained through the balance between incoming solar insolation and energy deficits resulting from emitted longwave and reflected shortwave radiation [Ardanuy *et al.* 1992]. The effect of volcanic ejecta on the global energy budget is determined by radiative transfer calculations at visible and infra-red wavelengths and a cooling effect due to volcanic ejecta has been observed [Baldwin *et al.* 1976; Pollack *et al.* 1976; Lamb 1970, Mitchell 1971; Hansen & Lacis 1990; Sigurdsson 1990]. The accepted measure of the transmission of solar radiation through the atmosphere is of degree of **optical depth**. Optical depth is the logarithm of the transmission of sunlight through the atmosphere, an increase in the optical depth by 0.1% translates to a reduction, by 10%, of the amount of sunlight reaching the lower atmosphere. Pollack [1981] measured the influence on transmitted energy of the tropospheric and stratospheric plume of the May 1980 eruption of Mt. St. Helens. He showed that an increase in the stratospheric load of silicate and acid particles and the multiple scattering of intercepted sunlight would lead to an increase in global albedo, tropospheric cooling and stratospheric warming.

Are these cooling mechanisms effective enough to allow us to accept that volcanic-forcing of climate is responsible for the environmental stress and settlement abandonment postulated in northern Britain? A study of the mechanisms involved and the criteria by which volcanic eruptions may be judged climatically significant will allow this question to be addressed.

Volcanic eruptions and climate change: mechanisms.

Volcanic mechanisms which result in a disturbance to global albedo may be summarised under four headings. A fifth mechanism which may result in significant tropospheric warming has been identified as a result of the research for this dissertation, and will be presented in detail below.

1. Cloud Condensation Nuclei.

The introduction of volcanic gases and tephra into the troposphere can raise the levels of condensation nuclei and generate cloud formation. This may raise tropospheric albedo and lead to localised surface cooling [Ardanuy *et al.* 1992]. The residence time for particulate volcanic material emitted into the troposphere is thought to be limited. Studies of the May 1980, Mt. St. Helens eruption indicated that fine ash particles may aggregate into larger particles in the eruption plume, which may lead to fallout within hours or days of the eruption [Carey & Sigurdsson 1982; Gilbert *et al.* 1991; Rogers et al. 1981] and any climatic impact may be limited to the short-term. No study has assigned a significant role to this mechanism and we cannot assume that unseasonable rainfall is the mechanism by which volcanic eruptions had a significant environmental impact in northern Britain.

2. Volcanic Dust.

Basaltic and silicate material injected into the stratosphere will increase the global albedo and absorb and reflect solar radiation which may lead to surface cooling and stratospheric warming [Baldwin *et al.* 1976; Hansen & Lacis 1990; Pollack *et al.* 1976; Ogren *et al.* 1981]. A volcanic aerosol containing basaltic and silicate particles > 1 µm in diameter may absorb solar radiation and radiate infra-red radiation. This may lead to warming which, in principle, may counterbalance the cooling effect an aerosol cloud. This effect is likely to be short-term since the residence time for such material is limited to weeks [Deepak & Newell 1982]. Chou *et al*, [1984] estimated that such infrared warming may reduce the cooling effect of the volcanic aerosol by c. 40%, while Harshvardhan [1979] found that infrared warming by volcanic aerosols could reduce the net radiative loss of an atmospheric column by approximately 30%. The role and importance of particulate matter in generating significant surface cooling has been the subject of considerable debate, with particular reference to their atmospheric residence time [Farlow *et al.* 1981; Mackinnon *et al.* 1984].

Early studies of volcanically generated climate change suffer from an over estimation of the importance of stratospheric residence time of volcanic dust [Lamb 1970]. The assumption that the residence time of the volcanic dust would extend over several years was shown to be incorrect. Stratospheric residence times for particulate matter >1μm in diameter failed to extend beyond two to three months after many eruptions, while climatic fluctuations persisted into the third year [Farlow *et al.* 1981; Mackinnon *et al.* 1984]. Exceptions to this settling rate were discussed by Reitmeijer [1988], who suggested that residence time of sub-micron sized tephra in the stratosphere was related to their size and shape. This was confirmed when sub-micron sized dust particles from the 1982 eruption of El Chichón were detected in the atmosphere in 1989 [Reitmeijer 1990]. While these findings model the behaviour of volcanic dust from Holocene eruptions, the finding of tephra up to 300 μm in diameter in ice of Wisconsian age [69000-79000 yr B.P.], in the Dye 3 ice core [Ram & Gayley 1991], raises interesting questions about the long range transport of tephra and the longevity of its residence in the stratosphere in earlier periods.

The importance of particulate matter in generating long-term cooling was called into further question as a result of studies of the May 1980 eruption of Mt. St. Helens. Whilst this was an extremely explosive event, assigned a VEI of 5 [Simkin *et al.* 1981], the eruption had minimal climatic effect, and caused an estimated depression in polar winter temperatures of <0.1°C [Kerr 1981; Robock 1981]. The failure of this eruption to generate significant cooling focused attention on the mechanisms by which volcanic material was able to generate climatic fluctuation. In a study of the temperature response to eruptions with a VEI 5 [Self *et al.* 1981] an "inconsistent" climatic response to such eruptions was noted. While some large explosive eruptions appeared to have been associated with a hemispheric temperature departure, of $\Delta T = 0.2 - 0.3$°C, for 2 - 3 years, some appeared not to be related to any temperature departure and in one case, the 1956 eruption of Bezmymianny, there was an increase in ΔT. The failure of the 1980 eruption of Mt. St. Helens to produce a climatic perturbation where the smaller, VEI 4, 1963 eruption of Indonesian volcano Mt. Agung, had lowered tropospheric air temperatures by < 0.3 - 0.4°C [Angell & Korshover 1985] confirmed the importance of sulphur output in this context. Where Mt. St. Helens is estimated to have introduced < 0.64 million tonnes of sulphur into the stratosphere, Mt. Agung is estimated to have introduced > 30 million tonnes of sulphur into the stratosphere [Kerr 1981], increased optical depth by 0.3 [Pollack *et al.* 1976] and decreased solar transmittance by approximately 1.5% [Sigurdsson 1990]. Sampling of the stratospheric aerosol following the Mt. Agung eruption showed that it was mainly composed of sulphuric acid [Castleman *et al.* 1974]. To put this in perspective, Sulphate concentrations in the wake of the Mount St. Helens eruption were 216 times the normal background level [Gandrud *et al*, 1981], whilst the specific measurements of $S0_2$ taken 24 hours after the 18 May eruption showed a 1000 % enhancement over non volcanic concentrations [Hobbs *et al.* 1981; Inn *et al.* 1981].

The climatic effects of a volcanic eruption are not a simple function of the volume of tephra, nor of the explosive energy of the eruption. The presence in British sediments of Icelandic tephra [Dugmore 1989; Pilcher & Hall 1992] need not indicate the occurrence of a climatically-significant eruption. The review of both the DVI and VEI has demonstrated that neither the explosivity, nor the magnitude of the erupted mass, determine the ability of a volcanic eruption to generate climatic fluctuation and that measures based on these criteria are an ineffective record of the occurrence of such events. Eruptions with a small VEI or DVI were shown to be able to generate climatic perturbations whilst larger eruptions measured by these criteria failed to have any such effect [Deepak & Newell 1982; Rampino & Self 1982, 1984; Self *et al.* 1981]. The significant criteria by which a climatically-significant volcanic eruption may be detected is in the volume of acid volatile material emitted.

3. Erupted Volcanic Gases.

The knowledge that volcanic dust of >1 micron in size had an extremely limited residence time in the stratosphere, was countered in terms of its potential for inducing climatic fluctuations, by the knowledge that sulphate aerosols had:

(i) A much longer residence time.

(ii) Were a significant factor in increasing the optical depth of the atmosphere.

(iii) Reduced the amount of solar radiation reaching the earth's surface [Turco *et al.* 1982].

The introduction of volcanic gases into the stratosphere will also disturb the global albedo. Acid gases are oxidised into an aerosol form, primarily from SO_2 to H_2SO_4. The aerosol cloud impedes and backscatters solar radiation which may result in surface cooling and stratospheric warming [Baldwin *et al.* 1976, Pollack *et al.* 1976; Sigurdsson 1990]. The impact of an aerosol cloud of this nature can be detected for up to three years following an eruption, but it is unlikely to generate cooling in excess of normal temperature fluctuation after year one [Bradley 1988; Kelly & Sear 1984; Taylor *et al.* 1980]. The relative importance of acid gases in comparison to particulate matter will be discussed below.

In the stratosphere the residence time of acid volatile material is enhanced beyond that of silicate dust. Sulphur gases are converted to sulphuric acid aerosols, these acid aerosols are the main inhibitor of incoming solar radiation [Pollack *et al.* 1976; Rampino & Self 1982; Rampino *et al.* 1985]. Eruptions which introduced sufficient volatiles into the stratosphere, to increase optical depths by 0.1, appeared to be climatically significant [Deepak & Newell 1982].

The photochemical conversion of volcanic gases to an aerosol form within the stratosphere has been observed to be relatively slow, and maximum perturbation of global albedo may not occur until several months after an eruption. Following the 1963 eruption of Agung, peak sulphur aerosol levels were not reached until one year after the eruption [Castleman *et al.* 1974] and following the 1983 eruption of El Chich6n maximum optical depth perturbation did not occur for 11 months [Ardanuy *et al.* 1992].

Recent large eruptions failed to increase Optical Depth sufficiently to cause major climate perturbation. Electron microprobe analysis of volcanic tephra allowed estimates of sulphur and halogen yields of specific eruptions to be made. Devine *et al.*, [1984], and Palais and Sigurdsson [1989], correlated observed mean surface temperature decrease with sulphur yield. They found a direct link between the sulphur output and temperature response. It is interesting to note that when the sulphur output of the Hekla 3 eruption is fed into the regression equation successfully applied by Devine *et al.* [1984] and Palais and Sigurdsson [1989] to Twentieth Century A.D. eruptions, the estimated temperature response is a fall of **0.1°C.**

A sulphur-aerosol cloud will reduce transmittance of solar energy to the ground and back scatter solar energy within the stratosphere. As a result the lower atmosphere should be cooled and the stratosphere warmed. In the wake of the 1963 Mt. Agung eruption a stratospheric warming in the order of 6°C was observed [Hansen *et al.* 1978] and a fall in northern hemisphere surface temperature of approximately 0.3°C [Rampino & Self 1982] is reported. Similar results were obtained following the 1982 eruptions of El Chich6n, in Mexico. The lower stratosphere was warmed by approximately 6°C [Parker & Brownscombe 1983], but sea surface temperatures exhibited a maximum cooling in the order of 0.15°C which is not a significant temperature departure from the normal [Parker 1985]. The monitoring of sea-surface cooling was obscured by a particularly strong El Niño event which resulted in warmer than average sea temperatures [Handler 1986, 1989; Handler & O'Neill 1987; Parker 1988].

4. Non-eruptive volcanic degassing.

Non-eruptive, volcanic degassing may also emit significant levels of sulphur and of greenhouse gases such as CO_2 which may theoretically lead to surface warming. Stoiber *et al.* [1987] suggested that at least 6.8 million tonnes of sulphur was produced by volcanoes which are actively degassing but non eruptive. The ability of such emissions to reach the stratosphere was suggested by Jakosky *et al.* [1986] who postulated that heat energy from the volcano supplied the necessary buoyant rise to reach the stratosphere. Volcanogenic emissions of CO_2 however, are not estimated to approach the anthropogenic enhancements of recent decades [Allard *et al.* 1991; Dittberner 1978; Gerlach & Graeber 1985; Gerlach 1991]. However volcanic enhancements of the atmospheric content of CO_2 may be significant, if a critical threshold is approached [Caldeira & Rampino 199].

5. Tropospheric Loading In Excess Of Settling Rates.

Volcanic material emitted by a fissure eruption may also lead to short term but significant tropospheric warming. The frequent eruptive activity associated with a fissure eruption may counterbalance the settling mechanisms which reduce the warming effect of 1 and 6 above [Discussed in detail below]. The presence of sulphur aerosols in the lower atmosphere can lead to warming in the bottom 1km of the atmosphere [Preining 1991].

The identification of the mechanisms by which volcanic eruptions may affect climate is insufficient to assess the relative impact of individual eruptions. The discussion above illustrates that much theoretical debate fails to identify the degree of cooling to be expected from specific volcanic eruptions [Angell & Korshover 1985; Miles & Gildersleeves 1978; Sear *et al.* 1987; Taylor *et al.* 1980]. Nor did it point to a prediction of, nor the degree (if any) of disturbance to global atmospheric circulation patterns. In order to assess the ability of these events to disturb climate and hence have an impact on the environment of northern Britain, the temperature and circulation response of several eruptions in the Nineteenth and Twentieth Century A.D. will be reviewed next.

ANALYSIS OF TEMPERATURE TRENDS.

Superposed Epoch Analyses have been used to establish the scale of the impact of volcanic eruptions on climate [Taylor *et al.*, 1980; Kelly & Sear 1984]. A recent study [Mass and Portman 1989] of Nine volcanic events between 1883 and 1982, Krakatau in 1883, Tarawera in 1886, Mt.

Pelee/Soufriere/Santa Maria in 1902, Ksudach in 1907, Katmai in 1912, Agung in 1963, Awu in 1966, Fuego in 1974, and El Chichón in 1982; investigated the question of climatic effect and causality. They concluded that whilst for the largest eruptions, there was the suggestion of post-eruptive cooling of 0.3°C in the composite temperature records, there was no obvious volcanic signal in pressure and precipitation. Temperature declines, of a similar scale to post eruptive cooling, were noted to have occurred within the ten months preceding the eruptions with a pronounced temperature rise in the 2-3 months immediately preceding the event. These anomalies generally fall within the normal standard deviation present in the temperature records.

Conversely the apparent cessation of volcanic activity between 1880-1935, is held responsible for raising mean temperatures by 0.2-0.5°C [Pollack *et al.*, 1976; Miles and Gildersleeves 1978]. Given a standard deviation for northern hemisphere temperatures, of 0.7°C in January, and 0.2°C in July [Self *et al.* 1981; Kelly and Sear, 1984] it is difficult to accept that volcanic activity is the source of any or all of these perturbations and that changes on this scale could trigger the abandonment of settlements in northern Scotland.

This discussion has considered at length the theoretical framework on which the impact of volcanic eruptions on surface temperature has been based. It has been shown that in many instances the arguments are inadequate. Many eruption chronologies are seen to be insufficiently accurate to demonstrate volcanic cause and environmental effect. They are also, in addition, are geographically- and temporally-biased. The mechanisms by which volcanic eruptions are held able to perturb climate have been examined and many of these have been shown to be in need of revision. That volcanic eruptions may perturb surface temperatures has been demonstrated both theoretically and by observation, but temperature response has been shown to be limited, and in many cases to fall within the normal variation of the climate, making volcanic forcing difficult to detect. However, it has been established that a sulphur-rich eruption, such as the Hekla 3 eruption, may perturb climate, though admittedly to a limited extent. It is difficult to justify a model which would suggest that a fall in northern hemisphere mean temperatures of 0.1°C would bring about the drastic response postulated by archaeologists.

Is it possible that the minor temperature fluctuations identified in the wake of volcanic eruptions may disrupt global atmospheric circulation patterns? This question will be addressed in the following chapter.

Chapter three.

Volcanic mechanisms of circulation disruption.

Summary of Chapter.

This chapter analyses the theories and mechanisms which have been advanced in earlier attempts to link atmospheric circulation disruption and climatic change on a hemispheric scale to the presence in the upper atmosphere of a stratospheric aerosol created by material ejected in a volcanic eruption. Critical criteria are established against which different models of circulation disruption are assessed. It is established that all the models presented fail to satisfy the criteria necessary to associate unequivocally a climatic phenomena with a particular volcanic eruption. The possibility that volcanic eruptions may be responsible for regional or sub-regional scale climatic change, rather than the hemispheric scale events studied in this chapter, is introduced.

A whole battery of climatologists [Lamb 1970, 1972; Kelly 1977; Schneider & and Mass 1975; Flohn 1978, 1979], have suggested that insolation caused by volcanic eruptions could engender climate change in the North Atlantic region by affecting the exchange of energy between the different components the weather systems, including components such as the atmosphere, the oceans, the continents, and the polar ice masses. The temperature decrease, related to an increase in the optical depth of the stratosphere, caused by an eruption would it is said affect the strength of the upper air westerlies and associated weather systems. Volcanic eruptions, it was argued, could be a significant variable in the triggering of low frequency "climatic fluctuation". A stratospheric volcanic aerosol would both reduce the amount, and alter the distribution of solar energy reaching the Earth's surface. This in turn would affect the strength of the upper air westerlies and the associated upper air advection currents. The upper air westerlies are a major factor in determining climate in western and northern Europe, and in North America. Studies of the surface temperature response and global dispersion of the eruption cloud of El Chichón in 1982, showed that the surface temperature decrease after volcanic eruptions was in the order of a few tenths of a degree centigrade [Robock and

Matson 1983]. Stratospheric veiling was initially restricted to a narrow range of latitudes [Figure 3.1], before slowly dispersing around the Earth [Figure 3.2], and as a result the consequent cooling was non-uniform over the surface of the earth. Such differential cooling may generate a volcanically-induced temperature gradient between the equator and the poles and between the sea and land. Since the land masses of the continents cool before the oceans a further gradient will be established. There will be an increase in air pressure sea level on land relative to the air pressure over the oceans. In response to this, the air pressure at sea level over the oceans must be reduced [Handler 1989]. Because the majority of land is in the northern hemisphere, the induced cooling will transfer air mass from the oceanic anti cyclones in both northern and southern hemispheres to the continents especially to southern Eurasia. It is the redistribution of air mass, anomalous sea level pressure gradients, and anomalous winds, which are argued result in anomalous climate on a global scale.

High latitude eruptions may result in cooling at high latitudes and enhance the thermal gradient between the poles and equator, conversely the cooling effect of low latitude eruptions at the equator may diminish the thermal gradient. Cooling of the Oceans at the Equator may reduce the northwards shift of the Inter tropical Convergence Zone and reduce monsoon rainfall [Mukherjee *et al.* 1987]. Since, ultimately it is the temperature differential between these areas which drives the Earth's atmospheric circulation, volcanically induced cooling may theoretically have an impact on global circulation patterns.

In the months following an eruption, the aerosol cloud from a low latitude eruption may move pole-wards [Figure 3.2], while that of a northern hemisphere eruption will be confined to the hemisphere of origin [Cadle *et al.* 1976; Danielsen 1981; Jakosky 1986; Handler 1986; Kelly & Sear 1984]. The influence of volcanic aerosols may not then be simply modelled since northern and southern hemisphere eruption will disturb the global heat balance in different ways, and the aerosols from a low-latitude eruption may have different consequences as they travel northwards.

Volcanic forcing of the climate system is necessarily irregular and while a response may be observed, a single volcanic eruption is unlikely to be able to overcome the thermal inertia of the oceans and cause rapid and persistent climate change. But it may enhance changes already in progress [Hansen & Lacis 1990]. Circulation modelling by Hunt [1977] indicated that following a single volcanic eruption the:

> *"impact of volcanic debris on the dynamical behaviour of the general circulation was quite small, at most slightly reducing the zonal wind".*

Would such a disruption to the normal patterns of atmospheric circulation have a serious environmental impact in north Britain? Could this have triggered the physiological response observed in the Irish dendrochronology and the apparent abandonment of settlement in the Scottish Highlands? It would be simple to suggest that the disruption of north Atlantic circulation patterns following a volcanic eruption accounts for environmental stress in northern Britain [Baillie & Munro 1988]. But if we accept that an eruption is responsible for fluctuation on a particular scale, how may we account for similar fluctuations for which no eruption is recorded? Do we suggest that unrecorded eruptions accounted for these events? A real danger of circular reasoning exists. The studies reviewed below will be assessed in the light of this discussion.

To investigate the relationship between volcanic aerosols and climatic circulation in the North Atlantic, the major studies which claim to have established a relationship between volcanic aerosols and circulation response are reviewed here. In particular the response of the Indian and Sri Lankan monsoons and of the El Niño / Southern Oscillation is examined.

Theoretical Considerations.

The complex interaction of the many feedback processes which control the atmospheric circulation patterns of the Earth, are imperfectly understood and difficult to model [Hansen & Lacis 1990; Robock 1984]. Global circulation patterns will fluctuate naturally without the contribution of nominally independent variables such as reduced insolation caused by a volcanic aerosol cloud. The temperature fluctuations which drive atmospheric circulation are often as great, if not greater than the observed temperature response to a volcanic eruption [Sigurdsson 1990], and minor climatic fluctuations may persist and be magnified as a result of the thermal inertia of the oceans [Hansen & Lacis 1990]. Volcanic activity is not the only agent which may affect insolation, decreases in solar output, orbital fluctuation and the dynamic nature of the climate system itself may introduce change and the influences of these are not easy to isolate in the environmental record [Chester 1988; Eddy 1977; Gilliland 1982; Kukla 1979; Kullman 1992]. As a result, identification of a clear volcanic signal is difficult and volcanic forcing of circulation must be sufficiently large in scale to be discernible "above" the background noise of the Earth, ocean, cryosphere system [Cook *et al.* 1992; Fitzharris *et al.* 1992].

Critical Approach.

Several studies have identified a link between volcanic activity and circulation response, but does a critical review of the evidence suggest that volcanic eruptions are capable of disrupting atmospheric circulation? The danger exists that the mere correlation of an eruption and a climatic fluctuation will be accepted as proof of a dependent relationship, despite the fact that many eruptions fail to produce the significant levels of acid volatiles necessary for the formation of a stratospheric aerosol cloud [Rampino & Self 1984].

Chronologies of Eruption and Climatic data.

Many attempts to identify volcanic influences on circulation have relied on imperfect eruption chronologies, temperature data of uncertain quality [Walton 1985]. Records of climatic phenomena which are often incomplete and subject to review [Quinn *et al.* 1978, 1987] and the correlation of volcanic eruptions with climatic phenomena, such as below or above average monsoon precipitation [Handler 1986b; Mukherjee *et al.* 1987] and the El Niño / Southern Oscillation [Handler 1986a; Handler & Andsager 1990; Nicholls 1988, 1990]. The use of such data makes any attempt to assign cause and effect or identify dependent and independent variables of doubtful value.

Statistical analysis.

Establishing a clear relationship between volcanic eruptions and circulation response relies on the use of incomplete records of eruptions and climatic phenomena. Statistical relationships based on such data are questionable. Kelly [1977] summarised the problems inherent in many studies which claimed to have established a dependent relationship between volcanic activity and circulation disruption:

> *"...many claims made for climatic cycles of any period are based on doubtful statistical analysis"* [Kelly 1977 p. 617].

The correlation of a volcanic eruption with anomalous circulation patterns may be fortuitous and composite data sets, where the atmospheric responses to a series of volcanic eruptions are overlaid in a "Superposed Epoch Analysis", have been constructed in an attempt to overcome this problem. The use of these analyses creates a new series of problems, when the results obtained from the composite may be weighted by one or two strong associations, and the use such information in studies of the volcanic "forcing" of climate [Kelly & Sear 1984; Handler 1986a] has been criticised [Mass & Portman 1989; Parker 1985; Nicholls 1990].

Within climatic systems it is extremely difficult to identify the operation of cause and effect, the significance of external forcing and the nature of the external forcing mechanism [Handler 1986a; Nicholls 1988]. As a result the sensitivity of climate systems to external forcing can only be estimated. The precise mechanism by which volcanic aerosols may be responsible for circulation disruption must be modelled. How, for instance, might an eruption affect the position of the Inter Tropical Convergence Zone [ITCZ]? Interactions between different parts of the global climate system make it difficult to identify the point at which external forcing may have been applied [Handler & O'Neill 1987]. The fortuitous coincidence of a volcanic eruption may not have forced the circulation disturbance observed. As a result the sensitivity of climate systems to external forcing can only be estimated.

In response to the problems highlighted above, studies of circulation response to volcanic eruptions must fulfil specific criteria:

A) Accurate eruption chronologies must be employed.
b) The mechanism by which the volcanic eruption was able to reduce insolation must be sustainable in the light of current theory. *i.e.* studies based on the DVI or VEI as measures of the climatic effectiveness of an eruption are suspect.
C) Accurate chronologies of climatic phenomena must be employed.
D) The mechanism by which the eruption may have disrupted circulation must be specified.
E) A consistent response-time between an eruption and a climatic phenomena must be established.

Disruption of the Atmospheric Circulation over the North Atlantic.

Several studies claim to have identified consistent volcanic forcing of northern hemisphere atmospheric circulation. Wexler [1956] suggested that the theoretical circulation response to a major eruption would be an expansion of the circumpolar vortex, an intensification of the upper level trough over North America in January, and a southerly displacement of summer westerlies. In this model July's weather would follow a similar pattern to May's and bring cooler weather to northern latitudes in the critical months of the growing season. Lamb [1970, 1972] expanded Wexler's study and suggested that the sub-polar low pressure zone, in the north Atlantic, was displaced southwards in the first July following a climatically significant eruption. Lamb suggested that the likely impact of volcanic eruptions with a DVI >100 for the weather in the British Isles in the summer is that:

> *"There is on average a southward displacement of the pressure minimum in the first July after a great eruption towards, or over, the British Isles... Examination of the July pressure gradient index suggests a tendency for more than usual northerly components in the British Isles - North Sea region developing over the years following high latitude eruptions... The same tendency is apparent in the second July after equatorial zone eruptions"* [Lamb 1970 p. 493].

and that in the winter there is:

> *"evident logic in the apparent expectation that the following two or three winters (after an eruption) have a tendency to enhanced atmospheric circulation, more prevalent westerlies and hence mildness, and that this tendency is set up immediately after high latitude eruptions: for these are the situations in which the chilling effect of the volcanic dust is likely to be concentrated over the higher latitudes, with an enhanced thermal gradient between the area so affected and the lower latitudes that are either unaffected or becoming free of the volcanic dust veil"* [Lamb 1972 p. 424].

Lamb suggested that in north western Europe, milder, wetter winters and cooler, wetter summers should follow a significant volcanic eruption. He also noted that low-latitude and southern hemisphere eruptions should have a delayed impact on northern hemisphere atmospheric circulation patterns. The quality of the eruption chronology used and the emphasis placed on dust rather than sulphur emissions prevent an unqualified acceptance of Lamb's findings. Lamb may simply have identified the fortuitous coincidence of volcanic and atmospheric events. Even if volcanic eruptions do cause atmospheric circulation disruption, could the small scale short term disruption to atmospheric circulation identified, have had the serious impact on settlement in north Britain which has been suggested [Baillie 1989; Burgess 1989] and trigger the long-term stress indicated by the Irish dendrochronology?

Kelly [1977] suggested that a link existed between the following three properties: winter temperature in central England, south-westerly wind frequency at London, and Lamb's DVI. A correlation was said to exist between winter temperatures and periods when the DVI was greater than 100. Taking Lamb's work further he proposed that a periodicity could be detected apparent in a 6.5 to 8 year cycle. However, Kelly was aware of the dangers inherent in assuming volcanic activity to be the sole independent variable responsible. He also and suggested that seismicity, variation in the Earth's rotation, atmospheric circulation and volcanicity could be combined in an interactive loop with a timescale of about seven years.

The quality of Lamb's eruption chronology, problems with the estimation of the DVI [Discussed above] and Kelly's acceptance that it was the level of volcanic dust emitted which significantly reduced solar insolation, undermine these studies. The data on which Kelly's association is based is therefore flawed and do not demonstrate a clear circulation response to volcanic forcing. This work is important however, in establishing that volcanic activity need not be considered the sole or main independent variable responsible for circulation anomalies

The theoretical basis on which the work of Lamb [1970, 1972] and Kelly [1977] was based now appears questionable. In particular the use of inadequate Eruption Chronologies, the use of the DVI and VEI as measures of the climatic effectiveness of an eruption, and the uncertain time-lag between volcanic eruption and circulation response, undermine the validity of their conclusions. It is unlikely that Lamb's chronology accurately records the levels of climatically significant volcanic activity, and it is the volume of acid gases emitted not the output of dust which reduces insolation in the long-term. There may indeed be a relationship between south-westerly wind frequency and winter temperatures in central England, but the suggestion that the DVI is also related to this phenomenon is questionable. The degree of response identified cannot be claimed to represent the forcing of the climate system by volcanic aerosols.

While the work of Lamb [1970, 1972] and Kelly [1977] failed to demonstrate a clear link between volcanic activity and circulation disruption, observations of recent volcanic activity has refined the models by which such disturbance may occur.

El Niño / Southern Oscillation [ENSO].

The El Niño is a manifestation of the Southern Oscillation; an atmospheric pressure gradient between a high pressure system centred in the south east Pacific Ocean and a low pressure centre centred over Indonesia. This system normally transfers air mass and warm water from the eastern to the western tropical Pacific ocean [Ramage 1986]. During an El Niño the pressure gradient between the two centres collapses and surface wind direction reverses. As a result sea surface temperatures warmer than normal by 1-3°C appear in the eastern tropical Pacific ocean between 5°N-5°S and 90°W-180°W. The Southern Oscillation Index [SOI] which is a measure of the amount of air mass transferred from land to ocean was devised by Walker and Bliss [1932] as a measure of this phenomena. Pressure records at Tahiti measure the air mass transferred to the oceans while records from Darwin, north east Australia are used to estimate the transfer of air mass from the oceans from the oceans to the Eurasian / Australian land mass.

A case can be made which relates fluctuation in the Southern Oscillation with responses in pressure in circulation systems around the world [Figure 3.3], and a tentative link has recently been established between extreme ENSO events and climatic phenomena in Europe {Fraedrich & Müller 1992]. The El Niño / Southern Oscillation [ENSO] has been related to wetter than usual winter conditions in New Mexico, U.S.A. [D'Arrigo & Jacoby 1991] and drier conditions in the Pacific north west [Lough & Fritts 1985]. Low-index years also appear to be warmer in south-western Canada and cooler in the central southern United States [Lough & Fritts 1985]. Walker and Bliss [1932] noted that when the SOI was low or negative, monsoon rains in India were likely to fail. Handler and O'Neill [1987] noted an apparent relationship between Atlantic Ocean tropical cyclones and the intensity of the Indian monsoon. The forcing of this phenomenon by an external mechanism may therefore have an impact on global circulation patterns, recent work described below, suggests that low latitude volcanic eruptions may trigger the ENSO and associated phenomena world-wide. Handler [1986a & b] and Handler and Andsager [1990] presented evidence which suggested that the sea surface temperature in the eastern equatorial Pacific Ocean was significantly warmer than normal [Figure 3.4] within nine months of the eruption of a low-latitude volcano eruptions, ≤ 20° north and south [at the >95% confidence level], and that sea surface temperatures were significantly cooler than normal, 9-13 months after the eruption of a high latitude volcano. [Figure 3.5]. The suggestion was made that the El Niño/Southern Oscillation [ENSO] was the direct result of the introduction of volcanic aerosols into the stratosphere. The ENSO phenomenon is associated with the simultaneous shift of the ITCZ to the longitude of the eastern Monsoon. Since monsoon circulation appeared to be connected to circulation in the north Atlantic these papers appeared to demonstrate a clear mechanism by which low-latitude volcanic eruptions might disrupt global circulation. Handler [1986a] concluded that the stratospheric aerosol of a low-latitude volcanic eruption:

> *"...could produce the global scale climate anomaly... of which ENSO is just a part".*

At face value this work appears to be firm evidence for a clear volcanic influence on low frequency circulation anomalies, however these studies fail many of the criteria established above.

Precursors of the ENSO. A Critical Analysis.

A note of caution with reference to the statistical reliability of the data was raised by Parker [1988] who confirmed Handler's observations but noted that:

> *"the occasional sequences of extreme temperatures in the random samples underline the need for numerical modelling studies to complement statistical investigations".*

Eruption Records.

In order to identify a clear volcanic signal, Handler [1986a] selected eruptions assigned a VEI ≥4 in the period 1866-1982 in years for which there was no prior eruption and ignored years when both high and low-latitude eruptions occurred. The VEI is an inadequate measure of the ability of an individual volcanic eruption to trigger climatic change [Bradley 1988; Deepak & Newell 1982; Chester 1988; Rampino & Self 1984; Sigurdsson 1982]. Handler's correlations were established using the VEI and as such the suggested dependence in the relationship appears questionable.

Records of Climatic phenomena.

The record of El Niño events used was also inaccurate. Handler used the data of Quinn *et al.* [1978] to list the strong and moderate El Niño events between 1935 and 1984. Handler [1986a] believed that only three ENSO phenomena were not preceded by the eruption of a low-latitude volcano, and suggested that unrecorded eruptions could account for this. But a revised list of ENSO phenomena [Quinn *et al.* 1987] showed ten ENSO events which were not preceded within six months by major low-latitude volcanic eruptions; in 1940-1941, 1943, 1951, 1957-1958, 1965, 1972-1973, 1976-1977, 1982-1983. While eruptions have gone unreported in the 1980's [DeLuisi *et al.* 1983; Sedlacek *et al.* 1983], to accept Handler's argument that each of the ten cases above may have been preceded by unrecorded volcanic eruptions, then we must assume that 75% of major low-latitude eruptions in the past 50 years must have gone unreported! This is, of course unacceptable.

The use of composites.

Nicholls [1988, 1990] criticised the use of composites to investigate the temperature and pressure data. While Handler had found a significant positive pressure anomaly following significant eruptions, Nicholls [1988] pointed out that the same data set contained evidence of a significant negative pressure anomaly **before** the eruption [Figure 3.6]. Post-eruption pressure anomalies may be a part of a trend which begins before the eruption so a dependent relationship appears unlikely. Indeed we may need to consider an alternative hypothesis where the air pressure anomaly may trigger the volcanic eruption [Rampino *et al.* 1982]. Nicholls [1990] pointed out that of the 12 eruptions used by Handler and Andsager only four were followed within 12 months by a strong or moderate ENSO event. He suggested that the composite was weighted by the strong 1982-1983 El Niño, and that a case by case analysis undermined the case that there was a dependent relationship. Of the six major low-latitude eruptions for the period between 1935-1984:

> *"One of the six was followed by a moderate El Niño...Another one [El Chichón in April 1982] occurred in a strong El Niño year but 4 months after the first appearance of positive SSTA's...Two eruptions [Rabaul in May 1937; Bagana in February 1952] were not followed by ENSO events. In fact the east equatorial Pacific cooled after these two eruptions. The remaining two eruptions [Agung in March 1963; Fernandina in June 1968] were not followed by strong or moderate El Niño events"* [Nicholls 1990 p. 426].

Handler assumes that the correlation of an eruption and an ENSO is the result of a dependent relationship. Of the 12 eruptions used by Handler, 8 occurred between March and June but El Niño is usually under way by March. The precursors of this phenomenon are imperfectly understood and those suggested are not present in all events [Ramage 1986; Wright 1986]. Rasmusson and Carpenter [1982] found that many of the precursors of an El Niño could be detected up to 12 months before the event. Wright [1986] found that anomalously high sea surface temperatures, low pressure, low cloudiness and weak winds occurred in the south east Pacific Ocean in the December-January-February prior to an ENSO year and in the same period the equatorial Atlantic is anomalously warm. There appears to be a relationship between these precursors and the ENSO and all occur **before** the volcanic eruptions advanced as the forcing mechanism.

The case against assuming dependent relationship between the eruption of low-latitude eruptions, sea surface temperature anomalies, and atmospheric circulation is further undermined by the work of Angell [1988] who investigated the impact of low-latitude eruption on continental temperatures. Angell suggested that following a low-latitude eruption there was a tropospheric thermal pulse which originated at the equator and spread polewards, cooling continental temperatures and decaying as it did so. The ENSO phenomenon appeared to mask the thermal impact of the volcanic aerosols. Tropospheric temperatures cooled after the eruption of Agung 1963, but warmed after El Chichón in 1982 when a strong ENSO was under way, Angell concluded:

> *"it seems clear that the effect of volcanoes on surface or tropospheric temperatures (especially in the tropics) cannot be accurately gauged without first considering the state of the sea surface temperature in the Eastern Tropical Pacific, i.e. the relation between air temperature and volcanism cannot be considered in isolation"* [Angell 1988 p.3703]

The hypothesis that low-latitude volcanic eruptions may be the external mechanism responsible for El Niño is seen to be unproved. The studies concerned fail to satisfy the criteria set out in the introduction to this chapter that the eruption and climatic chronologies used be accurate and consistent, that the mechanism by which the volcano may trigger the phenomena be established, and that the time lag between the two be consistent. Related studies of Indian Monsoon disruption will also be considered below.

INDIAN MONSOON DISRUPTION.

If volcanic aerosols are capable of disrupting global atmospheric circulation, then the Indian Monsoon ought to respond to volcanic eruptions. Handler [1986b] predicted that monsoon seasons which followed low-latitude eruptions would exhibit below average precipitation, and that high latitude eruptions would precede monsoons with above average precipitation. He further suggested that as the aerosol cloud from a low-latitude eruption moved northward, its influence would be reversed. Hence below average precipitation in monsoon years which followed low-latitude eruptions would be followed by a monsoon with above average precipitation.

Since reporting of low-latitude aerosols suffers is poor, Handler [1986b] used El Niño events were used as a proxy record of significant eruptions. This introduced a dangerous circularity into the Handler's argument. It was established above that the relationship between the ENSO and Volcanic Activity was not a dependent one, yet this assumption underpins Handler's [1986b] work. Walker and Bliss [1932] had already established that a relationship existed between the strength of the Indian Monsoon and a low or negative SOI. An El Niño could therefore be expected to occur in association with the Indian Monsoon and Handler's use of El Niño as a proxy indicator of the occurrence of significant volcanic eruptions introduced the likelihood of auto correlation. If it is accepted that the El Niño is a valid measure of volcanic activity, then volcanic forcing of the Indian Monsoon System is proven by default. Handler claimed that the association of volcanic eruptions and Indian Monsoon precipitation was above the 99% level of significance, but what he was in fact establishing was the relationship with the ENSO phenomenon, noted by Walker and Bliss fifty four years earlier.

Handler assumes that eruptions reported as "significant", that is assigned a VEI >4, were able to reduce insolation, but this has been shown to be an inadequate measure of an eruption's ability to reduce insolation [Bradley 1988; Deepak & Newell 1982; Chester 1988; Rampino & Self 1984; Sigurdsson 1982]. The time-lag for the response of the Indian monsoon to the presence of an aerosol is not established and as a result some of the correlations are questionable. Hence the June 10 1886 eruption of Tarawera [38°S 176°E] is correlated with the response of the 1887 monsoon, whilst the June 11 1968 eruption of Fernandina [0°S 92°W], is correlated with the response of the monsoon in 1968.

The problems highlighted above make it difficult to accept Handler's basic premise that the low-latitude volcanic eruptions will affect Indian monsoon precipitation. Independent studies of monsoon precipitation following volcanic eruptions fail to confirm Handler's findings. Mukherjee *et al.* [1987] noted below average precipitation in the Sri Lankan monsoon following low-latitude eruptions [20°N to 20°S] assigned a VEI of 4 or more. But above average rainfall in the second year following a low-latitude eruption, as suggested by Handler [1986b], was not observed. Consistent behaviour on the part of the eruption cloud was assumed. Twenty significant eruptions were identified and deficient rainfall was reported in between 53 and 80 per cent of eruption years, but the eruptions used occurred in every month except, March, July and December and it is unrealistic to expect that eruptions occurring in different seasons will disrupt the ITCZ in the same way. Climatic response was not consistent and below average precipitation was reported in between 53 to 80 per cent of eruption years. The VEI is used to indicate the occurrence of climatically significant eruptions. This study also fails to satisfy the criteria set out above which will allow the acceptance of a proven dependent relationship.

Hingane *et al.* [1990] tested the relationship between eruptions assigned a high VEI and the Indian monsoon further by examining the surface temperatures over India in the years identified by Handler [1986] and Mukherjee *et al.* [1987] as significant. Did Indian surface temperatures reflect the cooling which Handler and Mukherjee *et al.* suggested as the trigger for the circulation anomaly responsible for deficient rainfall? There was no evidence for a persistent decrease in surface temperature following low latitude eruptions. There was however an abrupt and significant drop in temperature in the two months following northern hemisphere eruptions. Again while these results are interesting they are questionable. Theoretical studies suggest that the cooling effect of the volcanic aerosol may not reach its maximum until seven to eleven months after an eruption [Ardanuy *et al.* 1992; Castleman *et al.* 1974] and that the aerosols from a single eruption are incapable of overcoming the thermal inertia of the climatic system in such a short time [Mass & Portman 1989]. Hingane and others note years when two or more low-latitude eruptions occurred within twelve months with the potential to overcome thermal inertia. Three in 1902, two in 1950-1951 and four in 1965-1966. There was a drop in mean annual surface temperature for three years following 1902 relative to temperatures in that year; 0.45°C in year one, 0.50°C in year two and 0.65°C in year three. Following the 1965-1966 eruptions temperatures dropped by 0.40°C in 1967 and 0.53°C in 1968. However a temperature increase was observed following the 1950-1951 eruptions 0.6°C in 1952 and 0.2°C in 1953 and a consistent temperature and circulation response to multiple eruption events cannot be assumed.

Indian Monsoon and North Atlantic Circulation.

Handler and O'Neill [1987] established that a correlation existed between deviation from the average occurrence in the frequency of Atlantic ocean tropical cyclones and below average precipitation in the Indian monsoon. It was suggested that this occurred in response to the reduction in solar radiation following the introduction of a volcanic aerosol into the stratosphere at low-latitudes. In the period 1900-1986 there were 19 years in which a low latitude aerosol is recorded. As in the work of Mukherjee *et al.* [1987] the presence of volcanic aerosols at low-latitudes appeared to coincide with a reduction in the northward seasonal shift of the tropical climate system. 94% of the seasons listed had a below average frequency of tropical cyclones, and 74% of such seasons had below average monsoon rainfall. Linkages were also apparent with other regions whose climate appeared to respond in tandem: low precipitation in S.E. Australia and northern South America, and high precipitation in south western U.S.A., and the Central Pacific Islands. In the North Atlantic the suppression of the northward shift of the system would result in the high level westerlies being south of their normal position and this should bring a cooler summer to the northern hemisphere.

The responsibility of volcanic aerosols for any or all of these events is questionable. Synchronicity between different circulation systems is to be expected since none operate in isolation. External forcing of any part of this system may generate a response in related systems which may ultimately extend around the globe and the evidence that volcanic eruptions have had an influence on this system within the last 100 years is open to question. The studies above demonstrate that it is difficult to estimate the impact of volcanic aerosols on an event as predictable as the Indian and Sri Lankan monsoon. We cannot assume that a particular circulation response will follow volcanic eruptions with similar characteristics, nor can we assume a consistent temperature response. Even if we accept a volcanic influence on monsoon precipitation there is no suggestion that disruption is severe or long lived.

VOLCANIC INFLUENCES ON CIRCULATION: DISCUSSION.

The above discussion has demonstrated that there is no easy correlation to be made between volcanic activity and circulation disturbance. The complexity of the global climate system prevents the assumption of a dependent relationship based on the simple association between an eruption and a circulation anomaly. An investigation of the ENSO phenomenon has demonstrated the importance and existence of precursors which commonly occur before a volcanic eruptions. The thermal inertia of the global climate system appears to be the single most important factor.

The studies which have concentrated on establishing a statistically probable response to a volcanic eruption fail to satisfy the critical criteria established above. As a result we cannot assume that a particular circulation anomaly occurred in response to any of the acid peaks in the Greenland ice-core. Circulation disruption does not appear to be the likely cause of volcanically induced environmental stress in northern Britain. Localised insolation may have an impact on the environments affected.

The localised modification of climate by volcanic eruptions can be illustrated by two events, the eruption of the Laki fissure, Iceland, in 1783; and the eruption of Tambora, Indonesia, in 1815. Both these eruptions fulfil all the criteria to be climatically effective. Both are several orders of magnitude greater than the Hekla 3 eruption and both are associated with extreme weather events. An investigation of these events then, will serve as a yardstick to assess the impact of the Hekla 3 eruption. The size of the acid peaks associated with physiological stress in the Irish tree-ring record indicates single rather than multiple eruptions. Ice-core acidity attributed to the prehistoric eruptions of Hekla is far lower than that found in 1783 and 1816 when major volcanic eruptions occurred [Clausen & Hammer 1988] which have been associated with climatic forcing [see Chapter 6]. The significant acid peaks in the Greenland ice-core **do not** suggest that the eruptions which occurred during the prehistoric period were of the magnitude where severe forcing of climate change may be anticipated; but rather events capable of generating small scale short term climatic disruption.

Chapter four.

Climate in the Northern Hemisphere following the Tambora eruption.

"The Year without a summer"

Summary of Chapter.

This chapter investigates the possible association between the eruption of the Indonesian volcano Tambora and a "poor summer" in the northern hemisphere in 1816. Several strands of evidence are used: temperature records, economic relationships, and palaeoenvironmental records such as tree-rings and ice core evidence. It is shown that the summer of 1816 was not unique, and that the association of the volcanic eruption with the weather in that year is a matter of historical perception rather than environmental fact. It is shown that it is unwise to assume that poor climatic conditions, which may be observed in one location, may be safely extrapolated across a wider region. In fact many areas of Europe and North America did not experience a "year without a summer" despite the prevalent myth. The palaeoenvironmental implications of this are considered and it is suggested that a major southern hemisphere eruption could not bring about sufficient environmental change to have triggered settlement abandonment in Scotland.

Introduction.

Could a southern hemisphere eruption have generated sufficient climate change to have caused the environmental and archaeological stress in Britain recorded by Baillie and Munro [1988] and Burgess [1985,1989] which has been associated with acid peaks in the Greenland ice-core record ? The climatic phenomena and social and economic stress associated with the eruption of the Indonesian volcano Tambora in 1815, are investigated. This event is used as an analogue to examine the impact such an event may have had on northern Britain in prehistory.

Atmospheric circulation patterns may result in the movement northwards of the volcanic eruption clouds from low-latitude or southern hemisphere eruptions. This transport will result in the reduction of insolation, first at the equator and up to a year later in high northern latitudes [Robock 1984a], and the response of northern hemisphere climate to southern hemisphere eruptions may lag by up to one year. Lamb [1970, 1992], Kelly and Sear [1984] and Handler [1986b] monitored the response of northern hemisphere climate to southern hemisphere eruptions, and believed that a link could be observed between poor northern hemisphere summers and major southern hemisphere eruptions. The observed temperature response to volcanic eruptions in the

Twentieth Century has been minor [Bradley & Jones 1992]; but reduced insolation at either the equator or northern latitudes may result in the southwards displacement of the North Atlantic Polar Front, which would bring unseasonable low temperatures and high rainfall to northern latitudes [Kington 1992; Lamb 1992].

There is ample evidence to suggest that northern hemisphere climate in the summer of 1816, following the eruption of the Indonesian volcano Tambora in 1815, was exceptional and that the eruption was responsible. The evidence for this will be reviewed and then critically examined.

Eruption Dynamics.

The volcano Tambora, on the Island of Sumbawa, Indonesia, erupted on April 5, 1815. This event was probably the largest eruption to have occurred in recorded history and possibly in the entire Holocene and has been assigned a VEI of 7 by Newhall and Self [1982]. Volatile emission was considerable with an estimated total acids output [Figure 4.1] of 3.94×10^{14} grams [Devine *et al.* 1984], an estimated sulphuric acid output [Figure 4.2] of 5.25×10^{13} grams - 1.75×10^{14} grams [Palais & Sigurdsson 1989; Sigurdsson & Carey 1992] and an erupted mass [Figure 4.3] estimated at 2.4×10^{17} grams [Stothers 1984]. Both the explosivity, and the massive volatile output, makes this eruption theoretically capable of generating northern hemisphere climate change [See Chapter 2]. The magnitude of the eruption and its occurrence in well documented historical times, makes it an ideal event from which to study the impact of southern hemisphere eruptions on northern hemisphere climate. If southern hemisphere eruptions are able to modify the environment in the northern hemisphere, the eruption of Tambora should provide unequivocal evidence of this.

Eruption impact?

The eruption had a devastating effect on the peoples of the Indonesian archipelago, resulting in up to 90 000 000 deaths [Stommel & Stommel 1983], but in the northern hemisphere the eruption is associated with the crisis year of 1816, the "year without a summer" [Post 1977; Stommel & Stommel 1979, 1983; Harrington 1992]. The year 1816 is enshrined in American folklore as:

> *"Eighteen hundred and froze to death,"*

and in Europe the bad weather and famine of that year has been described as:

> *"The last great subsistence crisis in Europe."* [Post 1977].

The June of 1816 was recorded as the coldest ever in the city of New Haven, Connecticut U.S.A. [Landsberg & Albert 1974], and the European city of Geneva had its coldest ever July and Summer for the period 1753-1960 [Post 1977]. July 1816 was the coldest recorded in Lancashire, England, between 1753 and 1945 [Manley 1946] and the date of the European wine harvest in 1816 was the latest on record [Post 1977].

Descriptions of 1816 in North America.

The most striking accounts of severe weather in the summer of 1816 come from the north eastern United States of America and the records of the Hudson's Bay Company in Canada. There were three outbreaks of severe frost in Ontario, southern Quebec and the north-eastern United States associated with unseasonable north to north-westerly winds. Frosts were reported between June 7-12, July 5 - 7, August 21 - 22 and September 25 - 28. The frequent recurrence of frosts had a serious impact on the crops grown by many subsistence farmers in New England and by indigenous people in Canada [Stommel & Stommel 1979; Suffling & Fritz 1992] and competition for scarce resources apparently led to conflict between different groups of settlers in Canada [Ball 1992 p.194].

Charles Dewey recorded the weather in new England in his journal:

> *"Frosts are extremely rare here in either of the summer months; but this year there was frost in each of them.* ***June 6th*** *the temperature about 44 Degs through the day - Snowed several times.*
>
> ***June 7th*** *no frost, but the ground frozen in many places.... Moist earth was frozen half an inch thick.*
>
> ***June 8th,*** *some ice was seen in the morning - earth very little frozen - no frost - wind still strong and piercing from the NW. Cucumbers and other vegetables nearly destroyed.*
>
> ***June 9th*** *less wind and some warmer.*
>
> ***June 10th,*** *severe frost in the morning... The trees on the sides of the hills presented for miles the appearance of having been scorched.*

> *June 29th and 30th some frost.*
>
> *July 9th frost, which killed parts of cucumbers.*
>
> *August 22nd cucumbers killed by frost.*
>
> *August 29th severe frost. Some fields of Indian corn were killed on the low grounds, while that on the higher was unhurt. Very little Indian corn became ripe in the region."* From Stommel & Stommel [1979].

The Hudson's Bay Company representative Peter Fidler, at Brandon House, Manitoba, recorded a severe cold spell on June 5:

> *"A very sharp frost at night killed all the Barley, Wheat, oats and garden stuff above the ground except lettuce and onion"* In Ball [1992].

June 8, 1816. *The North Star.* Danville, Vermont.

> *"The weather. The wind during the whole day was as piercing and cold as it usually is the first of November and April. Snow and hail began to fall about ten o'clock, A.M. and the storm continued till evening... the cold the preceding night having been so severe, that the ground was considerably frozen and water, in some instances, froze nearly half an inch thick."* In Stommel & Stommel [1983].

June 15, 1816. *The North Star.* Danville, Vermont.

> *"Melancholy weather ... on the night of the 7th and the morning of the 8th a kind of sleet or exceeding cold snow fell ... Saturday morning the weather was more severe than it generally is during the storms of winter ... Considerable snow has fallen in this state and N. Hampshire. Probably no one living in the country ever witnessed such weather, especially of so long continuance."* In Stommel & Stommel [1983].

David Humphreys, President of the Connecticut Society of Agriculture wrote:

> *"The principal injury done by early and late frosts, fell on our most important crop, Indian Corn. Of this there is not more than half the usual quantity: and in many places in*

> *this neighbourhood, not more than a quarter part sufficiently hard and ripe for being manufactured into meal"* In Stommel & Stommel [1983].

Famine followed the poor summer, but this was largely confined to the poor and to subsistence farmers living in isolated locations. Despite the apparent shortage of grain in New England, sufficient corn was produced to enable one hundred thousand barrels of grain to be exported to Europe. This questions the assumption that most of the grain had been destroyed by the unseasonable weather.

North American social and economic factors.

The apparent shortage of grain and high demand from Europe resulted in speculation and increased price. Between 1800-1811 wheat was $1.30 a bushel, in early 1817 it rose to $2.45 [Stommel & Stommel 1979 p.139]. In consequence the price of basic commodities rose and the poor suffered.

> *Halifax Weekly Chronicle:*
> *"great distress prevails in many parishes throughout Quebec province from a scarcity of food. Bread and milk is the common food of the poorer classes at this season of the year; but many of them have no bread"* In Stommel & Stommel [1983].

Following the harsh summer, migration from the eastern states to newly opened lands in the west increased [Stommel & Stommel 1979, 1983]. Ball [1992] studied the economics of the fur trade as a proxy indicator of social and economic stress in central Canada and found that the decade 1810 - 1820 was a period of stress, intensified by the arrival of groups of settlers from Europe. Suffling and Fritz [1992] found that indigenous people in northern central Canada suffered famine in 1816, but to a lesser degree than they had experienced in the years 1812 -1815. Numbers of moose, caribou and hare had declined for several years prior to 1816. A drought through much of 1815 had seriously damaged the potato crop and late summer rain had ruined the wild rice harvest and fishing. Conversely the cold dry conditions experienced in 1816, while causing distress, did allow the raising of a potato crop which staved off famine. For the indigenous peoples of Canada 1816 appears to have been marginally less stressful than previous years.

This analysis suggests that factors other than climatic conditions in a single season are involved in the perception that 1816 was a "crisis year". The role of the summer frosts cannot be ignored but the rising price of basic commodities, the pressure of immigration and a dwindling resource base must also be considered. These combined to cause hardship in some sections of the community, and the "memory" that conditions in 1816 were exceptionally hard.

1816 in Europe.

While not experiencing the severe cold spells described in North America, Europe also suffered from inclement weather, famine and social unrest. Summer temperatures were lower and rainfall was higher than average across much of Europe in the summer of 1816. Post [1977] reported that every region of Germany experienced cold and wet weather during the crop cycle of 1816. In the Netherlands the harvest was a complete failure and the potato crop rotted in the ground in several cantons of Switzerland. All the Swiss and French wine growing stations recorded 1816 as the latest date for the grape harvest in the period 1782-1879. Food riots are recorded in Zurich, Poitiers, Paris, and in Scotland, England and Ireland [Post 1977; Wood 1965].

Newspaper accounts suggest that much of Europe suffered from the inclement climate:

> *"Melancholy accounts have been received from all parts of the Continent of the unusual wetness of the season; property in consequence swept away by inundation and irretrievable injuries done to the vine yards and corn crops. In several provinces of Holland, the rich grass lands are all under water, and scarcity and high prices are naturally apprehended and dreaded. In France the interior of the country has suffered greatly from the floods and heavy rains."* The Norfolk Chronicle. 20 July 1816.

> *"Should the present wet weather continue, the corn will inevitably be laid, and the effects of such a calamity at such a time cannot be otherwise than ruinous to the farmers and even to the people at large."* The Times. 20 July 1816.

Other European evidence suggests, however, that it is unwise to assume that conditions reported in one region were prevalent everywhere. For example while western, eastern and central Europe suffered from poor weather and low harvest yields, northern Europe was experiencing good weather and surplus yields. The Baltic States and Russia had a surplus of grain to export to central and western Europe in 1816 [Neumann 1990, 1992; Bednarz & Trepinka 1992]. Sóren Pedersen, an Executive officer of a parish in SW. Sjæland, Denmark, wrote of 1816:

> *"This year was again a lovely fertile year, not only on account of the quantity of fodder but also because the kernels were so big. This was important for our country as this commodity was very much coveted in foreign lands...where there has been a general crop failure."* In Neumann [1990].

This contrasts markedly with accounts in English Newspapers and with his own description of 1811:

> *"The year 1811... a hard and barren year. There was a shortage of both grain and hay because of the too dry summer."* In Neumann [1990].

Despite the clement conditions which prevailed in northern Europe, in many central and western districts the summer of 1816 was cold and wet. Was the eruption of the volcano the previous year responsible for these anomalies? Other factors may be identified, as in North America, which place the reputation of 1816 as an "uniquely arduous year" in doubt.

European social and economic factors.

In Europe, 1816 was also a year of social stress. More than 300 000 soldiers had been disbanded following the end of the Napoleonic wars [Wood 1965]. In France an unpopular regime had been re-imposed by the victory of the Allies at Waterloo in 1815. 1816 was the first year for more than twenty years in which war had not been fought across Europe. The cumulative effect of the earlier warfare, blockade and economic instability cannot be ignored. These factors may have intensified the problems experienced as the result of the poor weather and food shortages.

A classification of harvest yields in Switzerland between 1812-1819 [Table 4.1], shows that poor harvests had been commonplace for several years prior to 1816.

Year	Yield.
1812	2
1813	3
1814	3
1815	2
1816	1
1817	2
1818	6
1817	6

Table 4.1. Classification of Swiss harvests. 1812-1817. 1 = dearth. 6 = abundance. [After Brugger 1956; Post 1977].

In central Europe, the Hapsburg Empire also suffered economic and social crisis in 1816, but the poor harvests of that year were preceded by several years in which crop yield had been low, and a Bubonic plague epidemic intensified hardship in the Balkans [Post 1977]. In continental Europe, both poor weather and unique social and economic pressures combined to cause a "crisis year".

Was the volcanic eruption was responsible for the poor summer climate? Was the climate in 1816 unique? How do the mild conditions in Denmark and elsewhere fit into models of volcanic forcing of climate?

Climate and 1816: a unique year?

The association made between the eruption of Tambora in 1815 and the widespread reporting of poor and apparently anomalous weather conditions in 1816, may be no more than coincidence. Landsberg and Albert [1974] pointed out that the temperature series for New Haven, Connecticut, recorded between 1780 and 1968;

> "were as close to statistical normality as one could find."

This point is reinforced by a consideration of temperature data from North America and Europe, shown in Table 4.2.

Station.	**Period of**	**Mean.**	**Std.Dev.**	**Coldest..**		**Temp**	**1816.**
	Record.	**Degs C.**		**Degs C.**	**Year**	**Degs C.**	**Std Dev.**
New Haven.	1780-1968	20.9	0.9	18.4	**1816**	18.4	2.5
Philadelphia.	1738-1972	23.6	0.6	21.8	1764	22.1	1.5
Edinburgh.	1771-1960	18.3	1.3	15.2	1832	16.9	1.5
Copenhagen.	1801-1970	16.2	1.1	12.9	1840	15.2	1.0
Wilno.	1781-1960*	17.4	1.2	14.5	1928	16.7	0.7
Berlin.	1756-1970*	18.0	1.2	14.8	1732	16.1	1.9
Vienna.	1775-1969	19.2	1.2	16.7	1913	18.7	0.5
Hohenpeissenburg.	1771-1960	14.0	1.3	11.4	**1816**	11.4	2.6
Budapest.	1781-1970	21.3	1.0	18.7	1913	19.7	1.6
Rome.	1811-1969*	23.5	0.9	20.9	1953	22.1	1.4

Table 4.2. Summer temperatures, in degrees Celsius, at selected stations, showing the position of the summer of 1816. (* = Interrupted sequence) After Landsberg & Albert [1974].

While all the stations above report temperatures below the mean for 1816, most fall within two standard deviations of the mean cannot be treated as manifestations of extreme or freak weather. Hohenpeissenberg, Bavaria, which like New Haven experienced its coldest year, is a high altitude station, and one might expect it to be more sensitive to any climatic perturbances than low level stations. Though based on a limited sample, the data presented in Table 4.2 does not suggest that 1816 was exceptionally harsh at all stations in the northern hemisphere. If a volcanic forcing mechanism is accepted for climate in 1816 in regions where records show that this year was harsh, how are extreme temperatures in other regions in other years to be explained?

Qualitative records of climate in North America.

D.C. Smith *et al.* [1981] constructed a temperature record for Maine which stretches back to 1785. These are based on instrumental records back to 1810 and on "qualitative" records, personal journals for the period back to 1785, which allow the climatic "trend" to be reconstructed with some accuracy. For the whole period 1785-1885, the climate of Maine was cool with short periods of warmer weather. May frosts were not uncommon, and occasionally occurred in June and August. June frosts occurred in 1778, 1794, 1797, 1800, 1807, 1816, 1817, 1832, and 1833. August frosts occurred in 1796, 1816, 1835 and 1836. Baron [1992] also noted the occurrence of late spring or early autumn frosts in 1793, 1796, 1812, 1816, 1817, 1835 and 1836. The summer of 1816 may be considered exceptional in that summer frosts occurred in both June and August.

But Summer frosts appear to have been common in the late Eighteenth century and early Nineteenth century and the association of summer frosts in 1816 and a major volcanic eruption in 1815 does not necessarily imply that a dependent relationship existed between the two phenomena.

Farming practice also suggests that summer frosts were considered a possibility. Seeds were often planted indoors and the seedlings were only transplanted outside after all chance of frosts appeared to have passed [Smith *et al.* 1981]. Summer frosts had not occurred for eight years before 1816. The settlement of migrants from Europe with little experience of summer frosts, and the years which had elapsed since their last occurrence in 1807, may have played a role in creating the conditions where farmers were either not prepared for summer frosts or no longer considered them a possibility.

The summer of 1816 does not appear unique when compared with records of other years. Baron [1992] studied eight weather diaries for this period and concluded that 1816 was not as cold as 1812 in northern New England, nor as cold as 1817 in southern New England. However, Baron [1992] suggested that 1816 was exceptional because of the extreme shortness of the growing season, measured as the length of time between the spring thaw and autumn frosts. In 1816, this was 70-80 days compared to a mean of 150 days for the period 1789-1841. The coincidence of the short growing season and the volcanic eruption need not be taken to imply a dependent relationship. Similarly short growing seasons were noted in 1808, 1824, 1829, 1834 and 1836. Catchpole [1992 a & b] used ships' logs and observations of sea ice data as proxy indicators of climate. 1816 was not shown to be an exceptional year as harsh conditions with extensive sea ice, late thaw and early freeze were apparent throughout the period 1811 - 1817. Again climatic conditions in 1816 do not appear to have been uniquely or excessively harsh.

1816 appears to be coldest in a sequence of cold years which lasted from 1812-1818 and which fell between two periods of relatively warm weather 1799-1810 and 1819-1832. When viewed critically, the qualitative data does not suggest that 1816 was an exceptional year for North

American climate, but that the hardship experienced in that year has come to represent the decade as a whole in North American folklore.

This brief study of qualitative data suggests that the summer of 1816 was not as unique as it has been presented. Quantitative data also questions the historic perception of the unique nature of the summer of 1816.

Analysis of temperature records.

The analysis of temperature data recorded 170 years ago has many problems, not least of which is how the data is analysed and presented. A common method of assessing the degree of historic climate change is to compare historic temperature records with a "norm" established from Twentieth Century measurements. In the early nineteenth century northern hemisphere temperatures were still influenced by the "Little Ice Age". Comparisons with Twentieth Century records may suggest the entire period was colder than the norm and fail to highlight individual poor years or seasons. The summer of 1816 will therefore be considered in the context of the early Nineteenth century.

A second problem is how to measure extreme weather? Studies of daily, weekly, monthly, annual or seasonal averages will present a range of sometimes conflicting results. For example both the mean annual and June temperature for 1816 is the coldest on Record at New Haven Connecticut, but both 1812 and 1817 experience colder summers (measured as the June/July/August mean). Daily temperatures are not easily accessible, and the sources used here have condensed this data into monthly daytime mean temperature. Details such as the location of thermometers, location and calibration are often missing. Establishing means and standard deviation is also problematic since these may have little significance. The data presented below will illustrate that temperatures varied on a decadal scale in the early nineteenth century. The length of the quantitative records is also problematic and for North America few temperature series stretch beyond 1805. These problems can often render detailed statistical analysis meaningless. Even if a statistically significant temperature departure was observed in a particular year, this does not imply that a volcanic eruption was responsible. This study will primarily concentrate on comparisons of the summer mean, the justification for this lies in the critical nature of the success of the **growing season** for communities under stress. A further test shall be applied by a study of the palaeoenvironmental evidence for climatic stress at this time.

Temperature series for North America.

Sigurdsson [1990] and Baron [1992] have compiled temperature series for north-eastern U.S.A. which shows that 1816 was not the coldest summer in the early 1800's and was part of a cooling trend which began in 1810 [Figures 4.4, 4.5 & 4.6]. In Brunswick, New Jersey, the summers of both 1812 and 1815 were colder than 1816 [Figure 4.4]. The cool period ended with a marked recovery in temperature in 1818. In New Haven, Connecticut, the summers of 1812 and 1817 were both colder than 1816 and the whole period can be seen to be one of considerable variation in temperature [Figure 4.5]. In eastern Pennsylvania 1818 again marked a recovery in mean summer temperatures from those which prevailed between 1810-1817 [Figure 4.6]. June temperatures are presented for comparison and although 1816 is clearly the coldest month in the period reviewed, a downward trend in monthly mean temperature can be observed from 1810. In north eastern America the summers for the whole period 1809-1817 appear to be cool and when viewed in this context 1816 does not appear exceptional.

It might be argued on the evidence from New Haven [Figure 4.5] and Pennsylvania [Figure 4.6] that the influence of the volcano on climate can be detected in a slight worsening of climate in 1816 and 1817, but this is challenged by data from Brunswick [Figure 4.4] where such a trend is not apparent. It is difficult from this, admittedly limited data set, to argue that the temperatures in 1816 were uniquely cool.

Temperature series for Europe.

The data presented below has been assembled from a variety of sources. With the exception of the data retrieved from Neumann [1990], which was already tabulated, all other temperature data has been gathered from the published lists of monthly temperature data, primarily from Manley [1974] and Mossman [1896]. Monthly mean temperatures have been transformed into a figure for the summer season by calculating the mean temperature for June, July and August.

A regional trend is apparent in the European temperature records studied below. Neumann [1990], tabulated temperature data for nine north European cities presented here as figures 4.7, 4.8 and 4.9. In Stockholm, Voyri, Trondheim, Copenhagen, and Gothenburg 1814 was cooler than 1816 [Figures 4.7 & 4.8]. In Uppsala and St. Petersburg the summer of 1816 was warmer than that of 1812 [Figure 4.9]. The summer of 1816 does not therefore appear to have been exceptionally cool in northern Europe.

In western Europe temperature series are available for central England [Manley 1974] and Edinburgh [1896]. I was unable to locate monthly temperature data for France. The English temperature record [Figure 4.10] is very similar to the north American record. A cool period began in 1809 and continued until 1817. Temperatures recovered steeply in 1818. The summer of 1816 was the coldest year in a series of nine cold years and was also the coldest summer in the period 1800-1830 with a mean daily temperature of 13.4°C. The summer of 1816 appears to be less unique when it is compared to the summer of 1823, when summer mean temperatures fell to 13.6°C. The seven summers prior to 1816 had all recorded summer mean temperatures of less than 15°C. Temperatures in 1823 fell to 13.6°C, following a summer in 1822 where the mean temperature had been 15.9°C. There is no suggestion that a volcanic forcing mechanism was responsible for the cool summer in 1823, but this single cool year appears more remarkable than 1816 which fell at the end of a cool trend.

In Edinburgh both 1816 and 1817 were cool [Figure 4.11], however the range of mean summer temperatures for the period 1800-1830 is considerable with the warmest summer in 1826 reaching 61.5° Fahrenheit, and the coldest in 1830 falling to 54° Fahrenheit,. The cool summer of 1816 falls at the end of a cool period which began in 1809 and can be viewed as part of a cooling trend. There is no suggestion that the cold summer of 1830 was caused by a volcanic eruption. As in England a cold summer was recorded in 1823 which was almost as cool at 55.1° Fahrenheit, as 1816 at 54.8° Fahrenheit, and appears all the more exceptional as it is not preceded by a series of cool years.

This analysis of temperature series has not provided conclusive evidence that a volcanic forcing mechanism is apparent in summer temperatures in 1816. Neither has it shown that temperatures and climate in the summer of 1816 were particularly unique. In Scotland and England, the summer of 1816 was cool. On the other hand temperatures in 1823 approached those of 1816 and a volcanic mechanism for these years is not suggested. The "year without a summer" falls at the end of a series of cool summers and the summer of 1816 cannot be interpreted without taking this trend into account. This summer may be interpreted as a natural event falling at the end of a period of deteriorating climate.

Alternatively it may be argued that volcanic forcing of climate may be detected in the abrupt fall in temperatures recorded in many areas in 1816. The presence of a volcanic aerosol may have acted to intensify an already deteriorating trend but this argument is difficult to sustain when temperature departures were as great, or greater in other years, such as 1823, for which no external forcing mechanism has been suggested.

The limited instrumental data available has failed to indicate that the summer of 1816 is unique or that a volcanic forcing mechanism can be detected. Palaeoenvironmental data may cast further light on the problem.

Palaeoenvironmental evidence.

Ice core data.

Alt *et al.* [1992] studied the climatic conditions on the ice caps of the Canadian high Arctic Islands. The oxygen isotope ratio in the Agassiz and Devon Island ice cores indicated warming rather than cooling in 1816. Holdsworth *et al.* [1992] studied the oxygen isotope ratio and the net accumulation rate from the ice cap of Mt. Logan, Yukon, and found no evidence for a climatic deterioration in the Yukon in 1816. However they did identify cooling in 1850, a year which is remembered by the Yukon Indians as "the year with two winters" and which is not associated with a volcanic eruption.

Growth stress patterns in trees can be used to reconstruct climatic conditions with some accuracy.

North American tree-ring studies.

Tree ring response to volcanic forcing of climate is discussed in detail in Chapter One, but examples which relate to 1816 are discussed here. Lough and Fritts [1987] suggested that volcanic eruptions were responsible for a wide range of climatic change across North America including both increases and decreases in temperature. Lough [1992] reconstructed the climate of 1816 in western North America from tree-rings and found that climate was not anomalous in either 1816 or in the decade 1811-1820 and that it was slightly warmer than the 1901-1960 mean. Other decades of the first half of the nineteenth century exhibited larger negative temperature departures and these were not associated with the volcanic eruptions of the magnitude of Tambora. Severe growth reduction in Canadian High Arctic fir trees began in the early 1800's but the coldest regional temperatures in 1816 were confined to eastern Canada, while temperature departures in western Canada were unexceptional [Jacoby & D'arrigo 1992] which is in agreement with the findings of Lough [1992] in western North America. In Colorado, Cleaveland [1992] found evidence for abnormal growth in 1816 rather than stress; and the studies of Lamarche and Hirshboek [1984] found no evidence for climatic stress in 1816 in either Colorado or California. In Maine, a state closely associated with hardship in 1816, Conkey [1986] found little evidence that 1816 was a year of exceptional climatic stress. In northern Quebec, Jacoby *et al.* [1988] found only limited evidence for dendroclimatic stress in 1816 and noted that it was largely limited to locations where the environmental conditions for tree growth were was particularly marginal. Graumlich and Brubaker in Washington State [1986], and Luckmann and Colenutt in the middle Canadian Rockies [1992], found that high alpine tree-ring chronologies failed to exhibit evidence for extreme conditions in 1816, but found that pronounced growth reduction had also occurred throughout the entire decade 1810 - 1820. Fayle *et al.* [1992] studied spruce trees [*Picea glauca*] growing at the tree-line in Manitoba and again detected a decline in growth for two decades before 1816, though a maximum low growth was recorded in 1817 and 1818. The "year without a summer" appears on this evidence to have been limited to eastern North America, while central, southern and western regions experienced normal or better than normal conditions.

European tree-ring studies.

Working in Fennoscandia Briffa *et al.* [1990] reconstructed temperature trends and short-term temperature anomalies for that region. Their work indicated that 1816 was not a year of particular stress in northern Europe. The work of Briffa *et al.* [1988], Briffa and Schweingruber [1992] and Graybill and Shiyatov [1992] confirms the instrumental data that 1810 saw the beginning of a short cool period in Europe which lasted until 1817. The work of Briffa *et al.* [1988], suggested that the summer of 1816 was cooler in both the United Kingdom and central Europe. Using tree ring evidence, Briffa and Jones [1992] suggest that 1816 was the coldest summer since 1750 in Britain, and the second coldest, after 1814, in central Europe, but that conditions in Scandinavia were near normal.

Summary of palaeoenvironmental evidence.

The palaeoenvironmental data confirms the instrumental data, that the summer temperatures are not cool everywhere, and that those regions which did experience cooler than average summer temperatures in 1816 did so at the end of a cool period which began in 1810. Western Canada and the western and Central United States experienced either an average or warmer than average summer. Colder than average condition appear limited to Northern and Eastern Canada and the north eastern United States. Even within these regions the evidence is not unequivocal, as tree ring studies from the State of Maine itself [Conkey 1986] do not suggest that the summer was one of particular environmental stress. In Europe the western and central regions experience worse than average conditions but northern areas experienced near normal or better than average conditions.

We cannot therefore assume that the correlation of poor weather and volcanic activity in one region can be extrapolated across a wider area. A uniform drop in temperature cannot be observed in North America or Europe, and a temperature response on a hemispheric scale appears unlikely on this evidence.

Circulation disruption.

Many observers report wet weather throughout the year with 130 days of rain counted in Switzerland from April to September 1816 [Post 1977 p.21]. Could a volcanically induced anomaly in atmospheric circulation patterns be responsible for the regional pattern of climate in 1816? Edinburgh rainfall in 1816 was 25.24 inches, the mean for 1770-1896 was 25.85 inches. The distribution of rainfall through the year was unusual, with 5.22 inches falling in July and 10.44 inches falling between July and September [Mossmann 1896]. Similar levels of rainfall occurred in 1817 and 1819 [Post 1977 p.17].

The circulation patterns for the summer of 1816 over Europe suggest that the subtropical high pressure system the "Azores High", which usually extends north-eastward and influences Europe's summer, failed to occupy its usual position [Von Rudloff 1967; Kington 1992]. Instead the "Icelandic Low" was positioned well to the south of its usual summer position [Figure 4.12] and brought unseasonable polar air to Europe [Lamb 1967, 1992]. This circulation anomaly is associated with the high rainfall observed for 1816 in many parts of Europe. This anomaly in not uniquely associated with volcanic eruptions, the synoptic map constructed for July 1816, is very similar to those constructed for July 1993 for which no volcanic forcing mechanism is suggested. However it should be noted that several areas, northern Scotland, the Outer Hebrides, Shetland, Orkney and large parts of Scandinavia had a drier than usual summer [Figure 4.13] and escaped the hardship experienced across much of Europe [Kington 1992; Lamb 1992].

	April.	May.	June.	July.	Aug.	Sept.
Milan						
1815	76	113	85	181	116	10
1816	84	76	109	74	79	54
1817	6	77	48	105	84	54
Paris						
1815	30	29	79	32	15	32
1816	13	38	54	97	51	63
1817	1	65	102	59	50	62
London						
1815	68	58	48	45	45	30
1816	53	55	60	108	63	55
1817	3	115	35	108	68	23

Table 4.3. Precipitation (mm) at selected European stations [From Neumann 1990].

Discussion: Tambora and the "year without a summer"

In the discussion above, instrumental temperature records, weather journals, rainfall records, social and economic conditions, and palaeoenvironmental evidence have been considered. While some regions experienced temperature minima and social and economic stress, other areas did not and it is clear that a general hemispheric cooling did **not** occur. Neither can the climate of 1816 be considered in isolation. The dearth and famine in 1816 appear to be the culmination of a series of poor years and were not solely caused by climatic fluctuation. It is difficult to conclude that the summer of 1816 exceptional. The climatic phenomena reported cannot be assigned with any confidence to the external forcing of climate by an aerosol cloud from the volcano Tambora. The suggestion by Lamb [1970, 1992] and Kelly and Sear [1984] that low latitude eruptions such as Tambora will cause a southward displacement of north Atlantic circulation, can account for the regional nature of the climatic phenomena. Nevertheless these models also propose several poor years following the initial perturbation. The contrary situation occurs for 1816 which appears to be the climax of a deteriorating trend, rather than the beginning of one. If we accept that the circulation anomaly was caused by the eruption of Tambora in the previous year, the resultant amelioration of climate in northern and western regions must also be attributed to the influence of the volcano. If we accept this model, then the likely impact of a southern hemisphere eruption on the critical areas in this study appears to be the amelioration of normal summer conditions in northern Scotland. We cannot therefore assume that the major eruption of a southern hemisphere volcano will automatically result in a deterioration of the environment in the areas of northern Scotland which were becoming marginal for human settlement in the bronze age.

Could a major northern hemisphere eruption cause sufficient climate change to bring about settlement abandonment? This question will be addressed in the following chapter.

Chapter five.

Climate in Britain and Europe and the Laki fissure eruption.

Summary of chapter.

Could Icelandic volcanic eruptions, and the Hekla 4 and Hekla 3 eruptions in particular, have brought about environmental change by triggering a climatic deterioration? "Conveniently dated" volcanic eruptions are often used by researchers to explain change in both human society and ecosystems. Such approaches assume a uniform, if unspecified, degree of climatic change, caused by the eruption of a physically remote volcano. This approach is challenged in this thesis by an analysis of the climatic phenomena in Europe which were associated with the eruption of the Icelandic volcano Laki in 1783. The observations of Benjamin Franklin are related and contrasted with the observations of Gilbert White, and though there are similarities between the two accounts, the descriptions of climate in 1783 are fundamentally different. An attempt is made to resolve these differences by use of monthly temperature records for England and Scotland compiled by Manley [1974] and Mossman [1896]; and by extensive research which draws on previously unexploited documantary material. The summer of 1783 in Britain is shown to be one of exceptional warmth which does not conform to existing models of climate response to volcanic eruptions. This warming is investigated and a new model is advanced to suggest how tropospheric temperatures may have responded to forcing by volcanic eruptions. This model combines the role of emissions of the volcano and the inhibition of outgoing radiation, with atmospheric circulation patterns at a regional / sub regional level. The notorious winter of 1783/84, also previously related to a volcanic eruption, is also investigated, and it is shown that it was in fact neither extreme nor exceptional when placed in the context of the climate of the late Eighteenth and early Nineteenth centuries. The cool summer of 1784 is similarly demonstrated to be unexceptional. It is illustrated that it is unwise to assume that "climatic extremes" recorded in one area, have an influence far beyond the area in which they are observed, and a plea is made for a realistic approach to the use of volcanic eruptions as scapegoats in cases of sudden, difficult to explain environmental or social change.

INTRODUCTION.

In order to investigate the association between Icelandic volcanic eruptions and environmental change in Britain, the eruption of the Laki fissure in Iceland in 1783 was selected and the climatic and environmental phenomena associated were investigated. Few volcanic eruptions approach the scale of emissions reached by the Laki eruption [Figure 5.1] and if, with the added contribution of the related eruption of the Grimsvötn caldera in Iceland [Thordarson *et al.* 1987; Thordarson & Self 1988, 1993] as well as the eruption of the Japanese Volcano Asama-Yama, the eruption failed to generate clear, unequivocal evidence of a climatic response, then the use of volcanic eruptions as a handy culprit to account for change in societies or ecosystems remote from the volcano becomes questionable. Personal observations of the climate in 1783 and compilations of temperature data are examined below in an attempt to resolve this issue.

The Laki eruption of 1783: eruption dynamics.

The eruption of the Icelandic fissure volcano Laki in 1783 was one of the largest producers of sulphur and acid volatiles in the Holocene [Figure 5.1]. It emitted sulphuric acid on a scale which should have resulted in a measurable effect on climate [Devine *et al.* 1984]. The total volume of acids emitted, the principal engine for volcanically-induced climatic change [Pollack *et al.* 1976; Deepak & Newell 1982], is demonstrably greater than in any other northern hemisphere eruption in the Holocene; $9.9X10^{13}$ grams of acid of which $9.19X10^{13}$ grams was H_2SO_4 [Devine *et al.* 1984; Sigurdsson *et al.* 1985; Palais & Sigurdsson 1989; Thordarson *et al.* 1987, 1992; Thordarson & Self 1993]. Approximately 60% of the total volume was erupted in five eruptive episodes between June 8 and July 8th; each of which was associated with the opening of a new fissure and a short period of phreatomagmatic activity [Thordarson *et al.* 1987, 1992; Thordarson & Self 1993]. Thordarson and others [1987,1992; 1993] concluded that although the eruption frequently possessed sufficient energy for the eruption column to reach altitudes of 5km a.s.l., and was also able to breach the tropopause during the initial stage of each eruptive episode, the majority of emissions were confined to the troposphere. If detailed observations of the recorded climatic phenomena associated with this eruption are inconsistent, we may begin to question palaeoenvironmental interpretative models which are based on the assumption of a uniform climatic or environmental response to smaller volcanic eruptions in prehistory [Figure 5.1]. Perhaps these had a lesser effect on climate than previously assumed.

The personal observations of Benjamin Franklin.

In 1783, Benjamin Franklin was Ambassador to France for the United States of America. The account, reproduced below, of the atmospheric and meteorological phenomena which he observed in the summer, autumn and winter of that year has been accepted as a classic description of the impact of a major volcanic eruption on climate. Indeed it may be seen as the foundation stone [Lamb 1970] for much of the research into the association between volcanoes and climate change which has taken place in the succeeding 200 years.

> *"During several of the summer months of the year 1783, when the effect of the sun's rays to heat the earth in these northern regions should have been greatest, there existed a constant fog over all Europe and great part of North America. This fog was of a permanent nature; it was dry, and the rays of the sun seemed to have little effect towards dissipating it, as they easily do a moist fog arising from water. They were indeed rendered so faint in passing through it, that when collected in the focus of a burning glass they would scarce kindle brown paper. Of course, their summer effect in heating the earth was exceedingly diminished.*
>
> *Hence the surface was early frozen.*
>
> *Hence the first snows remained on it unmelted, and received continual additions.*
>
> *Hence the air was more chilled, and the winds more severely cold. Hence perhaps the winter of 1783-4 was more severe, than any that had happened for many years.*
>
> *The cause of this universal fog is not yet ascertained. Whether it was adventitious to this earth....Or whether it was the vast quantity of smoke, long continuing to issue during the summer from Hecla in Iceland, and that other volcano which arose from the sea near that island, which smoke might be spread by various winds over the*

> *northern part of the world, is yet uncertain. It seems however worth the enquiry, whether other hard winters, recorded in history, were preceded by similar permanent and extended summer fogs"* [Franklin, 1784].

The clear conclusion to be drawn from Franklin's observations, is that the conditions which he observed in Paris, were typical of a far wider area stretching from Europe to North America. The "dry fog" is obviously not water vapour as the sun was unable to disperse it. If it was of volcanic origin, as Franklin speculates, then his account is a reasonable description of the presence of an acid aerosol layer in the upper atmosphere. The impedance of the sun's rays by a volcanic aerosol layer can result in surface cooling [Hansen & Lacis 1990; Sigurdsson 1982, 1990]. Franklin describes the ability of the sun to heat the ground in the summer of 1783 as "exceedingly diminished" and that in consequence the following winter was cooler than normal.

Franklin described a cool summer and a harsh winter, but were these phenomena caused by the volcanic activity in Iceland in 1783? If the conditions observed by Franklin were indeed caused by the influence of the volcano, then these phenomena should have been reported and duplicated over a wide area. The association of the climatic phenomena, the atmospheric phenomena and the volcanic eruption makes an assumption of dependence a simple step. If we accept Franklin's account as a model for the influence of other volcanic eruptions on climate then the search for other associations between anomalous weather and volcanic eruptions and the extrapolation of these conditions over a wide geographical area becomes a useful and respectable exercise. Franklin's account of the weather in 1783/84 could conveniently be taken as the basis on which to forward a model of climatic deterioration in response to other, lesser, Icelandic volcanic eruptions in prehistory.

Is it possible to support Franklin's observations with other contemporary European records? Did other areas of Europe experience similar atmospheric and meteorological conditions? I have discovered the following account of Gilbert White, which must challenge any model based solely on the work of Benjamin Franklin.

The personal observations of Gilbert White.

Gilbert White's "Natural History Of Selbourne" [1789] contains another contemporary description of strange atmospheric phenomena and weather in 1783. While similar in many respects to Franklin's observations, his descriptions of climate are strikingly different.

> *"The summer of 1783 was an amazing and portentous one, and full of horrible phenomena; for besides the alarming meteors and thunder-storms that affrighted many counties of this kingdom, the peculiar haze or smokey fog, that prevailed for many weeks in this island and in every part of Europe, and even beyond its limits, was a most extraordinary appearance, unlike anything known within the memory of man. By my journal I find that I had noticed this strange occurrence from June 23 to July 20 inclusive, during which period the wind varied to every quarter without making any alteration in the air. The sun, at noon, looked as blank as a clouded moon, and shed a rust coloured ferruginous light on the ground, and floors of rooms; but was particularly lurid and blood coloured at rising and setting. All the time the heat was so intense that butchers' meat could hardly be eaten on the day after it was killed; and the flies swarmed so in the lanes and hedges that they rendered the horses half frantic, and riding irksome."* White [1789] .

White's descriptions of the smokey fog, the blank sun and the lurid colours of the rising and setting sun, would be recognised by any volcanologist as the result of stratospheric veiling caused by a volcanic eruption. His descriptions of the atmospheric conditions are not dissimilar to those of Franklin, and the atmospheric phenomena described in both accounts are clearly the result of the volcanic dust and gases finding their way into the upper atmosphere. Both accounts demonstrate that the atmospheric effects of the volcano were clearly observed over a wide area.

Gilbert White differs strongly from Benjamin Franklin in his account of the extreme summer heat. On this count both records are mutually incompatible. If the volcano caused a cool summer in Paris it seems reasonable to expect a similar summer in Hampshire. Alternatively it may be reasonable to suggest that based on the evidence from England, Paris should have been experiencing a hot summer! By these accounts both sites appear to be experiencing extremes of weather, is it reasonable to blame the climatic phenomena at both or any of these locations on the eruption of the volcano Laki? If southern England was experiencing a hot summer at the same time that adjacent northern France was, according to Benjamin Franklin, experiencing a cool summer, while both sites describe the atmospheric effects of the eruption, then we must begin to question the association made between the eruption and the cool summer. The assumption that the climatic phenomena associated with the eruption of Laki was widespread, and by proxy the climatic phenomena of other volcanic eruptions, may also be questioned.

The exclusive use of the accounts of either Franklin or White would allow a researcher to model either anomalous heat or cold! Even if the eruption of Laki in the summer of 1783 is responsible for the anomalous weather at both locations, which should a researcher select? The similarities and contrasts which exist between the two accounts indicate that it is not safe to accept single, uncorroborated, descriptions of anomalous weather and assign them to a remote physical causes such as a volcanic eruption.

It is not the purpose of the above discussion to cast doubt on the veracity of Benjamin Franklin's statements. What it attempts to demonstrate is that observations of poor climate, even when positively correlated with an eruption cannot be held as proof of a causal link between the two events. Nor can such observations be held to be true for a wider geographical area, no matter how attractive the correlation, unless corroborating temperature records or reliable observations exist. Any attempt to relate ecological change or human response to the influence of a distant volcanic eruption must be made very carefully indeed. If a researcher is to use a remote volcanic eruption as the agent of change in their research area it is necessary to specify the exact mechanism by which such an impact was felt. It is no longer sufficient to establish that a volcanic eruption occurred in that or the previous year and assume a climatic response of sufficient scale to bring about the changes observed. A study of the warm summer of 1783 offers an opportunity to explore the mechanisms by which the warming may have occurred and relate them to volcanic activity.

Temperature analysis.

It is not intended in the analysis of temperature trends below, to identify a statistical association between temperature response and the volcanic eruption. In Chapters 3 and 4 it was shown that volcanic forcing was merely one of many variables responsible for climatic variability. Temperature records over 200 years old are an insecure base on which to suggest a dependent relationship, or to identify the full range of forcing mechanisms involved. This research sets out to investigate whether one of the largest volcanic eruptions of the Holocene, in terms of sulphur output, can be associated with temperature fluctuation which could be considered with temperature fluctuation which could be considered exceptional, As a result this analysis presents temperature trends and attempts to place the temperatures associated with the Laki eruption in the context of temperature range and variability of the late 1700's.

The summer of 1783.

Does the response of climate to the eruption of the Laki fissure, in the summer of 1783, offer any clues to the suggested abandonment of land in northern Britain in the Bronze Age? The monthly temperature records for Britain [Manley 1974; Mossman 1896] were analysed in an attempt to isolate a volcanic signal in the climatic records. Climatic response in the summer of 1783 is contrary to models of climatic response to northern hemisphere eruptions proposed by many researchers [Kelly & Sear 1984; Lamb 1970, 1972; Sear *et al.* 1987] which suggest that rapid surface cooling or unstable circulation should occur in the weeks immediately following a northern hemisphere eruption. On the contrary, qualitative and quantitative data from Europe suggests that late June and July in particular were notably hot [See Barker 1789; Manley 1974; Mossman 1896 and research presented below] and that atmospheric circulation was dominated by a stable high pressure cell [Kington 1980; 1988]. Models of climatic response to volcanic eruptions have emphasised the need for a clear injection of volcanic material into the stratosphere as a prerequisite for subsequent surface cooling of hemispheric temperatures [Pollack *et al.* 1976; Baldwin *et al.* 1976; Sigurdsson 1990]. The dynamics of the Laki eruption ensured that, throughout June and early July 1783, the tropopause was frequently penetrated by the eruption cloud and the tropospheric content of dust and gases was continuously enhanced [Thordarson *et al.* 1992; Thordarson & Self 1993]. Was the exceptional warmth during this period a result of the presence of the Laki aerosol cloud in the troposphere? An analysis of the atmospheric and climatic phenomena during the summer of 1783 may offer an answer to this question.

Contemporary Records.

Reliable contemporary observers have left records which establish the presence of considerable levels of volcanogenic material in the atmosphere in the summer of 1783, similar accounts may be found after many historic eruptions [Stothers & Rampino 1983]. The observations made in the summer of 1783, however, are unique in their association with hot rather than cool weather.

Benjamin Franklin, who was the United States Ambassador to France in 1783, described the summer presence of a constant fog which neither wind nor sun was able to disperse [Franklin 1784]. He found that this fog had weakened the sun's rays:

> *"They were indeed rendered so faint in passing through it that when collected in the focus of a burning glass, they would scarce kindle brown paper".*

This is a clear indication of the presence of an aerosol layer in the atmosphere, and Franklin's experiment demonstrates that the energy reaching the earth's surface had been diminished; conventional models suggest that surface cooling should have followed.

But consider the following contemporary accounts which were located during the research for this thesis. Temperature records for this period in Frane are difficult to obtain, but qualitative records challenge the common infernce from Franklin's account, that the summer in France was cool:

> *"Extract of a letter from Paris, July 4th. 'For considerable time past, the weather has been very remarkable here; a kind of hot fog obscures the atmosphere, and gives the sun, much*

of that dull red appearance'". [General Evening Post July 12 & The Ipswich Journal. July 19 1783]

> "*The hot fog still continues at Paris, the heat has been excessive, and thunder storms frequent*" [The Morning Herald and Daily Advertiser. July 26, 1783].

On June 25th Parson Woodforde, at Weston Longeville, Norfolk, recorded in his diary [Woodforde 1984]:

> "*Very uncommon Lazy and hot Weather. The sun very red at setting*",

and on July 28th,

> "*This has been the hottest day this year, and I believe the hottest that I ever felt, many say the same*".

Other material presents similar evidence. The Meteorological Register kept at Lyndon Hall, Rutland, by Thomas Barker [1771-1789] mentions "thick moist air" on June 21st and "very thick Smoaky air" on June 25th. On June 26th, Barker records very hot temperatures and an obscured sun:

> "*calm, very thick air, very hot till evening, sun scarce shone*".

The letters of the poet, William Cowper [King & Ryskamp 1981], confirm Barker's observations and clearly associate hot temperatures, mists and a red sun:

June 13th,

> "*The weather is still as hot, and the air as full of vapour*"

June 29th,

> "*So long in a country not subject to fogs, we have been cover'd with one of the thickest I remember. We never see the sun but shorn of his beams, the trees are scarce discernible at a mile's distance, he sets with the face of a red hot salamander and rises with the same complexion*".

Horace Walpole writing on July 15th [Cunningham 1938] also appeared to link volcanogenic aerosols with unseasonable heat and a constant mist:

> *"I am sorry your Ladyship has suffered so much by the heat...I am tired of this weather...it parches the leaves, makes the turf crisp...and keeps one in a constant mist that gives no dew but might as well be smoke. The sun sets like a pewter plate red hot."*

Contemporary newspaper accounts associate a sulphurous stench and the intense heat:

> *"As the storm came on in most places the thermometer kept rising. Where the rain fell the thunder was most violent; where there was no rain the sulphurous stench remained in the air the greatest part of the next day, when the heat was more intense than before."* [The Sherbourne Mercury July 21, 1783].

Gilbert White, a careful observer of natural phenomena, described both the atmospheric phenomena and the summer of 1783 in great detail [White 1789]:

> *"..the peculiar haze or smokey fog, that prevailed for many weeks in this island...was a most extraordinary appearance. By my journal I find that I had noticed this strange occurrence from June 23 to July 20 inclusive. All the time the heat was so intense that butchers' meat could hardly be eaten on the day after it was killed."*

All the accounts above suggest that the atmospheric phenomena, the "peculiar haze, or smokey fog", the obscured noonday sun, and lurid colours at sunrise and sunset, and reduced visibility are the result of a volcanic eruption. They clearly establish the presence of significant levels of volcanic aerosols in the troposphere. The "sulphurous stench" "the dry haze" and red appearance of the sun at rising and setting are all linked to descriptions of intense heat. None of the above describe the expected climatic or circulation response to a major northern hemisphere eruption [Kelly & Sear 1984; Lamb 1970, 1972; Sear *et al.* 1987], there is no evidence for rapid cooling, nor for unstable weather circulation.

Quantitative records.

Quantitative studies confirm these descriptions by contemporary English observers observers. High pressure and hot weather were common across Europe throughout late June and much of July [Kington 1988]. In the Central England temperature record [Manley 1974], July temperatures for 1783 appear exceptional [Figure 5.2], while both June and August lie close to the mean for 1770-1790 [Figure 5.3 & 5.4]. The June mean temperature for 1783, 14.8°C, is only 0.14°C above the twenty year mean. The mean temperature for July 1783, 18.8°C is the warmest in the Central England Temperature record [Manley 1974], and 2.7°C above the mean July temperature 1770-1795 [Figure 5.5]. August 1783, averaging at 15.8°C, was slightly cooler than the 26 year mean. Warmer than average July temperatures were not limited to central England. Mossman's records for Edinburgh [1896] shows that July 1783 was the second warmest July in the series from 1764-1896 [Figure 5.6]. Similarly, July was the warmest month in the Copenhagen temperature series from 1768-1893 and the fifth warmest in central Europe [Kington 1980]. In Edinburgh, the August mean temperature for 1783, was 14.67°C, which falls exactly on the 26 year mean.

Why were July temperatures in 1783 so exceptional? Gilbert White described the occurrence of the haze and the summer heat between June 23rd and July 20th and several other accounts also associate dry fogs, haze, sulphurous stench and temperature. Throughout this period a high pressure cell sat over southern Britain and north west Europe and a low pressure cell sat to the north and north west of Iceland [Kington 1980, 1988]. The weather observations made by Thomas Barker, at Lydon Hall Rutland [Manuscript: National Meteorological Library Bracknell] associate steeply rising temperatures and "thick air". The synoptic maps of Kington [1988] suggest that this coincided with the onset of a stable high pressure system [Figure 5.7].

Within a high pressure cell air descends and diverges, surface winds would therefore have travelled from north west Europe towards Iceland, it is therefore difficult to account for the transport of volcanic material reported in Europe at this time by low altitude winds. However under the circulation conditions prevalent from June 21st the transport of volcanic gases to Britain may have followed the model illustrated by Figure 5.8. Volcanic material confined to the troposphere may have been transported to north west Europe by high altitude winds converging on the high pressure area. The stability of the cell would ensure a concentration of gases at the bottom of the atmospheric column. This concentration could have caused the reduced visibility and "dry fog" noted above. Could these conditions have played a role in generating the high temperatures in July 1783?

Volcanically-generated warming of the lower atmosphere: theory and model.

Fissure eruptions may not achieve a clear injection of material into the stratosphere, and the majority of gas and material emitted may be confined to the troposphere [Tripoli & Thomson 1988]. The fine dust and gases emitted in the early eruptive episodes of the Laki fissure eruption appear to have inhibited outgoing radiation in excess of the reduction of incoming solar radiation, with the result that net warming occurred. The cooling which is conventionally expected to follow a volcanic eruption depends on the formation of a stratospheric aerosol [see Chapter 2]. The photochemical conversion of volcanic gases to an aerosol form within the stratosphere, has been observed to be relatively slow, and maximum perturbation of global albedo may not occur until several months after an eruption [Ardanuy *et al.* 1992; Castleman *et al.* 1974]. While the formation of the stratospheric aerosol is not well advanced, and its cooling effect minimal, silicate and basaltic particles also emitted in the eruption are present in the stratosphere. Such particles have the theoretical ability, at least in the short-term, to counterbalance aerosol-induced cooling due to the opacity of the volcanic aerosol to longwave and particulate absorption of infra-red radiation causing atmospheric warming [Pollack *et al.* 1976; Chou *et al.* 1984; Harshvardan 1979]. Several workers [Preining 1991; Chou *et al.* 1984; Harshvadhan 1979] have indicated that absorption of shortwave radiation by tropospheric aerosols has the potential to cause atmospheric warming near the ground, thereby reducing the cooling effect of the eruption. Preining [1991] noted that shortwave absorption by natural and anthropogenic aerosols near the ground not only caused heating that has been estimated at about 1°Kd^{-1}, but that emissions of particles into the lower stratosphere also had an important warming effect. Chou and others [1984] estimated that such infrared warming may reduce the cooling effect of the volcanic aerosol by c. 40%, while Harshvardhan [1979] found that infrared warming by volcanic aerosols could reduce the net radiative loss of an atmospheric column by approximately 30%. These estimates are based on the behaviour of material emitted into the atmosphere during conventional explosive eruptions. The weather phenomena recorded in June and July 1783 suggest that fissure eruptions are capable of reducing net radiative loss from an atmospheric column to an even greater degree.

The high pressure cell represents an air column in which volcanic gases and aerosols might have been concentrated. Radiative loss may then have been reduced in excess of the estimates of Chou *et al.* [1984] and Harshvardn [1979] and surface warming may have followed. In addition the research of Preining [1991] demonstrates that a concentrations of aerosols in the bottom kilometre of the atmosphere may also lead to warming. The conjunction of these conditions may have led to the warm temperatures recorded in July.

All the evidence presented above points to the emissions of the Laki fissure as being at least partially responsible for the extreme weather experienced in late June and July 1783. The warming generated by the absorption and reflection of short and longwave radiation, by volcanic material confined in a stable high pressure cell, may be in excess of the capacity of an immature stratospheric aerosol layer to impede incoming solar energy. This work does not suggest that the volcanic aerosols acted independently in generating the warm July. The air source was already naturally warm and stable atmospheric conditions were necessary to allow the enhancement of air temperatures by the volcanic aerosol.

A detailed study and the acquisition of new material by the present author, presented above, has demonstrated that volcanic eruptions may affect climate on the regional / sub regional level. The warming which occurred in July 1783 is explained by combining eye-witness accounts and an understanding of atmospheric circulation with modern studies of the warming potential of aerosols in modern pollution episodes. The summer of 1783 demonstrates that volcanic modification of climate need not automatically result in lowered surface temperatures. Nor that it is necessary to infer, or right to assume, a global environmental impact in the wake of a major volcanic eruption. A new model has been proposed above which suggests that such volcanic eruptions may have particular impacts in very small areas. This model relies on stable circulation, an air mass which is already warmed and tropospheric concentrations of volcanic material. The volcanic material then inhibits outgoing solar radiation and warming follows. Given a different set of antecedent conditions; winter temperatures, a high pressure cell originating in the polar Arctic, a cold or snow covered ground surface and similar eruption dynamics, atmospheric warming may not necessarily result in northwest Europe..

The winter of 1783/84.

The winter of 1783-84 is recorded in Iceland as the "volcano winter". In the aftermath of this eruption a quarter of Iceland's' population perished. Statistics such as these, the statement by Benjamin Franklin and Icelandic folk lore have all combined to present this winter as exceptional. This perception is common in much research and allows the assumption that prehistoric eruptions may have triggered similar phenomena [Thorarinsson 1979; Sigurdsson 1982; Jackson 1982]. However it is important to ask just how exceptional was this "volcano winter"?

Temperature trends in Iceland.

Was the "volcano winter" in Iceland in 1783/84 exceptional? Let us first examine other winters that happened during this period and place this winter in the context of the weather of that period. The available evidence suggests that the winter of 1781-82 was unusually severe in most of Iceland. Except for short periods they were the severest frosts that people could remember, and the governor of Bessastathir wrote that it was the coldest winter since he had come to Iceland in 1770 [quoted in Ogilvie 1986]. 1782 was an unusually cold year in Iceland, with sea ice appearing off the north coast in mid-march, [Table 5.1] and reported around much of the coast through spring and summer [Ogilvie 1986]. Jón Jónsson [quoted in Ogilvie 1986] recorded that there were nineteen ships anchored off Hrísey in Eyjafjord, afraid to leave because of the danger of sea ice. In July, the fields of Sudur Múlasysla were still covered in snow. In Dalasysla there were night frosts throughout the summer and heavy snow fell at the beginning of July. Jón Jónsson recorded that all hope of a harvest ended as early as mid September. In Snæfellsnessysla, the hay harvest was stopped by bad weather and rain, with mild southerly winds being replaced by frost and snow.

The following winter of 1782-83 was also hard. In the north, the cattle had to be kept and fed indoors from mid December to March. There were such amounts of snow "that old people can scarcely remember its like" [quoted in Ogilvie 1986]. The winter was also hard in the north and east, but in the south the winter, though cold, was dry and not considered severe. While in 1782 sea ice had appeared off the south coast, in 1783 it was absent. Nonetheless it appeared off the north, east and west coasts throughout the summer up to August of that year [Ogilvie 1986; Schell 1961].

The winter of 1783-4, the "volcano winter", was also poor, the impact of the climate intensified by the stresses created by the series of hard winters and the environmental pollution caused by the eruption [See Chapter 6]. The end of the winter was usually a time of shortage [Anddresson 1984, Rafnsson 1984], and after a summer where both pasture and livestock suffered, the people of Iceland were in a very poor shape to cope with yet another severe winter. Undoubtedly the economic reliance on livestock rather than grain and the colonial practises of the Danish crown, primarily a monopoly control of trade, worsened the situation [Jackson 1982; Andresson 1984; Gunlaugsson 1984]. It must also be acknowledged that the greatest number of human deaths did not occur in the "Famine winter", but later in 1786-87, with the Smallpox epidemic of that year [Hálfdanarsson 1984].

The "volcano winter" was therefore the third in a series of harsh winters. The winter of 1783/84 is viewed as catastrophic, but the severity of the winter must be viewed in the context of the impact of the volatile emissions of the eruption and the impact these had on vegetation and livestock [discussed in Chapter 6]. These combined with the severe winter to create exceptional hardship. Volcanic forcing of climate is therefore **not** the sole independent factor which might be held responsible for the reported hardship of the season.

With the catastrophe in Iceland caused by a possible combination of climatic, volcanic and economical factors, what other evidence supports Franklin's [1784] suggestion that in Europe the winter of 1783-84 was exceptionally cold?

Winter temperatures in Britain: the Edinburgh temperature record.

Winters of extreme hardship were not unknown in Scotland. The annals collected by Mossman [1896], while not statistically useful, reveal the presence of very severe winters.

These were in:

1595:

> *"Ane horrible tempest of snaw, whilk lay upon the ground."*

1615:

> *"In February the Tay was frozen over so strongly as to admit of passage for both man and horse."*

1634-35:

> *"The most tempestuous and stormy that has been seen in Scotland these sixty years past."*

1655:

> *"Severe and protracted storms, followed by a frost which continued to April."*

1675:

> *"Great cold "the most aged never remembered the like. Ale froze."*

1698:

> *"An extreme cold and winter like spring, great want of food and seed, sheep and cattle died in great numbers."*

1732:

> *"A great fall of snow. Ice so strong as to bear man and horse. Lambs succumbed to the excessive cold."*

1739:

> *"Snow lay deep on the ground for six weeks."*

1765:

> *"Severe snowstorm, many lives lost in the Border counties."*

These annals serve to indicate that severe winters were not unknown in Scotland in the period before temperature records were kept. None of these events correlate with the eruption of acid rich, and theoretically climatically-significant volcanoes. The winter of 1783-84, when the cooling effect of the stratospheric aerosol should have been at its greatest, was not considered unusual in Edinburgh, while the winter of 1784-85 was recorded as exceptional:

> *"From the 18th of October 1784 to the present time, which is a period of 143 days, there have been only 26 in which the thermometer has not been from 1 to 18 degrees and a half below the freezing point, which is a more constant succession of cold weather than has been known in this climate. Last year there were 89 days of frost and in the year 1779 there were 84; in 1763 there were 94 days of frost, and in the celebrated winter of 1739 there were only 103, which are 12 fewer than the present winter"* [Edinburgh Magazine. Quoted in Mossman 1896].

Mossman's [1896] collation of temperature records for Edinburgh allows a reconstruction of temperature trends. It is obvious that the winter of 1783-84, based on the means of January and February, was not exceptional. In the period 1764-1830 there were seven other winters which were as cold or colder than that associated with the eruption of Laki [Figure 5.9]. Using a more restricted sample based on the mean of January and February temperatures between 1764 and 1800, shows that January and February temperatures in 1784 were a mere 1.2 standard deviations below the 36 year mean [Figure 5.10]. A broader sample taking in data from 1764-1830, shows clearly that the winter of 1783-84 was not particularly severe [Figure 5.11]. The conclusion which must be drawn is that the winter temperatures in Edinburgh, associated with the eruption of the Laki fissure, were not exceptional. The year concerned can be seen to be part of a temperature series in which extremes of cold and warmth fail to correlate with volcanic events. The volcano can not be held responsible for causing extreme weather events in Scotland.

Winter temperatures in Britain: the central England temperature record.

In England, as in Scotland, analysis of temperature records indicate the occurrence of harsh winters in years which are **not** associated with recorded volcanic eruptions. Cooler Januarys are recorded in 1775 and 1779 [Figure 5.12]. February 1784 is warmer than February 1785 [Figure 5.13]. Mean temperatures reveal that the winter following the eruption of Laki was the fourth most severe between 1733-1833 but it is also part of a declining trend in air temperatures. Any suggested correlation of **one** volcanic eruption, with one of fourteen winters between 1733-1833, which falls beyond one standard deviation below the mean must be considered of dubious significance [Figure 5..13]. Working on Manley's data, the climatologists Dyer [1976], and Matyasovsky [1989] see this year as part of a **warming** trend, the **recovery** from the Little Ice Age, and not exceptional.

Discussion: extreme weather and the Laki eruption.

It seems plain that the severe weather in Iceland, blamed on the eruption, must be considered to be part of a deteriorating trend. Sea ice data and records compiled from contemporary annals [Jackson 1982, 1984, Ogilvie 1986; Schell 1961] indicte that Icelandic climate was deteriorating and that Icelandic economy and society was undergoing a period of stress. In the context of this thesis, the people of Iceland could be considered a marginal society and vulnerable to a combination of economic, climatic, volcanic and medical factors. The vulnerability of Icelandic society to environmental stress conditioned its response to the volcanic eruption. This example is particularly valuable in the context of the main subject of this thesis, the abandonment of marginal lands in northern Britain in the Bronze Age.

The assumption of previous writers [Baillie 1988; Burgess 1989] that the Hekla 3 eruption caused a severe climatic deterioration and forced the abandonment of marginal lands in Scotland must be called into question when an eruption, such as Laki in 1783, which was theoretically capable of a far greater climatic impact, **failed** to produce the expected "extreme" climatic phenomena. The failure of the

Laki eruption to trigger severe and long lasting climatic deterioration is significant for any models which attempt to correlate the Hekla 3 event and the "Upland Crisis" in Britain.

It has been demonstrated that the large scale climatic response to the eruption of the Laki fissure was not on the scale which would trigger abandonment of land in northern Britain. However an explanatory model has been proposed above, and is expanded in the following Chapter 6. This model suggests how the recorded concentration of significant quantities of volcanically generated volatile gases could occur on a regional/local scale in the lower atmosphere. Specifically this model suggests that the hardship recorded in Iceland was created, in part, by the direct impact of volatile emissions on vegetation and livestock, not by a lowering of air temperature. This raises the possibility that the distal transport of volatile gases could bring about severe disruption of the environment in Britain? This possibility is discussed in the following chapter.

Table 5.1 A summary of the seasons. Iceland 1781-1784. After Ogilvie 1986.

Year.	District.	Winter.	Spring.	Summer.	Autumn.
1781	North	Mild	Variable	Good	Variable
	South	Mild	Reasonable	Mild	Variable
	East	Mild	Reasonable	Good	Variable
	West	Mild	Reasonable	Good	Wet
1782	North	Severe	Severe	Cold & Dry	Very cold
	South	Severe	Severe	Cold & Dry	Cold
	East	Severe	Very cold	Very cold	Very cold
	West	Severe	Very Cold	Very cold	Cold
1783	North	Severe	Variable	Variable	Cold
	South	Reasonable	Mild	Cold	Cold
	East	Severe	Cold	Cold	Cold
	West	Cold	Reasonable	Cold	Cold
1784	North	Severe	Very cold	Cold	Reasonable
	South	Severe	Very cold	Cold	Reasonable
	East	Severe	Very cold	Reasonable	Reasonable
	West	Severe	Very cold	Cold	Reasonable

Discussion:
Volcanic eruptions, climatic change and society.

The preceding chapters have investigated the theoretical, modelled and actual impact of volcanic eruptions on climate in great detail and found little evidence for severe climatic change in the wake of the most severe volcanic eruptions of the Holocene. This must call into question any assumptions made previously of the climatic impact of the Hekla eruptions of the Second Millennium B.C. The calibre of these arguments, in press and in conference, has largely been based on finding the widest possible range of environmental phenomena which may have been related in time to an eruption, and then assuming that the eruption was large enough to have directly caused the phenomenon [Baillie 1989b; J.Barber *Symposium on Lairg* 1991]. In fact the Hekla eruptions did not approach the scale of the Tambora and Laki eruptions, and are extremely unlikely to have been responsible for the volcanic equivalent of a "Nuclear Winter" [Rampino 1988; Turco *et al.* 1982, 1983, 1984a & b, 1985]. But it is this argument which has found its way into the popular mythology [*cf* BBC Television's **Horizon** documentary "*A Time Of Darkness*"].

Do the Tambora and the Laki fissure eruption offer any clues as to the events which may have occurred in the Second Millennium B.C.? It is difficult to separate any volcanic signal in the weather for these years from the existing trends. While there are stations reporting exceptionally inclement weather, others appear to experience clement or average conditions. The ensuing famines appear to be the culmination of several bad years and it is difficult at this distance in time to isolate meteorological from social and economic factors as the sole cause of hardship. Just as the failure of the Danish government to act quickly in the face of Icelandic hardship in 1783-84 exacerbated the situation in Iceland. So high grain prices rather than a real shortage may have intensified the hardship of the poor, across central Europe, in 1816. The perception of 1783 and 1816 as crisis years can be seen to be the result of the complex interaction of social, economic and environmental factors, should we expect the events of the Second Millennium B.C. in northern Scotland to be any less complex?

The aftermath of both eruptions leads to the conclusion that volcanic eruptions cannot be conclusively blamed for extreme weather phenomena, no matter how attractive the apparent association. The temperature records do not support any conclusion that eruption or post-eruption years are exceptional. Both Laki, 1783 and Tambora, 1815, fulfil all the criteria to be climatically effective. Both emitted vast volumes of acids and both were massively explosive. Neither eruption can be shown to have caused extreme temperature fluctuation, nor to have caused long lasting changes to the circulation pattern.

The possible climatic impact of a volcanic eruption cannot then be considered in isolation. Perhaps these events can be used to model population response to environmental stress in northern Scotland. The factors involved can be broken down as follows:

1) The perception of the climate as unusually harsh.
2) An uncertain economic situation.
3) A vulnerable section of society..
4) Population pressure (in this case from immigration).
5) The perception that elsewhere conditions would be better.
6) A series of several poor years and gradually deteriorating climatic conditions.

How then can the Hekla 3 eruption be held able to have caused extreme climatic fluctuation. The acid output of Hekla 3, on any analysis is orders of magnitude below that of either Laki or Tambora. It does not appear reasonable to model a climatic decline in the wake of this eruption great enough to have caused widespread landscape abandonment when far more effective eruptions have patently failed to do so. Any model which does utilise the coincidence of a volcanic eruption must take into account the social and economic factors which were so important in 1783-5, and 1815-17. It must also account for the existing temperature trends and whether the society concerned is marginal in any way. It must also take into account other means by which the volcanic eruption may have an impact on the environment, other than climatic, and these shall be considered in detail below.

Chapter six.
The environmental impact of volcanic emissions.

Summary of chapter

Studies of the potential of Icelandic volcanic eruptions to modify the environment of the British Isles have concentrated on the degree of induced climate change [Lamb 1970, 1972; Kelly 1977; Kelly & Sear 1984], but the complex interaction of the processes which control the atmospheric circulation patterns of the earth are imperfectly understood and difficult to model [Hansen & Lacis 1990; Nicholls 1988, 1990]. As a result it is difficult to account for change in the palaeoenvironmental and archaeological record by modelling a climatic response to a volcanic eruption. An alternative mechanism, by which Icelandic volcanic eruptions may bring about environmental change via the transport and deposition of significant levels of acid volatiles and halogens, is proposed. Documentary evidence suggests that during the Laki fissure eruption, in the summer of 1783, severe acid damage to crops and trees occurred in eastern England and northern Germany, and that acid pulses killed fish in Scotland. Similar events may account for episodes of environmental stress identified in the palaeoenvironmental record which are difficult to explain by induced climate fluctuation.

Recent research has focussed attention on the potential impact of the emissions of Icelandic volcanic eruptions on the British Isles. Dugmore [1989] and Pilcher and Hall [1992] have identified tephra from Icelandic volcanoes in peats in Ireland and Scotland and Blackford *et al.* [1992] found Icelandic volcanic ash, from the Hekla 4 eruption, in association with a mid-Holocene pine [*Pinus sylvestris*] decline in Caithness, northern Scotland. Baillie [1988] and Baillie and Munro [1988] have associated stress in Irish oak trees with volcanically-induced acid peaks in the Greenland ice-core [Hammer 1977, 1984; Hammer *et al.* 1980, 1981], and Burgess [1989] speculated that the Hekla 3 eruption may have been responsible for the crisis apparent in the British archaeological record in the Late Second millennium BC. Attempts to explain these relationships have suggested that an induced climatic change was the primary mechanism responsible [Baillie 1989 a & b], but the degree to which atmospheric circulation responds to volcanic forcing has been called into question [Hansen & Lacis 1990; Hunt 1977; Nicholls 1988, 1990], and the scale of surface temperature response has been observed to be minimal [Bradley 1988; Kelly & Sear 1984; Mass & Portman 1989; Newell 1981; Self *et al.* 1981]. It is therefore unsatisfactory to suggest that stress in the palaeoenvironmental or archaeological record, associated with a volcanic eruption, has inevitably occurred in response to volcanic forcing of climate.

Volcanic eruptions which possess the theoretical ability to bring about climate change are those which emit substantial volumes of volatile gases [Rampino & Self 1984]. "Climate change theories" require that these be injected into the stratosphere to form an aerosol layer which will reduce insolation [See Chapter 2]. If the volatile gases are not injected into the stratosphere and remain in the troposphere they must inevitably settle out and be deposited on sea and land. The possibility that substantial volumes of potentially toxic volcanic volatile emissions may be deposited on distant ecosystems, offers an alternative mechanism by which environmental change may be brought about.

The discussion below explores the impact of these substances when delivered to an ecosystem in a variety of ways. This is done by analysis of medical, chemical, biological and historical literature. The proximal impacts of volcanic gases in Iceland are investigated as this will form a baseline on which to base estimates of impacts on distal environments. Much of the historical material presented below was discovered by archival study during the course of this research.

Volatile yield.

The volatile gases emitted during an eruption range from such ubiquitous and harmless elements as silicon, iron, and sodium to a wide range of harmful acids and halogens such as chlorine, fluorine, and sulphur [Table 6.1]. The yield of volatiles is not only dependent on eruptive mass and the atmospheric residence time of the eruption cloud, but also on the composition of erupting magmas. Thus the volatile yield of silicic or rhyolitic eruptions is likely to be an order of magnitude lower than a basaltic or trachytic eruption of a similar mass. The average yield of sulphuric acid from silicic magma eruptions is within the range 100-500 ppm, this is a marked contrast to the yield of basaltic eruptions, which normally fall within the range 1000-5000 ppm [Bernard *et al.* 1991]. The massive 131 A.D. eruption of Taupo, New Zealand, emitted 35 km^3 of silicic magma, but had a low yield of Sulphur, Chlorine and Fluorine [Newnham 1991].

Conversely fissure eruptions, which are not massively explosive in the conventional sense, may yield vast quantities of volatile gases. The 1783 eruption of the Laki fissure in Iceland, was basaltic and is noted for its large sulphur output, 9.9 X 10^{13} grammes [Thordarson *et al.* 1992]. Residual gas analysis, of minerals from this eruption suggest that 500 million metric tons of pollutants passed into the atmosphere [Oskarsson *et al.* 1984]. Trachytic eruptions, however, may yield significantly greater volumes of halogens than sulphur; the eruption of Tambora, 1815, yielded 2 X 10^{14} grammes of chlorine and 1.7 X 10^{14} grammes of fluorine [Devine *et al.* 1984: Palais and Sigurdsson, 1989]. The estimated volatile output of the Hekla 3 eruption was considerable with an estimated yield of; 1.58 X 10^{11} g Sulphur, 2.48 X 10^{11} g Chlorine, 4.84 X 10^5 metric tons H_2SO_4 and 2.55 X 10^5 metric tons HCl [Devine *et al.* 1984], and a total acids output of 7.39 X 10^5 metric tons [Palais *et al.* 1989]. The magnitude of an eruption is therefore an ineffective means of assessing its volatile output, however the acid peaks identified in the Greenland ice-core record the incidence of eruptions with a substantial acid output. These acid peaks may indicate the occurrence of eruptions with the potential to deposit acids and halogens on distal environments. The eruptions of Hekla 3 and Hekla 4 are associated with both an acid peak in the ice-core record [Hammer *et al.* 1980] environmental change in northern Europe [Baillie & Munro 1988]. I therefore ask a different question. Could environmental change sufficient to effect Bronze Age peoples in Upland Britain have occurred as a direct result of the deposition of volcanic volatiles, rather than as a result of an induced climate change?

DAMAGE CAUSED BY VOLATILE GASES.

Proximal damage.

A study of the environmental damage associated with eruptions in Iceland itself will establish the scale of response in proximal vegetation. This will be used to assess the likely degree of impact of volcanic volatiles on distal ecosystems.

Toxicology of Volcanic gases.

AMMONIA.		
Animal Thresholds.	100ppm in air.	Irritation of mucous membranes, coughing, dyspnea and vomiting. Conjunctivitis,retention of urine, lung oedema.
Plant Thresholds.	10ppm in air.	"cooked" appearance becoming brown on drying.
CARBON DIOXIDE.		
Animal Thresholds.	5000ppm in air.	Asphyxiation, drowsiness, weakness.
Plant Thresholds.	No marked effect.	
CARBON MONOXIDE.		
Animal Thresholds.	100ppm in air.	Shortness of breath , impairment of hearing and vision.; dizziness, at high concentrations unconciousness and death.
Plant Thresholds.	500ppm in air.	Epinasty, chlorosis, shedding of leaves.
FLUORINE.		
Animal Thresholds.	0.1 ppm in air.	Powerful caustic irritant, conjunctivitis, skin irritation, bone degeneration, mottling of teeth, lung inflammation.
Plant Thresholds.	0.1 ppm in air.	Marginal leaf lesions, shedding of leaves.
HYDROCHLORIC ACID.		
Animal thresholds.	5ppm in air.	Irritation of mucous membranes, spasm of the larynx, higher levels can result in pulmonary oedema.
Plant Thresholds.	10ppm in air.	Marginal leaf lesions, shedding of leaves.
HYDROFLUORIC ACID.		
Animal Thresholds.	3ppm in air.	Ulcers in respiratory tract. Skin burns, degeneration of subcutaneous tissues, gangrene, eye irritation, blindness, lung oedema.
Plant Thresholds.	Variable.	Marginal leaf lesions, shedding of leaves.
HYDROGEN SULPHIDE.		
Animal Thresholds.	20ppm in air.	Skin irritation at 20 ppm, respiratory paralysis at 500ppm, photophobia, inflammation of cornea and respiratory tract.
Plant Thresholds.	1ppm in air.	Chronic degeneration depending on concentration.
SULPHUR DIOXIDE.		
Animal Thresholds.	10ppm in air.	Eye irritation, burning of trachea, lung oedema, lung paralysis.
Plant Thresholds.	1ppm in air.	Chronic degeneration depending on concentration. Chronic, yellowing and bleaching of leaves. Acute, collapse of marginal and inter-coistal areas, drying to ivory or brownish red.
SULPHURIC ACID.		
Animal Thresholds.	0.1ppm in air.	Burning, rapid disintegration of tissue, lung damage.
Plant Thresholds.	Variable.	Scorching or charring, depending on moisture content and size of aerosol droplets.

Table 6.1. [After Wilcox 1959; Mandl 1974; Blong 1984].

Historic annals suggest that the deposition of volcanic volatile material has been a recurring problem throughout Icelandic history.

The Hekla eruption 1341 A.D.

> *"Coming up of fire in Mt. Hekla with great sandfall...great famine. Great loss of stock, both sheep and cattle, so that between the flitting days and the feast of St. Peter, Skálholt alone lost 80 cattle."* The Annals of Skålholt. Translated in Thórarinsson [1967].
>
> *"A greater part of the cattle stock in the south of the country perished because of this ashfall...Many farms were deserted in the Skálholt district and on Rangárvellir."* Gottskållksannåll. Translated in Thórarinsson [1967].
>
> *"Then fire came up in Mt. Hekla with such great sandfall that much stock died as a result during the spring and both sheep and cattle died out on Rangárvellir."* Einar Haflithason. Translated in Thórarinsson [1967].

The Hekla eruption 1693 A.D.

> *"nearly ruined in pastures and meadows...In the following eleven places the meadows and pastures are unusable and in some of them the home-fields yield little."* Rev. D. Halldórsson. Translated in Thórarinsson [1967].

Halldórsson also recorded that all the woodland trees in Thjórsárdalur were injured:

> *"and look decayed and withered, none of them with a leaf to be seen and that in the middle of May."* Rev. D. Halldórsson. Translated in Thórarinsson [1967].
>
> *"for a long time afterwards here, has no Iceland moss to be had from the mountains"* Jarthabók. Translated in Thórarinsson [1967]

Following the 1693 eruption of Hekla, chroniclers also described the death of *Ptarmigan* in areas where the grassland had been severely damaged, up to 120 Km from Hekla, and trout died in large numbers in lakes and rivers up to 180 km away [Thórarinsson 1979].

Hekla 1766/68.

> *"in many places through the summer there was heard neither the sound of the churn nor the shout of the shepherd."* Rev M. Pétersson. Translated in Thórarinsson [1967].

Volcanic eruptions in Iceland in 1783: Grimsvötn caldera and the Laki fissure eruption.

Volatile emission and proximal impacts.

The year 1783 was marked in Iceland by the eruption of the Grimsvötn caldera and the Laki fissure. The eruption of the Grimsvötn caldera, which began on July 18th has only been recognised recently [Thordarson *et al.* 1987; Thordarson & Self 1988, 1993] and no study has been made of its volatile output. Nevertheless, it is reasonable to assume that a contribution was made to the consderable volume of volatiles emitted by the Laki fissure, which is studied in detail below. The Laki fissure eruption was associated with the most extreme examples of the impact of volatile emissions on proximal ecosystems. After the 1783 eruption of the Laki fissure in Iceland, grass growth across the island was stunted and 50% of the cattle [Figure 6.1], 79% of the sheep]Figure 6.2], 76% of the horses and 24% of the human population had died by the end of 1784 [Hálfdarnarson 1984; Jackson 1984; Ogilvie 1986; Pétursson *et al.* 1984; Thórarinsson, 1969, 1979, 1981] and remote settlements were also abandoned [Gunnlaugson 1984; Guthbergsson & Theodórsson 1984; Rafnsson 1984].

The Laki fissure eruption began on June 8 1783, and continued until early February 1784 [Thórarinsson 1969]. During this period up to 9.9 X 10^{13} grammes of acid were emitted [Devine *et al.* 1984; Palais & Sigurdsson 1985; Sigurdsson *et al.* 1985; Thordarson *et al.* 1992]. The eruption cloud also contained hydrochloric and hydrofluoric acids [Pétersson *et al.* 1984]. Thordarson *et al.* [1992] suggested that 60% of the total volume was discharged over the first 48 days. An estimate of the discharge of sulphur dioxide in June and July based on this work suggests 13.75 X 10^{11} grammes/day. Fissure eruptions rarely possess sufficient energy to penetrate the stratosphere [Tripoli & Thompson 1988] and Thordarson and others [1992] concluded that although Laki eruption frequently possessed sufficient energy to reach altitudes of 5km above sea level the majority of emitted material was confined to the troposphere [Thordarson *et al.* 1992]. The resultant damage to plants and animals and the social and economic hardship which ensued in Iceland is recorded in harrowing detail.

The Sheriff of Rangárvallsysla recorded:

> *"The grass was singed and seemed to wither and stopped growing, so now there is a great lack of grass everywhere."* [Translated in Ogilvie 1986].

The Sheriff of Kjós district recorded:

> *"then the eruption, both in the western sea, and in Skaftafell district occurred with dust and fumes and megrass, which had been green, was made quite yellow and white by the sulphurous rain. After that the grass withered to the roots."* [Translated in Ogilvie 1986].

The Sheriff of Snæfellsness recorded:

> *"The air has smelt strongly of sulphur...The mouths of sheep and cattle have also been yellow with sulphur..and all the animals have been restless."* [Translated in Ogilvie 1986].

The Sheriff of Suthur Múlasysla recorded:

> *"Leaves on trees withered so that in June it looked as though it was far into October. The grass in the homefields became pale and in some places stopped growing."* [Translated in Ogilvie 1986].

Magnús Ketilsson in Dalasysla recorded:

> *"From early June and to this time we have lived in continual smoke and fog, sometimes accompanied by sulphur-steam and ashfalls. The grass has withered and the livestock have been extremely restless."* [Translated in Ogilvie 1986].

Across Iceland cultivated fields turned yellow and grass withered down to the roots. Birch trees and shrubs withered and shed their leaves. Clover [*Trifolium repens*] disappeared for up to three years in districts over 100 Km distant from the fissure. Across the island the Icelandic moss [*Lichen islandicus*], which in many places supplemented the human diet, disappeared [Thórarinsson 1979 p.154; Andresson 1984 p.232].

Animals and humans also suffered the effect of volcanic emissions.

Jón Steingrímsson in Sída district Wrote:

> *"The pestilential effect of the fire caused death and damage to horses sheep and cattle after the following fashion. The horses lost all flesh; on some the hide rotted all along the back; manes and tails decayed and came off at a sharp pull. Knotty growths appeared about the joints particularly around the fetlock. The head swelled inordinately, whereupon followed a paralysis of the jaw, so that the beasts could not graze or feed, for what they were able to chew dropped from their mouths again. The entrails corrupted, the bones withered, quite drained of marrow.....Sheep suffered yet more grievous harm; there was hardly a member but knotted, particularly the jaws, so that the knots pushed out through the skin close to the bone. Brisket, hips and legs - around those parts large bony excrescences developed which caused the leg bones to curve or else deformed them in various ways. Bones and knuckles as soft as if chewed lungs, liver and heart, in some swollen, in some shrivelled, the entrails rotten and soft, full of sand and worms. The shred of flesh that remained was after the same fashion. What passed for meat was both rank and bitter, and thereto full of strong poison, wherefore the eating of it proved the death of many a man, notwithstanding that people tried to cure it, clean it and salt it, according as their skill and means permitted.*
>
> *Cattle, too, were subjected to this same plague, large growths formed on jaws and collarbones, the leg bones sometimes split, sometimes knotted variously, with knobs as large as a man could grip with both hands. Of the hips and other joints the same was true; they became deformed, and then knitted and so lost all pliancy. The tail fell off with*

the tuft of hair, sometimes half of it sometimes less. The hooves loosened and slipped off, or sometimes split in the middle (a beast becoming footsore was the first sign of the pestilence). The ribs were deformed all along the side and then broke apart in the middle, being unable to support the weight of the beast when it needs must lie on its side. No knuckle bone was so hard that it might not easily be shaved with a knife. The hair of the hide fell off in patches, the inward parts were soft as already said of the sheep, and in many respects unnatural. A few cows that were not overly crippled were saved by pouring back down their throats the milk that could be pulled from them. In this matter one thing was noteworthy, namely that calves thrown during these hard times had excellent marrow in their bones with but little withering, although the dams had famine withered marrow in every bone.

Those people who did not have sufficient old and wholesome food, throughout this time of pestilence also suffered grievous distress. On their breastbones and ribs, the back of their hands, their insteps leg and joints, bumps and knots and hard knobs appeared. Their bodies puffed up, the gums swelled and cracked, with sore pains and toothache. The sinews contracted especially at the hough, which disease is called Scorbutus, that is to say curdle or water dropsy in its extreme stages. Of this pestilential disease having so severely afflicted any man that his tongue rotted and fell out, I know no instance here or elsewhere, unless there be truth in a certain report to that effect, concerning a man of this parish, who died in the district of Sudurnes, he having often in the past been troubled by a sore throat.

The pestilence affected the inward powers and parts, causing weakness, shortness of breath, throbbing of the heart, excessive discharge of urine and enfeeblement of the parts thereto pertaining, from which ensued diarrhoea, dysentery and worms in the intestines, sore boils on the neck and thighs and particular loss of hair in many both young and old. This sickness and the mortality that followed in its train proceeded, in my judgement, from insalubrious air, overmuch drinking of water, and unwholesome food such as was the flesh of the plague stricken beasts and also the Barley which the person then in

> *authority was so forward in proffering; in which matter the observed facts speak for themselves, that people died having store of barley, but survived wondrously if they had plenty of rye".*
>
> From Steingrímssom 1915-1917. Translated by Hannesson, in Thórarinsson [1979].

An English visitor to the island also witnessed the sufferings of man and beast at first hand and noted the social and economic consequences of the eruption.

> *"The volcanic eruption having thus been productive of devastation and sickness, both among man and beast a great famine ensued and unexampled misery throughout the country, naturally ensued. The peasant, who, with the loss of his cattle was likewise deprived of his sole means of subsistence, and of the best and most valuable part of his property, had nothing else (after having eaten the animals that died of famine or sickness) wherewith to satisfy the painful cravings of hunger but skins and old hides, which he then boiled and devoured. Many, driven to the last extremity, have killed the few healthy sheep and cattle that still remained, and afterwards, when these had been consumed, wandered with their whole families down to the sea side, where they have become an intolerable burthen and source of impoverishment to the inhabitants of the coast. At the same time, too, that the uplands are become desolate, the condition of the inhabitant of the coast is become so much the more pitiable; as he can no longer continue his laborious toil through storms and frosts, with vigour and energy, unable as he is to obtain the smallest quantity of butter or other strengthening articles of food to add to his present wretched fare: and being reduced to water, too as his only drink, since whey which was his usual beverage is denied him. All this, as is known by long and sad experience in Iceland, renders the fishermen weak and dispirited, and unfits them for ordinary occupations: thus, hanging on each, the misery that began with one runs through all. The want of skins for sea-clothing will likewise for some years be a great obstacle to the carrying on of the fisheries with advantage; for although, since the mortality among the cattle, there is so great a quantity of hides in the country that they are considered as scarcely of any value, yet it is well known that those of animals which have died of hunger are in general unfit for use, and these therefore will neither answer*

the purpose of making coats or even of being manufactured into the shoes in use in the country...

The loss of the horned cattle and sheep was very severely felt by the Icelanders, but that of the horses was equally so, especially by the inhabitants of the interior of the country, who thus found themselves deprived of their last resource, the means of having provisions and other necessaries conveyed from the coast, through long and tedious roads. Nay, many who are totally destitute of horses are under the necessity of carrying every load of hay into the outhouses upon their own backs, and frequently from a very considerable distance. Nor is their any likelihood of these invaluable animals being soon replaced...

All the quadrupeds of the island had thriven wonderfully and gained strength, during the mild winter and beautiful spring of 1783; but this did not prevent them from dying off in considerable numbers, during the week or fortnight immediately subsequent to the eruption, with inflammatory diseases caused by the poisonous quality of the food. Such was particularly the case with the sheep, of which, in the district of Skaptefield, it was remarked that, whereas in Iceland they generally walk facing the wind, they now regularly turned away from it; naturally anxious to avoid the strong sulphurous smell, which the infected breezes brought along with them... Nor was the situation of the cows and the horses much better, for although the disease was to them not equally fatal, yet they became excessively lean, and, even in the best season of the year the cows gave scarcely any milk...

In addition to the inflammatory disease just mentioned as so fatal to sheep: so early as the commencement of autumn 1783, when they were collected from the hills, several of them were found to be attacked with a distemper hitherto unknown to the natives. The poor animals could neither walk nor stand; their teeth were loose so as to prevent them from chewing their food; their cheeks were full of swellings; and their joints were contracted. Towards Christmas the disease began to show itself in a still greater degree, even among the stall-fed sheep, and also among the horned cattle, which rendered it

> *necessary for them to be slaughtered. Many, however, fell victim to the distemper much sooner than expected, when the disease attacked them internally. Thus it was found that the hearts, liver, lungs and kidneys were covered on all sides with boils and ulcers: they were in some cases much swollen in others quite destroyed and hollowed out: one of the kidneys was frequently considerably distended, while the other was proportionably shrivelled. The jaw-bones were perforated as if they had been bored with an instrument, and the ribs were knit together in a most extraordinary manner. The bones were reduced to a substance resembling gristle, and even the hardest became at the joints so tender, that they might easily be separated from each other...*
>
> *No striking external marks of disorder were perceptible among the horses, out of the district of Skaptafield, but it had nevertheless prevailed there, if not as the sole cause, yet certainly in union with others, to produce a general destruction both among them and the horned cattle: many having died suddenly when they had a plentiful supply of hay; others when in pasture of which there was a sufficiency of grass, of which they were never deprived either by ice or snow. To our utter astonishment we saw horses in the most miserable state of leanness, in the richest meadows, and even actually starved to death, having preferred eating substances the most injurious, such as the wood of houses, the hair off each others coats, or whatever else was within their reach, rather than touch the grass of last year's crop, still remaining in the pastures. This appears to me to be a sufficient proof of the poisonous state of the herbage, during the year 1783, and although the circumstance has not yet been investigated, I am fully convinced, that the entrails of the horses, have been equally, with those of other animals, infected with the distemper. The few inhabitants, who had still left with them some of the old hay, of the year 1782, preserved their cattle in a healthy and good condition, but even here when the new hay came into use, the disease began to appear among them."* Stephensen 1785 pp.229-248. In Blong [1984]

The degree of climate change associated with this eruption was discussed previously [Chapter 5]; but this study written accounts, made at the time of the eruption, suggests that it was the emission of acids and halogens which had the most serious impact on the environment and on the lives of the unfortunate Icelanders. The recorded effects described above are almost certainly due to the reaction of plants and animals to the deposition and ingestion of halogens, acid rain or acid aerosol droplets. The symptoms exhibited by the animals are typical of fluorosis, but fluorine was not the only noxious volcanic emission [Table 6.1]. The eruption cloud also had high concentrations of sulphuric, hydrochloric and hydrofluoric acid [Pétursson *et al.*, 1984; Devine *et al.*, 1984; Palais and Sigurdsson 1989; Thordarson *et al.* 1992], all are potentially damaging to plants [Le Guern *et al.* 1988] and in combination can affect the thresholds at which damage occurs [Mandl *et al.* 1975]. Lichens are particularly sensitive to air pollution [Seaward 1988] and their disappearance following volcanic eruptions is another indicator of the degree of air pollution.

The inhalation of ash may cause lung lesions while the ingestion of ash particles clinging to fodder or grazing will have a deleterious effect on the digestion of animals [Thórarinsson 1981].

Direct impacts such as the death and sickness of livestock and the destruction of crops are obvious, but the associated effects should also be noted. Peasants were forced to slaughter their few surviving livestock in order to stay alive. The death of the horses meant that the acquisition of supplies and the working of the farm became a major problem for people already weakened by famine. Those people who were forced to abandon their land became a burden on other communities and coastal communities were no longer able to trade fish for dairy produce and as a result their diet was restricted. The social and economic impact of this eruption therefore persisted long after the chemical impact had been neutralized.

The Eldfjell eruption, volatile emission and proximal impacts, 1973.

Following the eruption of Eldfjell, 23/25 of June 1973, the concentration of fluorine sixty kilometers away in Myraldur was 3000 ppm in air: where the threshold for plant damage is only 0.1 ppm, [Garrec *et al.* 1977; Thórarinsson 1979]. The pine needles of mature conifers turned brown, young conifers were killed and mosses were severely affected or eradicated. Sheep exhibited symptoms of chronic fluorosis within the 1mm tephra deposition isopach and acute sickness was observed within the 0.5mm tephra deposition isopach [Thórarinsson, 1979]. To put that figure in perspective: during the 1755 eruption of the Icelandic volcano Katla, large quantities of tephra fell on the Orkney Islands [Mitchell 1757] and Pilcher and Hall [1992] suggest that tephra deposition in Ireland, from the Hekla 4 eruption, was in the order of 1 tonne km^{-2}. The critical isopach at which tephra deposition may result in damage to plants and animals, may therefore lie far beyond the Icelandic mainland.

A consistent theme running through these accounts is the destruction of plants and the death of animals. These are consistent with the damage to be expected from volatile deposition [Table 6.1]. While these events undoubtedly represented times of severe hardship for the people of Iceland, little mention was in the accounts to fluctuations or changes in weather or climate. Climate was important, but perhaps as a factor which could mitigate or exacerbate the impact of the volcanic material. A mild winter would be necessary to mitigate the destruction of spring pasture or crops, but a severe winter would increase the pressure on suddenly limited pasture, crops or animal resources in a subsistence economy.

Non-eruptive emissions and plant tolerance.

Volatile output from volcanoes is not limited to eruptive activity. For example Mt. Etna, Sicily, emits 30 tons of fluorine daily through non- eruptive degassing, as well as annual outputs of sulphur dioxide which are the equivalent of the total industrial emissions of modern France [Allard *et al.* 1991]. Despite this output, only small concentrations of hydrogen fluoride have been detected in surveys of the leaves of plants downwind of the emissions [Mandl 1975; Garrec *et al* 1977]. Synergistic relationships between volatiles may lessen the intensify their impact. The emission of sulphur dioxide in train with the fluorine may have caused the stomata of the plants to close and thus hinder the absorption of fluorine [Reinert 1984]. Alternatively the vegetation growing in the vicinity may develop tolerance by natural selection and long exposure to these emissions. Austrian pine [*Pinus nigra*] growing on the slopes of Mt Etna were first planted at the turn of the century and initially had a mortality rate of 80%. The trees growing today are the descendants of the surviving 20% and have a high tolerance to fluorosis and acidification. Austrian pines planted from fresh stock had the same 80% mortality rate as the original planting [LeGuern *et al* 1988]. While these studies demonstrate the potential of non-eruptive emissions to damage immediately proximal environments, they are unlikely to be lofted to sufficient altitude to cause damage over a wide area.

Having established above that the volatile-gas emission of Icelandic volcanic eruptions have been capable of a serious impact on proximal ecosystems in Iceland. Dispersal and transport of volatiles will now be examined. Could volatiles be transported and deposited in sufficient concentrations to cause serious environmental disruption in Britain? The theoretical mechanisms by which volatile gases and tephra may be transported over great distance are examined below, and documentary evidence is presented which suggests that extreme volatile damage occurred as far away as eastern England in the summer of 1783.

Volatile dispersal.

Acid gases and halogens may be transported considerable distances [Fisher 1981; Heidam 1986; Rahn & Lowenthal 1986] and be deposited as dry particles [Fowler 1984], as acid rain and snow [Davies *et al.* 1984, Koerner & Fisher 1982; Oskarsson 1992] or as an acid fog, mist or dew [Wisniewski 1982]. Volcanic aerosols and gases can be transported considerable distances to the polar ice-caps, but often in extremely low concentrations [Herron 1982; Hammer *et al.* 1980; Petit *et al.* 1990; Ram & Gayley 1991]. The distribution of volatiles following an eruption will depend on the mass distribution and sorting of the tephra during the plinian phase of an eruption, the height of the eruption column and the velocity of transport. The suspended load within the eruption cloud contains the finest particles of the erupted mass and thus the fraction of finer particles is expected to increase towards the margins of the tephra deposit. Chuan *et al.* [1981] found that while the particle size distribution of the eruption cloud from the 1980 eruptions of Mt. St. Helens was multi-modal, the phreatic aerosol was characterized by a monomodal size distribution of less than 10 micrometers. Mackinnon *et al.* [1984] found that a significant portion of the eruption cloud of El Chichon consisted of particles between 10 and 50 microns in size, and that this size range had the longest residence time in the stratosphere. Significantly it was these smaller particles that were coated with sulphuric acid droplets and gels as well as with a wide range of other volatiles.

Rose [1977] demonstrated that the dominant component of a volcanic aerosol is thought to be particles of acid, predominantly sulphur dioxide which rapidly converts to sulphuric acid. Sulphuric acid is the agent in which water vapour and other volcanic acid emissions are dissolved. Droplets of dilute acids become attached to airborne tephra grains and leach soluble elements from the particle. Effectively this process also results in the scavenging, by tephra particles, of acids and halogens from the gas plume. Oskarsson [1980] investigated the distribution of fluorine following the 1970 eruption of Hekla, and described the transport mechanisms which are used here as an analogue for most other volatiles. In the vicinity of the erupting volcano, volatile distribution is controlled by the particle size of the deposits, but at a distance from the eruption the distribution of mass of the tephra becomes important. Adsorbed soluble fluorine reached a maximum at a distance from the volcano determined by the velocity of the transporting medium. Curiously and importantly, this process will be less effective near the source of the emissions, where an aerosol has not formed, than at distances downwind where aerosol production is at its greatest, and where the passage of time has facilitated the adsorption of toxic materials onto the tephra grain. The finest tephra particles are therefore those which travel the greatest distances, have the longest atmospheric residence time and scavenge the greatest volume of toxic volatiles from the eruption cloud. Plant damage caused by tephra deposition need not therefore be associated with a massive ashfall. In fact the reverse may be true.

The phenomenon was described in Alaska in 1913, following the eruption of Katmai.

> *"Leaves of the currants, Salmon berries and many other of the shrubs and herbs....were blighted by the dust or acid rain which fell there. This effect, curiously enough, did not occur in the district of thicker ash"*[Martin 1913].

Acids and halogens adsorbed onto the surface of tephra grains may therefore be transported over long distances. The deposition of acid volatiles either as an occult dust, or as acid rain, or both, may have serious consequences in ecosystems which have a limited capacity to neutralize acid inputs. Tephra layers recovered from lakes and peats in Britain and Ireland may act as isochrones [Buckland et al. 1981, Dugmore & Buckland 1991; Einarsson 1986] which indicate the deposition of toxic pollutants and it is these which may have brought about changes detectable in the palaeoenvironmental record. Evidence of the distal damage caused by the emissions of Icelandic volcanic eruptions is presented below.

Distal damage.

Icelandic eruption clouds are conventionally transported to the north, east and south-east of Iceland [Figures 6.3 & 6.4] by the prevailing westerly winds [Thórarinsson 1980]. Tephra fall has been reported in the Faroe Islands [Mitchell 1757; Persson 1971; Thórarinsson 1980] and Scandinavia [Nordenskiöld 1876; Thórarinsson 1967] and acid rain associated with volcanic eruptions has been reported in Norway and Sweden [Thórarinsson 1981].

In more detail, the Laki fissure eruption caused notable plant damage in Scandinavia.

The Bishop of Bergen wrote:

> *"Here we could only smell the smoke and yet we got sick. It was the fog which approached the country, which must have diluted the poison, it fell on the leaves of various vegetation which then withered. It is, therefore, no wonder that the valleys and fields in Iceland were quite destroyed and became useless as pastures for the cattle.* [Brun 1786. In Thórarinsson 1981].

In Copenhagen S.M. Hólm wrote:

> *"At the time when the acrid rain fell in Iceland an unusually penetrating rain fell in Trondheim, at some other places in Norway and also in the Faroe islands. Because of this rain the leaves on the trees were partly burned through and the grass on the ground turned almost black."* [Hólm 1784. In Thórarinsson 1981].

Newspaper accounts also reported crop damage.

> *"In this week the haymaking started at some places. the rye crop round here is poor. Other crops seem to grow well. However, although the barley in most places has exuberant spikes the paleae are beginning to turn white and the leaves yellow, but nobody knows why, unless it could be the result of the thick "sun smoke" which has been in the*

> *area for about two weeks. Today a northern wind has cleaned up the air which is now quite clear"* A letter in The Stockholms Posten, 11 July 1783. [In Thórarinsson 1981].

> *"South Halland 16 July. The so called "sun smoke" has now for many weeks been continuously resting over our horizon and is so thick that the sun has been completely red in the morning and in the evening. If the origin of this smoke were exhalations from the ground, it should have disappeared with wind or after rain, but the opposite is the case: after a rainy day it has been almost stronger than before. Probably it is injurious to the vegetation, because broadleaf trees as well as some other foliate plants wither and drop their leaves. In addition noxious dew occurred at midsummer time in some places and damaged the trees and the summer corn, which turned yellow. Together with a heavy drought (as since Easter the ground has not been drenched) the crop, especially the rye, has been attacked by a tiny grey insect, which in some places has destroyed a third of the crop."* A letter in The Götebergs Allehanda, 22 July 1783. [In Thórarinsson 1981].

> *"Eidsberg Parish in South Halland, 11 August. With aching heart and tears in their eyes the farmers in the parish harvest their crops, as in general the harvest is poorer than the oldest people can remember... Many fields look so that it is impossible to see what kind of crops had been sowed there. Many farmers who normally harvest two barrels expect not even a single bushel this time and the same is the case with the oats."* A letter in The Stockholms Posten, September 4th 1783. [In Thórarinsson 1981].

These accounts demonstrate that damage to crops in Scandinavia occurred in 1783, but little evidence has been presented for the impact of volcanic emissions outside this area, beyond accounts of tephra fall in Caithness [Geikie 1896] and the death of insects and a tarnishing of kettles in Kent [Lamb 1970]. Thórarinsson's tephra isopach maps are now being reinterpreted [Hunt 1993] and significant southerly tephra distributions have been identified in Iceland, along with the identification of twenty-seven tephra fall locations in Ireland and Scotland [Figure 6.5]. Theoretically the presence of tephra in British sediments implies the transportation and deposition of volatile material to the British Isles, either adsorbed onto tephra grains, as a gas or in solution in a variety of forms. These may be deposited at concentrations above the critical threshold for damage to plants and animals, or concentrated by micro and macro meteorological factors to the degree that damage will follow. New documentary evidence, presented below, illustrates the very real potential for crop damage in Britain, possessed by toxic material transported from volcanic eruptions in Iceland.

Volcanic pollution Britain 1783.

An examination of contemporary records has revealed extensive evidence for acid related crop damage in the summer of 1783 [Table 6.2], which is presented below in summary form. The summer of 1783 in Europe is remarkable for the smokey haze which obscured the sun and reduced visibility:

> *"We never see the sun but shorn of his its beams, the trees are scarce discernible at a mile's distance"* [Cowper 1783, in King & Ryskamp 1981].

Benjamin Franklin speculated that the fog may have had its origins in an Icelandic volcanic eruption [Franklin 1784] and a letter published in a Scottish newspaper confirms that the haze was not simply water vapour:

> *"A letter from Provence, July 11th.*
>
> *...fog sometimes emits a strong odour and is so dry it does not tarnish a looking glass and instead of liquefying salts it dries them."* The Aberdeen Journal. Monday August 18th.

Gilbert White observed:

> *"... the peculiar haze or smokey fog, that prevailed for many weeks in this island and in every part of Europe, and even beyond its limits, was a most extraordinary appearance, unlike anything known within the memory of man. By my journal I find I had noticed this strange occurrence from June 23 to July 20 inclusive..."* [White 1789]

These are not descriptions of a stratospheric aerosol layer nor are they descriptions of a fog composed of water vapour. A letter from Germany, published in the Ipswich Journal, suggests that the fog was composed of acid gases at sufficient concentrations to damage trees:

> *"Extract of a letter from Embden, July 12th.*
>
> *The thick dry fog that has so long prevailed seems to have spread over the whole surface of Europe; several mariners have also observed it at sea; in the day time it veils the sun and towards evening it has an infectious smell; in some places it withers the leaves, and almost all the trees on the borders of the Ems have been stripped of theirs in one night."* [The Ipswich Journal. Saturday August 9th 1783].

Severe damage to plants was reported in eastern England:

> *"Throughout most of the eastern counties there was a most severe frost in the night between the 23rd and 24th of June. It turned most of the barley and oats yellow, to their very great damage; the walnut trees lost their leaves and the larch and firs in plantations suffered severely."* [The Sherbourne Mercury. July 14th 1783]

This event is described in greater detail in several accounts. The Reverend Sir John Cullum described the impact of an unseasonable frost on the 23rd of June 1783.

> *"About 6 o'clock, that morning I observed the air very much condensed in my window chamber; and on getting up was informed by a tenant, who lives near, that finding himself cold in bed about 3 o'clock in the morning, he looked out at his window, and to his great surprize saw the ground covered with a white frost; and I was afterwards assured, on indubitable authority, that two men at Barton, about 3 miles off, saw between 3 and 4 o'clock that morning, in some shallow tubs, ice of the thickness of a crown piece, and which was not melted before 6.*
>
> *This unseasonable frost produced some remarkable effects. The aristæ of the barley, which was coming into ear, became brown and weathered at their extremities, as did the leaves of the oats; the rye had the appearance of being mildewed; so that the farmers were alarmed for those crops. The wheat was not much affected. The Larch, Weymouth*

> *Pine, and hardy Scotch fir, had the tips of their leaves withered; the first was particularly damaged and made a shabby appearance the rest of the summer. The leaves of some ashes very much sheltered in my garden suffered greatly. A walnut-tree received a second shock (the first was from a severe frost on the 26th of May) which completed the ruin of its crop. Cherry-trees, a standard peach tree, filbert and hasel-nut-trees, shed their leaves plentifully, and littered the walks as in autumn. The barberry-bush was extremely pinched, as well as the hypericum perforatum and the hirsutum: as the last two are solstitial and rather delicate plants, I wondered the less at their sensibility; but was much surprized to find that the vernal black-thorn and sweet violet, the leaves of which one would have thought must have acquired a perfect firmness and strength, were injured full as much. All these vegetables appeared exactly as if a fire had been lighted near them, that had shrivelled and discoloured their leaves. -----* penetrabile frigus adurit.
>
> *At the time this havoc was made among some of our hardy natives, the exotic mulberry tree was little affected; a fig tree, against a north-west wall remained unhurt, as well as the vine on the other side, though just coming into blossom. I speak of my own garden which is high; for in the low ones about Bury, but a mile off, the fig trees in particular were very much cut."* [Cullum 1783].

Similar accounts are found in several newspapers published in eastern England.
In Cambridge:

> *"...on Monday night last,* [June 23rd] *a very sudden and extraordinary alteration in the appearance of the grass and corn growing in this neighbourhood. The occasion of it is supposed to be owing to an unexpected change from excessive heat to its opposite extreme intense cold - in so much that the grazing land, which only the day before was full of juice and had upon it the most delightful verdure, did, immediately after this uncommon event, look as if it had dried up by the sun, and was to walk on like hay. The beans were turned to a whitish colour, the leaf and blade appearing as if dead. The stag of the wheat did also undergo the like change; but the ear not being entirely shot forth the*

> *farmers hope the corn will not be impaired."* Our brackets [Cambridge Chronicle and Journal, Saturday July 5th. 1783]1.

In Ipswich:

> *"On Wednesday June 25th it was first observed here, and in this neighbourhood, that all the different species of grain, viz, wheat, barley, and oats, were very yellow, and in general to have had all their leaves but their upper ones in particular, withered, within two or three inches at their ends; the forward barley and the oats most so. The former had not yet quitted their spatha or what is called by husbandmen at least their hose, but their awns appeared as far as they did appear, were withered also. Many of the oats were in their panicle, or had entirely quitted their hose, and all the ends of their calyces, or chaff husks were withered in like manner; but the grain within them did not appear to have suffered the least injury, being sufficiently protected by their coverings. The ears of wheat likewise, which were equally forward, were neither injured nor discoloured, except in the awns of what is generally called bearded wheat. About this time, and for 3 days both before and after, there was an uncommon gloom in the air, with a dead calm. The dews were very profuse. The sun was scarce visible. even at mid-day, and then entirely shorn of its beams so as to be viewed by the naked eye without pain."* [The Ipswich Journal. Saturday July 12th, 1783].

The damage described is too selective to have been the result of frost damage; it is difficult to imagine a midsummer frost which would blight a fir tree but have little effect on a mulberry bush. The wheat crop was not damaged while the husks and leaves of Bearded wheat, barley, oats, rye and beans are all described as withered, spotted or discoloured while the grains protected by the husk were undamaged. Pasture and beans are reported to be dried. Some trees species are reported as shedding their leaves while the larch, Weymouth pine and Scotch fir had the tips of their leaves withered. Cullum described the damaged plants in his garden as appearing "*exactly as if a fire had been lighted near them.*" These symptoms are typical of damage by acids and halogens [Lang *et al.* 1980; and see also Table 6. 1]. The sensitivity of trees to acid depsoition has been discussd by Gilbertson and Pyatt [1980], who found that species of *Pinus* and *Larix* were very sensitive to acid deposition defoliation and could be protected features such as walls and other vegetation and is further confirmation of the nature of the 'event' in the Reverend Cullum's garden.

Barrett and Benedict [1970] suggested that wheat was less susceptible to acid damage than barley and Craker and Bernstein [1984] found that wheat was able to efficiently buffer sulphuric acid. Fluoride may also have been present in the aerosol but MacLean and Schneider [1981] found that wheat exposed to fluoride did not exhibit signs of foliar damage. The damage to the leaves of the trees, and in particular the scotch fir, is typical of the damage caused by the absorption of sulphur dioxide [Caput *et al.* 1978]. Leaf lesions may be observed at a pH <3.5 and serious leaf damage will occur pH 2.8 [Watt Committee on Energy Report 1984]. The shedding of leaves is a classic response to concentrations of fluorine and hydrofluoric acid, and charring is typical of damage caused by a sulphuric acid aerosol. The micro-climate within a forest or plantation, can enhance the effect of acid deposition [Unsworth 1984]. The mulberry is able to absorb and accumulate sulphur dioxide and hydrogen fluoride [Chia-hsi *et al.* 1982] which may explain its why it appeared unscathed. All the symptoms described above suggest that volatiles were present in sufficient concentration to cause serious plant damage. The Laki fissure eruption is the most likely source for these volatiles.

Kirchner and others [1992] emphasized the role of micro- and macro-climate in determining the impact of acidification episodes. Certain themes common to these accounts, calm anti-cyclonic weather, heavy dews and frosts, suggest that the phenomena described are the result of an extreme episode of acidification, classed by Wisniewski [1982] as a "special event," these are associated with dews frosts and fogs. The process of coalescence gathers water soluble material on the leaf into one spot, concentrating any contaminants present, with the result that necrosis follows [Jacobsen 1984; Lang *et al.* 1980]. The formation of a frost may also scavenge volatiles from the lower layer of the atmosphere, and cause a net flux of chemical compounds onto plant surfaces which are released when the frost melts [Giordiadis *et al.* 1993]. Usually plants are able to replace leached cations, even when treated to a low pH rain, but exceptional damage and leaching can occur when the cell membrane has been damaged, either by gaseous pollutants such as sulphur dioxide, or by frost, or both [Miller 1984].

Fish kill in Scotland.

If the accounts above detail the damage caused to plants by the volatile emissions of the Laki fissure, the following account of a fish kill observed in Scotland following a thunder storm appears typical of an acid pulse.

> *"On Wednesday night we had a great storm of thunder and lightning, accompanied by a very heavy fall of rain. No damage was done in this city; but we are sorry to have accounts from different parts of the country that they have not been equally fortunate. We hear, that next morning, after the storm of thunder and lightning here, there were found in the dam above the sawmills on the water of Leith, a number of different kinds floating on the surface of the water supposed to be killed by lightning."* [The Caledonian Mercury. Saturday July 5th, 1783].

Waters may be polluted by an acid pulse, where acids which had been dry deposited over a period of time into are concentrated by one burst of rain and washed into a body of water; lowering the pH to levels which may be lethal to fish [Brown & Turnpenny 1988; Gagen & Sharpe 1987; Leivistad & Muniz 1976]. The concentration of volcanically-generated fluoride, deposited over several days, into a short lived toxic pulse, is illustrated by Oskarsson [1992] and Gudmundsson *et al.* [1992; see also Figure 6.7].

Scale of damage.

A comparison of the descriptions of plant damage in Iceland and East Anglia suggest that distance had not lessened the toxicity of the volatile material. Icelandic records talk of withered pasture and of the leaves of trees withering and being shed. All these phenomena are described in East Anglia, the localized damage to plants described in England is clearly as severe as that described in Iceland. The description of the fish kill from Leith in Scotland, suggests that toxic material was either deposited dry as an "occult" dust between June 8th and July 3rd, or that the rain from the thunder storm described was polluted with volcanically-derived volatiles.

Meteorological factors.

What meteorological factors might have led to these pollution episodes? The micro-climatic factors which led to the pollution episodes have been discussed above. What more general atmospheric circulation patterns might have transported toxic material to Britain and Europe in June and July. The work of Kington [1980, 1988] demonstrates that during the critical period, the dominant wind direction was from the south west; how then might volcanic material have been transported from Iceland to Britain against the prevailing wind? Anti-cyclonic weather dominated Europe's weather between June 21 and July 20 [Figure 6.8] while a low-pressure area existed in the vicinity of Iceland [Kington 1980, 1988]. Under these conditions volcanic material could not have been transported to Britain by surface winds, since these will converge towards a low pressure centre and diverge from a high-pressure cell. The dynamics of the eruption of the Laki fissure in 1783 ensured that the majority of emitted material was lofted to high altitudes but confined to the troposphere. The dispersal of material ejected to high altitudes depends on the speed and direction of high level rather than surface winds. High altitude winds converge on high pressure areas, volcanic material may therefore have been transported to Europe by high altitude winds converging on the high pressure cell. The removal of acid particles, smaller than 1µm in diameter, from the atmosphere, is by turbulent diffusion and depends on windspeed, surface roughness and the temperature stratification of the atmosphere [Fowler 1984]. This process is inefficient and during calm, dry, anticyclonic weather there will be an increase in particle concentration and a decrease in visibility [Whelpdale 1978; Leavey & Sweeney 1990]. Meteorological factors which limit atmospheric dispersal and produce ground level exposures may lead to pollution episodes [Scorer 1968]. A schematic model which explains this phenomenon is presented as Figure 5.8.

Remarkably the weather journal of Thomas Barker [1777-1789], kept at Lyndon Hall, Rutland, describes both decreasing visibility and calm weather over the critical period.

June 20th, *"Chiefly cloudy, calm and sometimes wetting"*. June 21st: *"Cloudy and calm, thick moist air."* June 22nd: *"Hot, some sunshine, calm and thick air"*. June 23rd: *"Hot, calm. Sunny* *and thick air"*. June 24th: *"Sunny, calm, very thick smokey air"*. June 25th:*"Calm, very thick air, very hot till evening."*

The conjunction of a stable, high pressure cell, calm conditions, high altitude convergent winds carrying volcanic material and the increase in particle concentration in the atmosphere inferred from the record of Barker, led to the pollution episodes between June 23rd - 25th [Figure 6.9].

This chapter has established that the toxic emissions from Icelandic volcanic eruptions may cause serious damage to the environment in Britain. The palaeoenvironmental implications of this will be discussed below.

Discussion:
Acid deposition in 1783.
Implications for palaeoenvironmental studies

The documentary evidence described above and in Table 6.2 suggests that the Laki eruption of 1783 caused significant environmental damage in southern Britain and western Europe due to acid deposition rather than climatic change. This has important implications for the interpretation of palaeoecological and archaeological records in Britain where Icelandic tephra falls, such as that of Hekla 4, have been located [Dugmore 1989]. So far such locations are limited to northern Britain and Northern Ireland (Dugmore, 1989; Bennett *et al.* 1992; Pilcher and Hall, 1992), and Scandinavia (Thórarinnson 1967, 1981) yet if this interpretation of the documentary evidence is correct, the impact of volcanically generated volatiles, transported in a gaseous or aerosol form, on vegetation may extend well beyond this region. Soil sensitivity to acid loading also needs to be considered. The soils in south eastern Britain generally have high 'critical loads' (Bull, 1991) and are therefore relatively insensitive to acid deposition. However, Skiba *et al.* (1988) and Smith *et al.* (1993) have demonstrated that large areas of upland and northern Britain are sensitive to minimal levels of acid deposition and have a limited capacity for recovery. Therefore volcanic events with lower volatile emissions than the 1783 Laki fissure eruption may have possessed the potential to have a long-term toxic effect on acid sensitive ecosystems in these regions and this needs to be considered in palaeoenvironmental research.

Baillie and Munro (1988) noted a correspondence between evidence for volcanic activity recorded in the Greenland ice-cores (Hammer *et al.*, 1980) and environmental deterioration indicated by narrow tree rings recorded in the Irish dendrochronology. One of the features of the Irish tree ring record is that the narrow tree rings persist for up to 20 years. Baillie (1989) suggested that these may be taken to indicate climatic impact and/or long term water logging. However, any climatic perturbation that does occur as a result of volcanic activity typically lasts only 6 months after an equivalent delay (Sear *et al.* 1987). In recognition of this problem, Baillie (1989) raised the possibility of a 'short trigger period which raises the water tables quickly and from which the system takes time to recover'. However, mire hydrologists suggest that ombrotrophic peat lands have a zone of high lateral hydraulic conductivity in the surface peat (the 'acrotelm'; Ingram, 1978) which would be likely to conduct rapidly away any excess precipitation which occurred over a relatively short period of time. Impacts due to acid pollution may provide a more plausible explanation. Direct physiological stress from contact with leaves and branches would constitute a short term acute impact but the longer term effects could be caused by leaching of buffers and the lowering of the bog pH (Lee *et al.* 1988). The low nutrient status of the bog and the sensitivity of the Irish Bog oaks to aerial inputs is illustrated by Pilcher (1990), who noted a positive relationship between the growth of sub fossil oaks growing on peat and the inputs of nutrients via summer rainfall. Pilcher (1990) also speculated that the end of the Irish bog oaks woodland, may have been brought about as the result of the increasing acidity of the peat. Even a small change in the base status of the already acid peat substrate would be likely to have deleterious effects on the trees. A slow replacement of base cations by inwash or by atmospheric deposition may then have followed (Mulder *et al.* 1989), and the time lag involved between base depletion and base replacement may then account for the persistent stress recorded in some Irish bog oaks.

Acid impacts may also explain the apparent cultural catastrophe in northern Scotland at the time of the Hekla 3 eruption (Burgess, 1989). Even in environments marginal for human survival, it seems unlikely that minor temperature changes and short lived increases in soil moisture would provoke mass desertion of quite large areas of occupied land. Severe direct damage to one season's crop followed by selective soil acidification over a longer period may have been more significant.

The eruption of Hekla 4 around 4000 BP is associated with the recession of pine in northern Scotland and both direct effects of acid pollution and volcanically induced climatic perturbation have been invoked as possible causal mechanisms (Blackford *et al.* 1992). The evidence and arguments we have presented here suggest that the former mechanism is likely to have been more severe than the latter. This is contrary to most previous speculation on the cause of this event which usually includes increased mire surface wetness as a key factor (Bennett, 1984; Bridge *et al.* 1990; Gear and Huntley, 1991). While there is some evidence for long term increases in mire surface wetness, it seems unlikely that this would arise as a result of short lived climatic perturbation for the reasons discussed above. Gaseous emissions from historical eruptions of Hekla, much smaller than Hekla 4 and Hekla 3 have been associated with crop damage in Iceland (Thórarinsson, 1969), there seems little reason why volatiles produced in the prehistoric eruptions of this volcano could not have been transported to the British Isles and Europe.

DISCUSSION

Following a volcanic eruption a range of environmental impacts may occur at a variety of geographical scales. While specific effects may be relatively easy to identify close to volcanic sources, this becomes increasingly difficult and more speculative as larger areas and the induced degree of climatic change is considered. Contemporary documentary evidence, reviewed here, clearly suggests that during the Laki fissure eruption 1783, acid pollution occurred in several locations distant from the volcanic source and probably beyond the limit of recorded tephra deposition. This was due to a particular combination of the nature of the fissure eruption itself and the atmospheric conditions prevailing during the initial eruptive episode. This study has necessarily been constrained by space in the material presented, and largely limited to British sources. The British newspapers studied make frequent mention of similar events on the European mainland, more detailed accounts of these ought to be easy to locate by interested workers with access to the relevant archives. This work does not attempt to replace one volcanic mechanism of environmental change with another, but rather suggests that the distal impact of volcanic gases deserves serious consideration. Where an environment is vulnerable to acid deposition, or where local meteorological conditions intensify the impact of volatile material, the resultant environmental stress may be more important than that arising from climatic perturbation.

The nature of the environemntalresponse in northern Scotland will be investigated by an investigation of the geochemical response to tephra deposition in a variety of sediments extracted from several locations. The results of these investigations will be discussed in the following chapters.

Table 6.2. Summary of `acid damage' in Britain and North Germany.

Source	Location	Date	Climatic conditions	Damage reported
Cowper, 1783 in: King and Ryskamp (1981)			Reduced visibility Smokey haze	
Ipswich Journal July 12th, 1783	East Anglia (Ipswich)	June 22nd-28th	'Uncommon gloom' Profuse dews Sun partially obscured	Cereal crops yellowed Wheat:least damage (awns of bearded wheat) Barley:withered awns Oats:Calyces withered, grain unaffected
Cambridge Chronicle and Journal July 5th, 1783	Cambridge	June 23rd	Frost	Dried pasture Beans and 'stag of the wheat' whitened, dying
Cullum (1783)	Bury St Edmunds	June 23rd	Severe frost	Barley and oats brown and withered Rye mildewed Wheat unaffected Larch, Weymouth pine, Scotch fir: leaf tips withered Ash, walnut, cherry, peach, filbert, hazel: leaf loss Barberry, Hypericum perforatum, H.hirsutum, Blackthorn, sweet violet 'pinched' Mulberry, fig, vine in sheltered places undamaged
Sherbourne Mercury July 14th 1783	East counties of England	June 23rd-24th	Severe frost	Barley and oats yellowed Walnut leaf loss Larch and firs 'suffered severely'
White (1789)	Uk and Europe	June 23rd-July 20th	Haze, smokey fog	
Caledonian Mercury July 5th, 1783	Leith, Scotland	July 2nd	Storms, heavy rain	Various fish killed (attributed to lightning)
Aberdeen Journal August 18th, 1783	Provence, France	July 11th	Odorous, dry fog	
Ipswich Journal August 9th, 1783	Embden, Germany	July 12th	Thick, dry fog 'Infectious smell'	Withered leaves Leaf loss in trees

Chapter seven.
Analytical methods and Pilot Study.

Summary of chapter.

This chapter will discuss the use of Energy Dispersive X-ray micro Analysis [EDMA] in the study of palaeoenvironmental change. The application of the technique, questions of geochemical stability and mobility and the theoretical framework by which the results may be interpreted are all discussed. The methods by which tephra was extracted from the sediments and counted will also be discussed. A pilot study will then be analysed.

SEDIMENT GEOCHEMISTRY INTRODUCTION.

Conventional methods used to assess the geochemical content of sediments rely on techniques such as Atomic Absorption Spectrophotometry, Flame Photometry, or techniques which create aliquots of particular elements which are then titrated or measured by optical depth. While these are accurate all have several limitations: the most serious of which is that they are all very time consuming, and as a result necessarily limit the range of elements which may be considered, the number of locations from which samples may be analysed, and the sampling interval selected. Use of such conventional techniques to investigate the impact (if any) of Icelandic volcanic eruptions on the environment of northern Scotland was rejected in favour of a relatively new approach to the analysis of sediment geochemistry which involved the use of a Scanning Electron Microscope fitted with an Electron Microprobe. This technique has the advantage of being, relatively quick, extremely accurate and allows a wide range of elements to be analysed. In addition these advantages allowed more sample locations to be considered and a closer sampling interval to be used than might have otherwise been the case. In addition, the use of an Electron Microscope to reconstruct palaeoenvironments is a new and potentially powerful technique, and in part this research is conducted to investigate the feasibility of the method.

Method.

Cores were extracted as for pollen analysis, and to avoid mobilising elements within the sediment the cores were kept cool and out of direct sunlight. The Samples were extracted from the undisturbed central part of the core by the simple expedient of pushing a clean glass tube into the sediment. The tube and sediment were then slowly oven dried overnight in order to remove moisture content. Once dry the tubes were capped and stored.

A portion of each sample was then mounted on a 13 mm diameter carbon stub. Trial and error, and inexperience ,resulted in a wide range of sample sizes tested being used before the a standard size was established. The ideal sample size was found to be a light "peppering" of material, from the glass tube onto a 13mm carbon stub, which was secured by conductive carbon cement and given a light coating of antistatic Duron spray to eliminate the problems caused by a electrostatic charges, an alternative to this is to place the samples in a vacuum chamber and to give the samples a fine coating of carbon. When dry, the samples were placed in an electron microscope. Two machines were used in this study; at Nottingham Trent University a Cambridge Stereoscan 600, and at the University of Plymouth a Jeol -6100. The use of two machines raises the question of replicability which will be addressed later. The samples were then analysed by means of electron probe X-ray microanalysis, with a Link System 860 Series 2 Computer using a ZAF-4 program which detected the presence and relative proportion of every element from and above sodium. In the EDMA procedure, an electron beam strikes the solid specimen and a series of interactions occur, including the production of X-rays. These are detected by a lithium drifted silicon director and passed on to a multi-channel analyser. Suitable areas for examination on each sample were selected for analysis using the microscope visual display monitor, and analysed at a magnification of 500 x for 100 seconds of live time at 20*kv*. As a result of such factors as the variable geometry of the sample face to the X-ray beam, the quantitative accuracy of this procedure on biological samples may be restricted to ±10% relative of the true value (see Pyatt and Lacy, 1988, Goldstein *et al.* 1984),. To ensure accuracy, 10 random areas were examined in each case, and three replicates were employed. The EDMA approach generates data in the form of percentage values, which inevitably limits direct comparisons with the type of information provided by more conventional techniques (*e.g.* Atomic absorption spectrophotometry), typically on a notably fewer elements and this has resulted in resistance to its use. However, the interpretation of data generated by EDMA is considered below, and a theoretical framework advanced which will allow the meaningful interpretation of the data. Though the EDMA technique is capable of identifying most of the elements in the spectrum the results of such an analysis would produce an overwhelming volume of data. In order to reduce this information to a manageable size a range of elements are selected. The relative proportion in the core of all the elements specified is calculated by the ZAF-4 program and normalised to 100%. This process is not as subjective as it may sound since the program will identify, and warn, if elements are present which have not been specified. There is also a visible check as the probe operator observes the acquisition of the spectrum graphically on a computer monitor which will identify any elements which have not been selected. This process will however ignore fluctuations in the ratio of elements present in trace concentrations, and these must be selected with care. This will be discussed further where the pilot study is analysed, and assessed, see below.

Issues of replicability.

The replicability of the data is addressed at several levels.

1. Replicability between cores and between analytical methods.

The geochemical signature for the Late-Glacial/Holocene transition is clearly identified on all the long cores, which were extracted from various locations and were analysed on two different machines. This signature corresponds closely with those established by other workers using conventional techniques, most notably Bennett *et al.* [1992], Mackereth [1966] and Pennington *et al.* [1972].

2. Replicability between different Scanning Electron microscopes.

A substantial part of one core, from the Strath of Kildonan, was examined on machines in both Nottingham and Plymouth and the results were found to be in close agreement. Replicability can be enhanced by careful working procedures. The unit must be carefully calibrated on a wide range of elements to a high standard. The standards used in this analysis were set in the factory and checked during frequent services. The carbon stubs were placed in a holder in which a cobalt pin had been mounted and polished flat. The detector was recalibrated on this cobalt standard every time a new set of samples were loaded into the scanning electron microscope. Frequent recalibration ensures that the results obtained are as accurate as the system will allow.

Care must be taken to ensure that the sample holder within the electron microscope is at the optimum height in relation to the dispersed energy detector, and related to this the detector itself must be placed as close to the samples as possible.

When the electron beam strikes the sample the dispersed energy is detected and analysed. The degree of dispersed energy can be greater than the technical ability of the detector to cope with, and the detector may cease counting until the data already gathered have been processed. Care must be taken to ensure that "Dead" time, is kept to below 20% , this is done by reducing the energy striking the sample.

3. Replicabilty between different measures of Si.

In an attempt to identify geochemical responses to tephra deposition a count of tephra grains in the cores was made under polarised light using an optical microscope, and the results plotted against the geochemistry. Tephra is predominantly silica and the ratio of silica identified by the microprobe, to the physical count of tephra in the core is exact [See Chemizones 2, 4 and 6 in the Strath of Kildonan]. The close correspondence between what was in effect two measures of silica, carried out several months apart, is a clear test of the replicability of the EDMA data.

4. Geochemical similarities between cores. Identification of trace elements.

The peak ratios of elements which indicate industrial pollution occur at the same depth in cores of similar length extracted from the island of Barra in the Outer Hebrides and the Strath of Kildonan in Caithness. In particular a peak ratio of copper can be found in both cores at around 270 cm.

5. Relationship between interpretations of EDMA results and established palaeoecological models.

The analysis here of Loch Sediments retrieved from the Outer Hebrides suggest that the lochs did not become acidified until relatively recent times, post "industrial revolution" times. This is in clear agreement with the observations made by several workers for the timing of acidification in Scotland and Scandinavia [Kreiser *et al.* 1990; Battarbee 1990].

Interpretation of results.

The principal argument against the adoption of EDMA for the analysis of palaeoenvironments is that the results are not produced in a form with which many workers are comfortable. Rather than express the precise milligrammes/gramme, millilitres/litre, or parts per million, EDMA results are expressed as a ratio of the total elements analysed in a sample. This raises issues of comparability between individual samples, and also the possibility that apparent increases or decreases in the ratio of an element may arise, not from a genuine increase or decrease in the concentration of a specific element, but because of the increase or decrease in an other element. Given a firm theoretical foundation these problems are not insurmountable and it should be pointed out that conventional pollen analysis, which by any standards is a well established technique, is subject to the same criticisms. In consequence all geochemical changes described in this and later chapters are changes in proportion - not total concentration.

A: Relationship between elements, zonation and facies modelling.

The interpretation of any single element is problematic as most elements have a variety of sources. The advantage EDMA enjoys over other techniques is that a wide range of elements may be analysed. Therefore the relationship between several elements can be used to reconstruct environmental processes. For example, **Mg** has several probable sources: from mechanical weathering, the breakdown of chlorophyll, or from rainfall. The elements which rise or fall in tandem with **Mg** may give clues to the environmental sources involved. When associated with **K,** mechanical erosion can be suggested. With **Na** and **Cl** rainfall intensity is indicated. **P** or **S** may imply the breakdown of chlorophyll. The assumptions on which these associations are based are presented in Table 7.1, and are based on the work of Bengtsson and Enell [1986],Engstrom and Wright [1984], Mackereth [1966] and Pennington *et al.* [1972]. Having established that a relationship exists between several elements, sections of the core can then be identified where these relationships are maintained. The maintenance of a relationship between several elements over several centimetres implies that the controlling environmental variables may be stable. These areas can then be identified and separated from other areas of the core, where the relationships have been disturbed or the ratio of the elements has fallen, or where the ratio of other elements dominate the zone [for convenience these zones will be referred to as Chemizones]. All of these circumstances indicate that the balance between the controlling variables operating within the environment has been disturbed. Each chemizone can then be viewed as a chemically defined litho-facies, representing a particular sedimentary environment. The relationships between each facies in the core may then be used to reconstruct the changing environment and the changing relationships which once operated within the environment.

B: Behavioural trends.

The behaviour of each element in the core and the behaviour of groups of elements may be interpreted as a product of the relationship between time and of the processes operating within the environment. That being the case, the geochemical data presented in the investigations below can be interpreted. Fluctuation along the X-axis of the graphs of geochemical changes with depth down the sediment cores is an expression of time, and fluctuation along the y-axis indicates change in the controlling variables and fluctuation of the environmental processes operating in the landscape. If this is accepted, then the models devised by Butzer [1982] to interpret change in environmental systems may be adopted.

Table 7.1. Possible sources of elements used in analysis.

Magnesium. Mg.
Sources: Often associated with mechanical weathering, the breakdown of chlorophyll in terrestrial and aquatic plants. Also precipitated in rain in exposed western environments.

Potassium. K.
Sources. A clastic mineral. Commonly used to infer episodes of soil erosion in a catchment.

Silicon. Si.
An abundant element. Can indicate, soil erosion, and biogenic activity. Si can be found in the silicified remains of aquatic flora and fauna.

Aluminium. Al
Sources. An abundant inorganic element. deposition can indicate, soil erosion, the depletion of bases from a soil and the influence of the sea.

Sulphur. S.
Sources. Primarily associated with biological productivity in a lake, and often correlated with Si. However S can also be deposited in Industrial pollution.

Chlorine. Cl.
Sources. Sea water, Rainfall.

Titanium. Ti.
Sources Commonly used to indicate mechanical erosion.

Calcium. Ca.
Sources. Present in some lake sediments as a clast, it can also be associated with humic and fulvic acids. Thus Ca concentrations in a core may indicate the deep weathering of a soil profile.

Vanadium. V.
Sources. A rare trace element and a component of several minerals.

Iron. Fe.
Sources. A common element. Can indicate the chemical weathering of a catchment soil. I.E. Podzolisation and / or the acidity of catchment waters.

Nickel. Ni.
Sources. Nickel is a common element and has a variety of sources. It is difficult to interpret.

Sodium. Na.
Sources. Can indicate the depletion of bases in a soil but is frequently associated with climate and in particular, rainfall intensity.

Copper & Zinc. Cu & Zn.
Sources. Background levels in most sediments, but peaks indicate industrial pollution. Can be used for dating.

Manganese. Mn
Sources. Mechanical or chemical weathering. Where Mn dominates Fe mechanical erosion is suggested, but where the opposite is true chemical weathering of soil profiles is implied.

Phosphate. P.
Sources. Many, can be sorbed by many elements in particular by iron. However can indicate a nutrient inwash and the activities of people.

Butzer [1982] described seven models which we can adopt [Figure 7.1].

i) Static equilibrium. In which no external force disturbs the equilibrium of the system investigated.

ii) Static equilibrium with recovery.

In which a slight variation is observed around the mean. This fluctuation may be an integral part of the system and need not imply the presence of an external force or a significant change in the balance of external forces.

iii) Unstable equilibrium with stabilisation at a new level.

Where a new equilibrium is achieved in the absence of the existence of any threshold. This may imply that such variation is a random process and part of the internal order of the system.

iv) Metastable equilibrium with a threshold separating different equilibrium levels.

The existence of a threshold may imply the action of an external force such as climatic warming or cooling.

v) Steady state equilibrium with no net change in equilibrium level.

This behaviour is typical of several of the elements analysed, in particular nickel. Variation around the mean is frequent and apparently random, and significant environmental forcing cannot be assumed where an element fluctuates in this manner.

vi) Dynamic equilibrium with a long term trend.

Variation around the mean is frequent, but there is a long term trend in the mean itself. This suggests that each minor fluctuation around the mean may not be environmentally significant, but that the long-term trend in the mean is. For example see Ca in the Strath of Kildonan analysis; where there is a steady decline in the mean of this element throughout the Holocene. This must reflect the declining base status of the catchment soil, and specifically the concentration of this element in the soil.

vii) Dynamic metastable equilibrium.

With long term trends separated by a threshold to a new higher (or lower) level. The process of destabilisation, and the establishment of new equilibrium levels, may indicate a change in the environment.

TEPHRA EXTRACTION.

In order to investigate the geochemical response of catchments to the input of volcanic tephra it is first necessary to locate it in the core. This is not easy and several were tested before a simple method was devised.

X-ray examination of the core.

Butler [1992] demonstrated the use of X-ray examination as an accurate means of establishing the degree of bioturbation and locating mineral material in peat cores. Dugmore and Newton [1992] extended this technique to the location of tephra horizons within a core. The technique was used in this analysis but the results proved disappointing and expensive. The peat core extracted from Borve Bog, was examined by X-rays. No tephra layers were located, but many mineral horizons were. The mechanics of the technique, in particular the degree of exposure and the current used to obtain the best results were difficult to determine and varied depending on the density of the organic material and the degree of wetness. Several exposures were necessary to establish the correct exposure for even one short 20 cm segment of the core and the waste of X-ray film was considerable. In view of these problems the use of the technique was not pursued. The results of the X-ray examination of the Borve core were used by Pratt [1992].

Bulk sampling.

In order to examine the entire length of each core contiguous samples were taken from each ten cm section. This ensured a complete coverage of the core, which could then be analysed to locate tephra concentrations. This technique proved quite successful at locating low concentrations of tephra within the core. Once tephra was located in any 10 cm segment the section was subsampled at contiguous 1 cm intervals for tephra counting and geochemical analysis. This method has been described recently by Pilcher and Hall [1992].

Isolation of the tephra grains from the organic matrix.

The method devised by Dugmore [1989] was tried. This involves a complex acid digestion and the mixture of several volatile reagents. After experimentation this method was rejected as being too dangerous given the equipment at Sheffield and my level of skill. A simple method to remove the organic matrix of the core is to burn the material in a Muffle Furnace at 370°C for 4 hours. This method was simple and effective but had the disadvantage of introducing charcoal into the mounted samples which occasionally obscured the mineral material. Finally a simple and effective method was devised at the University of Plymouth by a technician, Anne Kelly, which is presented in Table 7.2. This method has the advantage of being simple, cheap and effective and does not involve the application of particularly volatile chemicals.

Tephra counts.

Seven transects were made along the long axis of each slide and the tephra grains present, if any, were counted. This method has been used by Bennett *et al.* [1992] and found to accurately indicate the maximum and minimum concentrations of tephra in the core.

Tephra identification.

Tephra was extracted from Icelandic sediments kindly supplied by Dr Paul Buckland. This material was mounted on glass slides and formed a reference against which problematic identifications could be checked. Care was taken that fragments of opaline phytoliths were not misidentified as tephra. To do this the phytoliths keys provided by Gilbertson [1991] and Powers and Gilberston [1987] were used.

Tephra Extraction Method.

1.Place 1cc material in a plastic centrifuge tube and add 10 ml NaOH 10%.

2. Heat in a water bath for ten minutes.

3. Filter through 180 micron sieve into beaker washing through with de-ionised water.

4.Centrifuge (2000 rpm 5 minutes), decant.

5. Continue step 4 until all beaker fluid has gone.

6. Wash residue into tubes with de-ionised water, centrifuge, decant until the water becomes clear.

7. Pour a small amount of H_2O_2 into sample tubes and mix well. Transfer liquid back into beakers, and top up with H_2O_2 (to 50ml).

8. Heat beakers gently over water bath for 2 hours (do not allow to boil)

9. Pour into centrifuge tubes, washing beakers thoroughly so that all material is transferred.

10. Wash, centrifuge and decant (X4.).

12 Transfer Liquid to labelled vials and allow to separate.

13. Pipette a small amount of solution onto glass slide. Evaporate water gently using hot plate set at its coolest setting.

14. Place a small amount of mounting medium (Canada Balsam or Euparal) in centre of slide and allow to warm on hot plate.

15. Remove and cover with a glass slip.

Table 7.2. A simple method for extracting tephra from organic material.

Pilot Study.
Loch Hellisdale, South Uist.

Environment and climate of the Outer Hebrides.

The relevant information on the modern terrestrial environment of the area has most recently been described in Pankhurst and Mullins [1991] and Boyd and Boyd [1990]. The local bedrock is Lewisian Gneiss and comprises mainly coarse-grained meta-igneous gneiss [Smith and Fettes 1979]. In places, there is a thin covering of till which is provisionally attributed to the Devensian [See Peacock 1984, for discussion]. The wind climate is usually considered of great importance for understanding many aspects of life in the Hebrides [Angus 1991, Manley 1979, and especially Murray 1973]. Although there have been suggestions that at least parts of the Outer Hebrides have been treeless throughout the Outer Hebrides [Birks and Madsen 1979], more recent work points clearly to the former presence of trees [see Angus 1979, Bennett and Fossit 1989, Bennett *et al.* 1990, Brayshay 1992, Bohncke 1988, Edwards 1990, Gearey 1992, Pratt 1992, Whittington and Ritchie 1988, Wilkins 1984]. In general, the history of the terrestrial vegetation of the islands is well-known from the studies of Bennett *et al.* [1990] Brayshay [1992], Edwards [1990], Blackburn [1946], and Heslop Harrison and Blackburn [1946]. In brief, between 10,500 to 10,200 years *B.P.*, the area was partially covered by an open vegetation of *Empetrum* with grasses, sedges, and *Huperzia selago*. From 10,200 to 4,000 *B.P.* the landscape appears to have contained woodlands with *Quercus, Alnus, Ulmus*, and perhaps *Pinus* [which are now extinct as native genera in the Outer Hebrides], together with *Fraxinus*, *Betula* and *Corylus/Myrica*, with open ground between woodland copses. Although *Calluna* was present from early in the Holocene - about 9,500 *B.P.*, frequencies of *Calluna* become sufficiently high to suggest a fairly wide spread of blanket bog occur from about 5,500 years *B.P.*, and becoming especially marked at about 1400 *B.P.*

INTRODUCTION

The application of EDMA to palaeoenvironmental studies is a new, and currently little practised, analytical approach. In order to investigate the potential of the technique and highlight areas where improvement was necessary, or possible, a pilot study was conducted. This involved the application of EDMA to a core which was also subjected to palynological [Brayshay 1992] and Diatom [Pyatt *et* *al.* In prep] analysis. The results of this study are presented below together with comparisons of the use of these different palaeoenvironmental techniques.

Palaeoenvironmetal investigations of Loch Hellisdale.

The loch was chosen for study because of its isolation, its apparent low productivity, and its topographic situation; which renders it relatively protected from the strong Atlantic winds which blow from the west and south west, and which otherwise might be assumed to have led to significant disturbance of loch-bed sediment by waves. The latter problem as thought very significant by Pennington *et al.* [1972]. It is located at 75 m O.D. in the enclosed, remote and inaccessible glacial trough of Glen Hellisdale which has been eroded into the east flank of Beinn Mhor (620 m) on the mountainous, east coast of the Outer Hebridean island of South Uist (National Grid Reference NF 828310 & Figure 7.2).

In common with much of the mountainous eastern side of South Uist, the area is today characterised by its bleakness and an absence of permanent *modern* habitation. The climate and vegetation of the immediate area have most been summarised by Bennett *et al.* [1990]. This site had advantage of being only 3 km distant from the radiocarbon-dated study of the nearby site of Loch Lang, 3 km to the west (Bennett *et al.* 1990), the palynological investigations of the early and middle Holocene by Edwards (1990), and the pioneering early palynological studies by Blackburn (1946), and Heslop Harrison and Blackburn (1946) (Figure 7.2).

The present soils of the area are described in Hudson (1991) and Hudson *et al.* (1982), who have recognised three soil mapping units of the Lochinver Association in the Glen.

1. Alpine/sub-alpine lithosols, described as map unit 398 by the Soil Survey of Scotland [Hudson *et al.* 1982] are found on the broad mountain flanks which support mountain heath communities. The only landuse possible is rough grazing.

2. Peaty gleys and rankers mapped as soil unit 396 by the Soil Survey of Scotland [Hudson *et al.* 1982] is found in the upper glen and abutting the western shores of the loch are peaty gleys, peaty podzols and rankers which support various bog communities, with a few scattered shrubby trees of *Salix aurita* and one individual of *Sorbus aucaparia.* The only landuse possible is poor quality rough grazing.

3. Peaty gleys, peat, some peaty podzols and peaty rankers of soil map unit 394 [Hudson *et al.* 1982], which again support bog communities, is found in the lower glen and along the eastern shore of the loch. Grazing values of this soil are low.

Over what time period did these soil types evolve? Studies of the changing chemical composition of Holocene sediment cores by Bennett *et al.* [1990] from the adjacent Loch Lang, which has essentially similar bedrocks and surficial deposits, are of particular importance. These authors concluded that from approximately 10,730 to 10,200 years *B.P.* that lake sedimentation in Loch Lang was dominated by the inwash of minerals physically eroding from catchment soils. Soils stabilised from 9,500 years *B.P.* to 6,500 *B.P.* and continued to be stable leading to the deposition of predominantly organic sediment in the loch until about 550 years ago, when soil erosion, attributed to human activity became important and led to mineral sediments becoming more important.

METHODS

The 4.98 metre core reported here was obtained by Russian peat corer from a sponson-stabilised boat in March 1987. This core did not reach the base of the lake's infill deposits. After extraction, it was sealed in plastic tubing, wrapped in polythene film and further black, heavy plastic sheeting and stored in a refrigerated room kept at 4 degrees Celsius. The results of pollen analytical studies are described in Brayshay (1992) and Kent *et al.* [in press].

In the pilot study, EDMA analyses of the elemental compositions of the sediments were determined using samples taken at 25 cm intervals from the central, uncontaminated part of the refrigerated core.

CORE DESCRIPTION.

The core retrieved comprised six distinct sedimentary units

Youngest

	Depth	**Description**
Unit 6.	0 - 20 cms	Organic silty clay with orange mottles
Unit 5.	20 - 90 cms	Blue/grey, silt/clay with charcoal at 90 cms.
Unit 4.	90 - 400 cms	Brown, weakly organic lake mud, with a 0.5 cms thick band of charcoal at 390 cms.
Unit 3.	400 - 425 cms	Brown, weakly organic mud becoming increasingly rich in clay with depth.
Unit 2.	425 - 460 cms	Blue/grey, silt/clay.
Unit 1.	460 - 498 cms	Grey/brown, weakly organic silty clay

Oldest

No sedimentary structures were seen in the deposits sampled. An AMS radiocarbon date of 7900±70 years *B.P.* (uncalibrated) (UtC-1666) was obtained from sediments from 215 - 216 cms depth. Other attempts to "AMS-date" critical points of this core failed, because of lack of organic matter (typically <0.1% LOI).

POLLEN ANALYSIS

A detailed analysis of the palynology of this core is presented in Brayshay [1992] and Kent et al. [in press]. The palynology is presented here in a skeleton form in order to place the sediment chemistry in its vegetational context [Figure 7.3.

Oldest LPAZ

Interpretation LSC1A-LSC1B: Late Devensian.

LSC1A: *Empetrum, Juniperus, Pinus, Huperzia.* 498 - 455 cms.

LSC1B: *Huperzia, Polypodium, Artemisia, Juniperus.* 455 - 425 cms. Non-tree/shrub pollen make up 80% of the total pollen assemblage.

Interpretation LSC2- LSC4: Early to middle Holocene.

LSC2: *Betula, Juniperus, Empetrum,* Gramineae. 425 - 400 cms. Total tree pollen increases rapidly from 20 to over 40% total pollen;

LSC3A: *Corylus/Myrica, Betula.* 400 - 355 cms. The proportion of tree pollen expands to over 50% of total pollen present.

LSC3B: *Betula.* 355 - 320 cms. Woodland taxa are poorly represented in a tree pollen assemblage that now represents over 65% of the total pollen assemblage. *Isoetes* frequencies increase to between 5 and 12%.

LSC4: *Corylus/Myrica, Betula, Pinus, Quercus, Ulmus.* 320 - 170 cms. Total tree pollen is over 80% of the assemblage near its upper boundary. The first occurrence of *Alnus* at 215 - 216 cms depth is dated to 7900±70 years *B.P.* (uncalibrated) (UtC-1666). Parts of this zone are characterised by an abundance of *Isoetes lacustris*.

Interpretation. LSC5-LSC7: Middle Holocene to Present.

LSC5: *Corylus/Myrica, Betula, Pinus,* Gramineae, Cyperaceae, *Calluna.* 170 - 90 cms. This zone is defined by the decline in tree pollen present, from the 80% at the end of the previous zone to below 20% and the upper boundary of this zone. There is a small peak of pollen of *Cannabis* at 135 cms, with a few grains of "cereal-type" pollen at 110 cms. Charcoal increases dramatically in abundance in this sub-zone.

LSC6: *Huperzia, Polypodium, Artemisia.* 90 - 20 cms. Pollen preservation is poor, and this biostratigraphic zone is co-incident with clay deposits, as opposed to organic muds.

LSC7: *Calluna,* Gramineae, Cyperaceae, *Sphagnum.* 20 - 0 cms. Tree pollen representation is below 2% of the total assemblage.

Youngest

Discussion

There is a remarkably clear and precise parallelism between the events in Loch Hellisdale and the adjacent site of Loch Lang, which encourages the extrapolation of the Loch Lang radiocarbon-dated sequence to the Hellisdale deposits. The present evidence appears to offer a satisfactory basis with which to interpret the information of diatom frequency and sediment chemistry described below. Closer examination of the antiquities of the "dated" and/or correlated sediments present in the Loch Hellisdale core, and especially when it is compared with the Loch Lang data (see Bennett *et al.* 1990), suggest that the Hellisdale sequence may have been affected by notable changes in the rate of sedimentation, and/or contain undetected hiatuses. For example, approximately 2,250 years of early Holocene sediment is represented between the depths of 415 cms and 215 cms, whereas the next 50 cms of sediment is dated to the period (approximately) 7,900 to 4,000 years ago (see Figure 7.4).

SEDIMENT CHEMISTRY

A range of eleven elements were selected for analysis; Aluminium, Calcium, Iron, Potassium, Magnesium, Titanium, Sulphur, Chloride, Vanadium, Nickel and Silicon. Variations in their relative abundance are shown in Figure 7.5. The geochemical history of the sediment column was been divided into four "chemizones" on the basis of similarities in elemental composition. Ni can be seen to exhibit steady-state equilibrium, with considerable variation around the mean, and as a result, it is difficult to use this element to interpret processes operating within the landscape

Chemizone Zone SC1 498 425 cms.

Youngest

425 cm. High Al, Ca, Fe, Ti, K,	Low Si, S, Cl.
450 cm. High Al, Ca, Fe, Ti, K, .	Low Si, S, Cl
475 cm. High Al, Fe, Mg, Ti.	Decline in K. Low S, Si, Cl.
498 cm. High Al, K, Mg, Ti.	Low S, Si.

Oldest

Summary

High proportions of all these elements occur, with relatively lower abundance of sulphur and silicon. Peak frequencies of several metals are attained at 425 -450 cms by several elements - **Ca**, **Fe**, **K**, **Mg**, and **V** which define zone **SC1**.

Interpretation.

The basal chemizone **SC1** corresponds exactly with the presence of mineral-rich silt and sands in the Hellisdale core. Chemizone **SC1** is dominated by the presence of elements - **Ca**, **Mg**, **K**, and **Al** - which are primarily associated with the erosion, transportation and sedimentation within the lake of particulate mineral matter as a result of widespread mechanical weathering of soils and sediments in the catchment. In the context of this chemizone, these elements exhibit steady state or stable equilibrium. But in the context of Chemizone **SC2** it can be seen that they exhibit metastable or Dynamic metastable equilibrium. This implies a significant change in the processes operating within and upon the landscape. The relatively high levels of vanadium and titanium may also reflect mechanical erosion, although they are rarely discussed in this context. They occur in the metamorphic bedrocks in the catchment and display broadly similar trends to **Al**, **Mg**, **Ca** and **K** throughout the lake sediment column. The highest levels of all these elements occur near the top of this zone at 425 cms, suggesting greatest erosional input at that level. The palynological evidence described below supports this interpretation, providing independent evidence of a cold, relatively open environment with much bare rock. These deposits were correlated with the Loch Lomond stadial.

Chemizone Zone SC2. 400 - 300 cms.

Youngest

300 cm. Peak in K	Decline in S.
325 cm. Stable.	Decline in S.
350 cm. Increase in Peak in S, Si.	Stable.
375 cm. Increase in Si, S, Cl.	Decline in Al, K, V.
400 cm. Increase in S.	Decline in Al, Ca, Fe, K, Mg, Ti.

Oldest

Summary

The zone is defined by a marked peak in sulphur, and the rise and stabilisation at a high ratio of silicon. **Ca, Fe, K,** and **Mg** decline to stable low levels. Palynological zones LHD2a and LHD2b are defined respectively by rising and falling abundances.

Interpretation

A significant change in the processes operating within the landscape is indicated by the nature of the boundary between this and the preceding chemizone. With the exception of S, **Cl** and **Ni** all the elements analysed reach a new equilibrium at the boundary between the zones. The ratio of S in the core increases from 01 to 1.6 % across the zones, but rather than achieving a new, higher equilibrium it peaked at 350 cm, following which the ratio of S declines to 0.23% at 300 cm. Comparisons between the behaviour of these elements in Hellisdale chemizone SC1 and the base of SC2 suggests that the previous widespread mechanical erosion within the catchment had greatly declined by this later time. The greater part of chemizone SC2 is, in contrast, dominated by the relative abundance of both sulphur and silicon. Sulphur is not associated with the introduction of detrital minerals into lakes. This feature suggests that it is associated with anaerobic respiration. In this Hellisdale context, the present evidence suggests that it is most likely to be a product of the decay of organic matter within the lake. The trends in the relatively abundance of silicon are exactly opposite those of aluminium, suggesting that the increased relative frequencies of silicon are not the result of the influx of alumino-silicate mineral matter. Silicon is abundant in freshwater diatoms and sponges. There is a distinct parallelism between the relative abundance of silicon, sulphur levels and the actual numbers of diatom frustules counted at each level (Figures 6.5 and 6.6) suggesting that much of the increase in silicon levels observed in chemizone SC2 is the result of the deposition of biological silica within the lake. There are no data on phytolith frequencies in the sediments which precludes the possibility of determining the input of silica derived from higher plants in and around the lake. The chemical composition therefore suggests two important developments:

(1) The catchment of the loch had developed a significant vegetation cover which had greatly reduced the extent and/or intensity of mechanical erosion of soils and sediments - an explanation which is supported by the palynological evidence described above.
(2) That there was a marked increase in biological activity within the loch.

Both changes would be brought about by climatic and environmental improvement with passage from the Loch Lomond stadial into the Holocene interglacial. The minor increases in **Al, Ca, Fe, K, Mg** and decrease in **Si** and S at 325 - 300 cms merit further research. The principal stratigraphic association is the major increase in the abundance of *Isoetes*, associated by Vuorela [1980] with human disturbance of catchments. This fluctuation might, therefore, be the result of minor decrease in biological activity within the lake and/or an increase in the products of mechanical erosion entering the loch. The extent to which this effect is a local, regional or purely random fluctuation is not clear.

Chemizone Zone SC3. 300 - 75 cms.

Youngest

325-75 cm. High ratio of S & Si.	Low ratio Al, Ca, Fe, K, Mg, Cl.
300 325 cm. Recovery in S.	

Oldest

Summary

Silicon rises slowly to maximum frequencies of nearly 90%, whilst sulphur rises and falls from a peak at 200 cms. Low and essentially stable frequencies occur in **Al**, **Ca**, **Fe**, **K**, **Mg** and **Ti**.

Interpretation

Chemizone SC3 is characterised first by stability in the relative abundance of the most abundant elements **Al**, **Ca**, **Fe**, **K**, **Mg**, **Ti**: and secondly by declines in the abundance of silicon and sulphur from the relatively high values reached at 200 cms. These data indicate a biologically-active loch into which a minimum of mechanically-eroded sediment was entering. However some minor changes can be detected. There is a progressive decline in the abundance of Ca - suggesting the progressive loss by weathering and leaching of carbonates, perhaps as a result of podzolisation and/or the spread of peats. There is a small increase in the relative abundance of Al - possibly also the result of podzolisation within the catchment. At about 200 cms, the quantities of silicon and sulphur show parallel declines, suggesting a small change in biological activity within the loch.

Chemizone Zone SC4. 75 - 0 cms.

Youngest

0 cm. Recovery in Si, S, Cl, V.		Decline in Fe, Al,
50 cm. Peak in Fe.	Recovery in S, Al.	Decline in Si.

Oldest

Summary

The zone is characterised by relatively high frequencies of **Al**, **Fe**, **Ti** and a progressive increase in sulphur from negligible levels at 75 cms. Silicon is comparatively low in abundance throughout.

Interpretation

The start of chemizone SC4 is marked by the evident change in sediment lithology from organic mud to clays/silts. The accompanying changes in chemical composition are fairly complex. This lithological evidence of an influx of eroded soils and sediments into this part of the loch suggests that the fall in the relative abundance of silicon is the result of a reduction in algal life in the lake and is not the result of a significant reduction in erosion of mineral soils and sediments around the lake. Again the Si curve parallels the diatom counts (Figure 7.6). The increase in the proportion of sulphur runs counter to these trends and suggests it is the result of the decomposition of biological debris washing into the lake from the surrounding catchment. Only the most minor of changes are shown by several elements - **Al, Ca, Mg, K** - again suggesting sources of these elements in the sediments and soils of the catchment, had by this time become extensively leached, and perhaps podsolised. The increase in **Fe** is more difficult to interpret. Peaks in **Fe** are often detected at or near the sediment/water interface in lake sediments - as a result of the mobilisation of **Fe** where anaerobic conditions occur. This is probably the situation in Loch Hellisdale. On the other hand, **Fe** is abundant in the podsols and peats of the area. However, the peak **Fe** levels in this core occur between 75 and 25cm, and are associated with allogenic-clastic sediments which have been derived from erosion of sediments and soils known to be podsolised. It appears possible that these peak are not an simply an artefact of the precipitation of iron in oxidised surface sediments, as noted by Carignan and Flett [1981], they may also relate to the history of sediment transport.

Discussion

The compositional changes in the Hellisdale loch sediments noted by EDMA suggest that a series of changes in climate, vegetation, soils, and land use have been clearly detected. The patterns found possess striking similarities to those reported at Loch Lang [Bennett *et al.* 1990], as well as elsewhere in northern Britain [*e.g.* Bennett *et al.* 1990, Mackereth 1965, 1966, and Pennington *et al.* 1972].

This lake sediment evidence suggests that in Glen Hellisdale, the Loch Lomond stadial was characterised by extensive erosion and deposition within the loch of detritus derived from unweathered sediments and soils in the catchment. This is in contrast to the very recent episode of accelerated erosion noted near the top of the core in which the source minerals had by this time become weathered and leached in a landscape with extensive podsols and peat cover. The start of the Holocene is marked by the sedimentary consequences of increased biological activity within the lake and stable soils in the catchment which were followed by a long period of comparative stability in the surrounding landscape. Minor changes are detectable from approximately 200 cms, which may be associated with podsolisation and/or peat growth. Whilst there are specific indications in the core's lithology of human activity in the catchment (charcoal layers and the upper clay/silt deposit) there are only suggestions of minor soil erosion associated with prehistoric activity within this catchment. This broadly corresponds with the conclusions from nearby Loch Lang [Bennett *et al.* 1990].

Several further aspects merit emphasis. The parallelism between the trends in silicon, sulphur and total diatom counts is marked [Figures 6.5 and 6.6], and emphasises the need to distinguish between biological activity within the lake as a source of sediments, and the influx of biological debris from the surrounding catchment. The interpretation of sulphur in this loch core presents problems. Whilst the initial peak at 375 cm corresponds with a peak in the diatom population and was interpreted earlier as a result of the scale of the biological decay processes, similar peaks in diatom numbers at 175 and 75 cm do not correspond to peak frequencies of sulphur. Mackereth [1965] suggested that the mechanism for the precipitation of sulphur into lake sediments may be largely biological. In general throughout this core, the strength of the relationship found between the proportion of sulphur and diatom numbers was not as strong as was expected. Recent work, however, suggests that inorganic sulphur reaches such catchments from a variety of sources including recent aerial pollution [Rudd 1986]. This sulphur will be reduced and stored in the sediment as organic sulphur compounds and this process may have clouded the link between diatoms and sulphur in the upper part of this loch core. Rudd further suggested a link between sulphur content and lake acidity, since the reduction of sulphate to organic sulphur compounds is responsible for the consumption of H+ ions. Nevertheless, such correlations will not necessarily occur, since Nriagu [1983] demonstrated that an anoxic hypolimnion was necessary for the reduction of inorganic sulphur. The acidity of source sediments and soils in a catchment and lake acidity have been shown to be not necessarily related. In particular, Battarbee *et al.* [1985] demonstrated that soil acidification does not necessarily lead to lacustrine acidity; especially where waters have a low alkalinity and where acids generated in organic horizons can be neutralized by cation exchange and weathering in mineral horizons. However, the general correlations between mineral input and peak biological activity observed by the present studies in Loch Hellisdale appear to reflect changing trophic conditions in the waters of the loch.

Whilst the source of chlorine in these sediments is precipitation which has the composition of dilute sea-water in the Western Isles [Waterston *et al.* 1979], the relative proportions of chlorine observed do not fluctuate in any interpretable manner, corresponding to the observations of Pennington and Lishman [1971] on iodine in relation to precipitation and loch sediments in northern Scotland. Further checks also failed to detect the presence of significant amounts of sodium in the core. The reasons for this absence are not clear. The relative frequencies of the rarely reported vanadium and titanium correspond broadly with those of Al, Ca, Mg, and K indicating that they reflect the erosional loss of mineral matter from the catchment soils and bedrocks. Nickel fluctuates in a manner that is at present very difficult to explain and it presumably reflects the rate at which streams happen to be eroding more nickel-rich gneissic bedrocks in the catchment. The study has failed to detect any evidence of lead, zinc, chromium, copper or any other elements associated with the long distance transport of atmospheric pollutants from industrial areas. These have been detected for example in Loch Lomond and Lough Neagh [Farmer *et al.* 1980, Rippey *et al.* 1986] respectively 200 km to the south east, and 300 km to the south. It is impossible to infer a lack of a north-west transport of such pollutants because of the uncertainty of age of the uppermost sections of the Hellisdale core. In several ways the pattern of Holocene lake sediment chemistry, retrieved from Loch Hellisdale resembles those initially identified by Mackereth [1966] in his studies of mountain lakes in the English Lake District, and in western Scotland by Pennington *et al.* [1972]. Whilst some of the early assumptions and models have been subsequently re-evaluated [Bengtsson and Enell 1986, Engstrom and Wright 1984], many aspects of the basic picture of soil erosion and stabilisation remain unchallenged. Metallic elements in lake sediment cores from the northern parts of the British Isles have also been investigated by several workers including Farmer *et al.* [1980] in Loch Lomond and Rippey *et al.* [1982] in Northern Ireland. In these cases the investigators noted an increase in metal concentration in the upper levels of sedimentary profiles broadly associated with the relatively recent historical past.

SYNTHESIS

Consideration of all these data indicates that despite its relative isolation Glen Hellisdale has been shown to respond quickly and (essentially) in tandem to sites on the Scottish mainland to the major climatic changes which affected the Late Devensian and early Holocene. The Loch Lomond stadial and its termination appear to be well-evidenced in all three sets of information. In Glen Hellisdale, the period was characterised by a very cold climate, with tundra and arctic scrub, bare rock, widespread soil instability and mechanical erosion which introduced significant quantities of base-elements into the water body to be deposited as mineral-rich sediments.

Discussion

The Loch Hellisdale sequence begins in the Late Devensian and indicates the presence of bleak landscape with (sub) arctic plant communities associated with much bare rock, and the erosion of fresh, mineral-rich soils or sediments. This environment produced a relatively base-rich lacustrine water body. Diatom numbers were low, perhaps as a result of climatic severity. The change to the Holocene interglacial is very clear and marked in the pollen-, sediment chemistry- and diatom evidence. The patterns of change evidenced by each of these datasets in the core reflect the interactions of a number of factors - climatic fluctuations, the progressive colonisation by tree taxa, changes in the nature of the ground cover, erosional rates and soil types, and the activities of people. Quantitative studies of the total numbers of diatoms in the loch sediments have been rendered difficult by the suspicions raised about periods of varying sediment rate, non-deposition, or erosional hiatuses in the core. Nevertheless, fluctuations (in both numbers and taxa) have been detected which appear to appear variously to relate to the changing nature of the water body - as detected by the changing chemistry of the associated loch sediments, whereas other fluctuations appear to relate to other - often unclear - environmental agencies. There are hints of pre-Neolithic human activity in the landscape, but the evidence is unclear. Later human activity appears to have been a significant influence on the vegetation and soils in the catchment, and hence for the water and sediments in the loch. The relative proportions of vanadium and titanium in the lake sediments appear to a further source of information on the past presence of physical erosion of soils and sediments in the catchment. Sometimes distinct relationships have been detected between actual counts of the numbers of diatom frustules present, and the relative proportions of sulphur and silica in the loch sediments, suggesting the importance of biological decay processes in determining the geochemistry of the sediment body. Where it is possible to make comparisons with other sites, the patterns of change detected at Loch Hellisdale correspond broadly with those identified at adjacent Loch Lang, as well as other sites in the Outer Hebrides and west coast of Scotland. There is, however, no evidence in the upper parts of the core from this remote loch for the long distance transport and input of metallic elements from agricultural or industrial sources.

Criticism of pilot study and reformulation of research strategies.

The pilot study of material retrieved from Loch Hellisdale and the clear association between the palynological and geochemical data demonstrated the value of the application of EDMA to the analysis of palaeoenvironmental change. It demonstrated that EDMA of sediment chemistry can explore the relationship between the sediment geochemistry and the evolution of the terrestrial and benthic environments. A clear similarity was observed between the geochemical history of the sediments of Loch Hellisdale, reconstructed by EDMA, and the analyses of other lochs in the Hebrides and the mainland which employed more conventional geochemical methods [Bennett *et al.* 1992; Mackereth 1966 Pennington *et al.* 1972]. Despite the fact that results from EDMA are presented in the form of ratios it has been possible to identify climatic processes operating at the Late-Glacial/Holocene transition, and clearly identify the onset of industrial pollutants in the steep rise in acid indicators at the top of the core. The sediment chemistry also proved sensitive to anthropogenic modification of the environment.

A clear correspondence was observed between the environmental history as reconstructed by geochemistry established by EDMA and the Palynological Analysis.

The pilot study also highlighted areas where the technique could be improved. The use of EDMA to analyse sediment chemistry, presents data in the form of the ratio of the selected element in the core rather than the conventional formats by which chemistry is presented, *i.e.* ppm, millilitres/litre, milligrammes/gramme. As the ratio of all the elements specified will always approximate to 100% the interpretation of minima or maxima may be problematic. The observed change in ratio of an element may be the result of a genuine change in the content of that element in the core, or the result of a variation in the concentration of another element. This can be overcome by adopting a suitable theoretical framework, by adopting multiple working-hypotheses, facies modelling, investigating the associations between several elements and considering the nature of change in the ratio of an element around a hypothetical mean. In this way the processes operating within and upon a landscape can be investigated and reconstructed.

The range of elements analysed was not wide enough to establish rainfall intensity, or industrial activity. The range of elements analysed should have been widened to include **Na**, **Cu** and **Zn**. Vanadium was found to be of little value for palaeoenvironmental research excluded.

This pilot study and established the value of EDMA in the analysis of palaeoenvironments, and established a theoretical framework with which to interpret results obtained by EDMA. Further cores were then extracted and analysed.

Chapter eight.

Geochemical investigations of environmental change in lacustrine sediments from North and South Uist.

Summary of Chapter.

Three Lochs on the Outer Hebridean islands of North and South Uist were cored in the hope that they would contain tephra deposits and preserve any associated environmental change in the geochemistry of their sediments. Minimal quantities of tephra were found and no geochemical response to its deposition was noted. Several episodes of soil erosion were noted in each Loch, and the role of anthropogenically derived atmospheric pollutants in modifying the lacustrine environment was highlighted. The erosion of calcareous material from the machair and dunes which line the western coastline of the islands, and its deposition in the lochs, was seen to be important in the maintenance of the lacustrine environment in the face the progressive acidification of the catchment soils.

Loch A'Barpa.

Loch A'Barpa lies on the island of North Uist, to the north of the A867 road, grid reference NF 835663 [Figure 8.1]. The landscape here has been severely disturbed by glacial activity, the dominant landform is hummock and hollow terrain. With the exception of Ben Langass [90 metres] which borders the loch and Uneval [140 metres] which lies to the north-west, there is little variation in relief. Machair vegetation and shell sand lie just three kilometres to the west, and the sea in Orasay bay is within 500 metres of the loch. The underlying bedrock consists of Lewisian Gneiss, but hummocky glacial drift is also found in the area. The loch is bordered by three main soil types.

1. Organic soil, described as map unit 4 by the Soil Survey of Scotland [Hudson *et al.* 1982]. Map unit 4 is blanket peat, which is acid, base deficient and has a high water holding capacity. This soil type is the principal one which borders the loch and borders the entire northern shoreline. The dominant land use is poor rough grazing. Peat cutting has occurred around the townships.

2. Peaty podzols and peaty gleys occur. These are described as map unit 391 of the Lochinver series by the Soil Survey of Scotland [Hudson *et al.* 1982]. This soil unit forms on hummocky valley moraines and is restricted around the loch to the south-western corner where the loch drains into Orasay Bay. The soil formed on this material is acidic and base poor and land use is limited to rough grazing.

3. Peat, peaty gleys, some peaty podsols and humic gleys occur. These are described as map unit 392 of the Lochinver series by the Soil Survey of Scotland [Hudson *et al.* 1982]. This soil unit is formed on hill slopes and is found here on the slopes of Ben Langass. The soil is acidic and base deficient. The dominant land use is poor rough grazing.

Other soil types which may have had an influence on the loch sediment are the extensive range of brown calcareous soils of the Frazerburgh series, which lie on machair and shell sands within three kilometres of the western end of the loch.

Archaeological remains are found on the flanks of Ben Langass. and evidence for cultivation in the form of Feannagean (relicts of spade cultivation) and peat cutting are in evidence.

The loch is oligotrophic and over 10 metres deep and it appeared possible that sediment would have accumulated here throughout post glacial times. The maximum sediment depth recovered was 126 cm and it is unlikely that this represents the accumulation of sediment throughout the Holocene. However, the presence of sedimentary structures in the core and the geochemical trends discussed below suggests that this accumulation is an undisturbed body of sediment. No volcanic tephra was observed during investigations on a geological microscope under polarised light, or in the studies using a Scanning Electron Microscope. Comparison will be made between the geochemical reconstruction from this site and from the lochs of Obisary , Hellisdale and Druidibeg also in the Outer Hebrides [Figure 8.1]. Loch A'Barpa is also interesting since the loch was Calcium bombed from a helicopter in the spring of 1990, in an attempt to raise the pH of the loch and ostensibly to lower the aluminium uptake of the farmed salmon. This is a shallow loch and the sediment column is unlikely to have experienced anaerobic, reducing conditions, this is important as under reducing conditions the location of elements in the core may be drastically altered and subsequently bear no relation to the processes which led to their deposition {Carignan & Flett 1981].

Core description.

Disappointingly only 126 cm of sediment was retrieved from the loch. This consisted of homogenous lake mud, with few distinguishing features. Darker bands of material were noted at 28, 33.5, 38, 41, 74, 78, and 92 cm; these were sampled for geochemical analysis.
To allow clearer interpretation the core has been divided into a series of chemizones. The interpretation of this data is facilitated by the construction of a series of facies and presented in Figure 8.2a and 8.2 b.

Chemizone BP1. 126 - 80 cm.

Youngest.

80 cm.	Peak in P, Mg.	Recovery in Si.	Decline in Fe.
90 cm.	Peak in Mg, Fe, Ca.	Recovery in P.	Decline in K, Si..
92 cm.	Peak in K.	Increase in Ca.	Decline in P.
100 cm.	Peak in P.	Recovery in Si.	Decline in Fe.
110 cm.	Peak in Fe.		Decline in Si.
126 cm.	Peak in Si.		

Oldest.

Summary.

At 126 cm, the base of the core, is marked by a high ratio of Si, 68%. At 110 cm Fe ratios rose to 65% and dominated the core chemistry. At the same depth the ratio of Si fell to 28%. At 100 cm the ratio of Fe fell to 25% and Si ratios rose to 45%. At 92 cm the highest ratio of K in the core occurred, rising to 12%; this episode is also associated with a rise in the concentration of Ca, to 8%. At 90 cm K fell to the lowest ratio recorded in the entire core, 0.3%. **Si** ratios also declined, to 20%, while ratios of **Mg**, **Fe** and **Ca** peaked at 4%, 62% and 9% respectively and ratios of **P** began to rise from 0.3% to 1.2%. At 80 cm the ratio of **Fe** fell to 37% and **Si** rose to 48%.

Interpretation.

With the exception of **Fe**, the minerals that dominate this chemizone are typical of a neutral body of water. The periodic increase in **Fe** indicates that paludification of catchment soils was underway and raises the possibility that episodic acidification of the loch may have occurred in the past.. However, other elements that are indicative of the acidification of soil and waters, **S** and **Mn** are largely absent and any such putative episodes may have been minor. **Si** in lake sediments is primarily autocthonous and biogenic [Battarbee 1986], and in Loch A'Barpa low ratios of **Si** coincide with high ratios of **Fe**. High **Fe** ratios appear to have suppressed the biological productivity of the loch and may indicate changes in the nutrient status of the Loch from Mesotrophic to Oligotrophic.

The substantial increase in the ratio of **K** at 92 cm, to 12% is the highest the entire core. Inwashes of this mineral commonly indicate an episode of the mechanical erosion of the catchment soils [Mackereth 1966, Pennington *et al.* 1972], and this is probably the explanation here. This episode may be interpreted as the result of changing patterns of land use, or environmental change. Whatever the cause, the ratio of **K** at 92 cm points towards a disturbance of soil stability within the catchment.

The inwash of **K** into the loch at 92 cm was followed at 90 cm by an increase in the ratio of **P**, of the base elements **Ca** and **Mg**, and by a substantial increase in the ratio of **Fe**. Ratios of **P** and **Ca** may be either autochthonous or allocthonous to the loch, indicating either an increase in biological productivity within the loch itself, or the leaching of this material from the catchment soils. Williams *et al.* [1971, 1976] considered that detrital apatite comprised a high proportion of total **P** in lake muds with a high calcareous content; while Engstrom and Wright [1984] considered that inorganic phosphorous occurs primarily as a sorbed component of amorphous iron oxides. The peak in the ratio of **P** in the core, between 90 cm and 80 cm, follows the peak in the ratio of **K** at 92 cm, and is also associated with a peak in the ratio of **Fe** at 90cm, and a recovery in the ratio of **Si** at 80cm. The continued high ratio of **P** when **Fe** declined suggests that the high ratio of **P** at this depth is not the result of sorbtion by **Fe**. The rise in **Ca** and **Mg** may have been caused by the leaching of these bases from catchment soils in the face of soil acidification. The high ratio of **Fe** at this depth supports the above explanation that the most probable source for this mineral is via the chemical weathering of the catchment soils.

An anthropocentric interpretation of this sequence would suggest that an attempt was made to farm the catchment soils, which in turn triggered the erosion episode. In their disturbed state the leaching of **Fe** from the soil was intensified, which in turn resulted in the high ratio of **Fe** following the peak in **K**. An alternative hypothesis that excludes human influence relies on a significant change to the environment which triggered the soil erosion and subsequent leaching. The absence of **Na** from the core at this depth does not suggest an increase in rainfall, nor does the leaching of **Fe** indicate a severe fall in temperature.

Regardless of the nature of the environmental forcing, the geochemical sequence in this chemizone does not suggest that significant acidification of the loch waters had occurred in the past and that feedback mechanisms must have existed which countered trends towards acidification. The existence of such a mechanism has been previously suggested by Battarbee [1990], and prior to the industrial revolution changes in the pH of many studied waters appear to have progressed at the rate of 0.1 pH units per 1000 years [Renberg & Hellberg 1982; Atkinson *et al.* 1990].

Chemizone BP2. 78 - 50 cm. Chemizone BP2a. 60 cm.

Youngest.

50 cm.	Peak in Si.	Decline in Fe.
60 cm.	Peak in Al, Ca & Na.	Decline in Fe.
70 cm.	Peak in Fe	Decline in P.

74 cm.	Peaks in K, Mg, Ti & Fe.	Decline in Si.
78 cm.	Peak in Si.	Decline in Mg, P & Fe.

Oldest

Summary.

Chemizone BP2 is very similar to Chemizone BP1. The geochemical sequence in this zone begins at 78 cm with a **Si** ratio reaching 70% indicating a return to mesotrophic conditions in the loch waters. Four cm higher, at 74 cm, **Si** declined to <40% and the proportions of **K**, **Mg**, **Ti**, and **Fe** peak. At 70 cm **Fe** peaked at 58%. Chemizone BP2a at 60 cm marks peak proportions of **Al**, **Ca**, **Mg** and **Na**. At 50 cm a decline in **Fe** and increase in **Si** records a return to mesotrophic conditions and a reduction in the rate of weathering of the catchment soils.

Interpretation.

The rise in **Si** ratio in the loch indicates an recovery in its trophic status. This recovery is ended by a phase of mechanical erosion at 74 cm depth suggested by peaks in **K**, **Mg** and **Ti**. The minerals associated with the erosion episode in this chemizone suggest that it was different to the episode which occurred in Chemizone BP1. The peak proportion of **K**, at 74 cm, is associated with, rather than succeeded by **Fe**, which indicates base depletion of the catchment soils occurring at the same time as mechanical erosion was occurring. Acceleration of base depletion in the catchment soils is indicated by the high proportion of **Fe**, 70%, recorded at 70 cm. The introduction of **Fe** into the loch sediment again coincided with a reduction in **Si**. The presence of **Fe** and the decrease in **Si** suggests that the waters of the loch became acidified and oligotrophic for a short period.

The trend described above is interrupted at 60 cm by high ratios of **Al**, **Ca**, **Mg** and **Na**, which indicate a short term but severe impact of the sea on the loch waters. Occurring in tandem, these peaks probably record processes that are allocthonous to both the loch and its catchment soils, for example the sea, or the input of salts in precipitation as described elsewhere by Waterston *et al.* [1979]. Whether this marks the ingress of the sea into the loch or a marked climate change in respect of the oceanicity of the weather regime or rainfall, is open to speculation. However, this episode appears to have countered the trends of acidification indicated at 70 cm, because at 50 cm **Si** proportions rose to 78%, the highest level reached in the entire core; while at the same depth **Fe** proportions fall to 0.1%, the lowest proportion of this mineral recorded in the entire sediment record.

If an "anthropocentric interpretation" of the geochemical sequence is pursued, then this zone represents a period of renewed exploitation of the catchment, and subsequent weakening of soil structure. The episode of soil erosion indicated by the peaks in **K** and **Ti** may have been prompted by a renewed phase of exploitation. However the proportion of **K** in Chemizone BP2 is lower than in Chemizone BP1 and suggests that this phase of exploitation was not as intense as the previous. This phase of exploitation may have been ended by a period of oceanicity of climate, indicated by Chemizone BP2a, following this episode the loch and catchment appear to return to mesotrophic conditions.

An alternative hypothesis, as in Chemizone BP1, relies on either a significant environmental change or the natural lowering of erosion thresholds within the soils of the catchment. The rapidity with which **Fe** is mobilised and then dominates the geochemical sequence following the episode of erosion, may reflect a more depleted base status of the soil; or alternatively the acidification of, and hence the degradation of soil structure and subsequent lowering of erosional thresholds. However, elements which indicate soil acidification and the acidification of waters, such as **Mn** and **S**, are still present in very low proportions, while bases such as **Mg** are still available. This would suggest that either the catchment soils were not degraded into podzolic conditions at this time or that there was little relationship between the acid status of the soil and the loch chemistry. The latter hypothesis is in accordance with the observations of Jones *et al.* [1986, 1989] and Battarbee [1990].

Chemizone BP3. 41 - 28 cm

Youngest

28 cm	Peak in P, Fe.	Decline in Si.
30 cm	Peak in Si.	Decline in Fe.
33.5 cm	Peak in Si.	Decline in Mg, Fe.
38 cm	Peak in Mg, Fe.	Low Si.
40 cm	Peak in K, Fe.	Decline in P.
41 cm	Peak in P. Fe.	Decline in Si.
50 cm.	Peak in Si.	

Oldest.

Summary.

Successive changes in sediment texture forced a frequent sampling interval in this chemizone. A recovery in the trophic status of the loch is indicated by the **Si** peak at 50 cm. This is followed at 41 cm by a decline in **Si** and an increase in **P** and **Fe**. High proportions of **Fe** were recorded between 41 and 38 cm. **Fe** features more prominently in this chemizone than in either BP1 or BP2, but base elements such as **Mg** are also present, while **Mn** and **S** are present in low ratios. At 40 cm an episode of mechanical erosion occurred, evidenced by the small increase in **K**. The peak proportion of **K** in this chemizone, 4%, is lower than those which occurred in zones BP1 and BP2, 12% and 8% respectively. At 33.5 cm **Fe** and **Mg** declined and **Si** recovered.

Interpretation.

Chemizone BP3 is similar to BP1 and BP2, with the geochemical cycle **Si**, **P**, **Fe**, **K** and **Mg**. At the bottom of this zone the **Si** peak, which may be interpreted as indicating mesotrophic conditions is succeeded by peaks in **P** and **Fe**. Phosphate deposition is often difficult to interpret in lake sediments as it is often co-precipitated with iron [Engstrom & Wright 1984]. In this case, since **Fe** ratios remained high after **P** proportions declined so co-precipitation of these minerals appears unlikely. The relatively high proportions of **P** at 41 and 28 cm, 1.15%

and 1.2% respectively, suggest that the loch was occasionally nutrient enriched A smaller episode of mechanical erosion than those noted in Chemizones BP1 and BP2 occurred at 40 cm and this was accompanied by an inwash of **Mg** into the basin. The cycle is completed by a recovery in the relative abundance of **Si** to 77% and decline in **Fe**.

If the proportion of **K** at 40 cm is the result of anthropogenic modification of the catchment, it appears to have been happening on a smaller scale than in previous episodes. However, if the physical component of the soil disturbance has declined, the chemical component, **Fe**, has not. In this zone the chemical weathering of sediments in the catchment, indicated by **Fe** dominates the sequence and the loch appears to be switching to oligotrophic conditions when **Fe** is deposited in the loch sediments.

Chemizones BP1 - 3 exhibit a geochemical cycle which suggests that feedback mechanisms operated to bring the loch back to mesotrophic conditions and the catchment soils to stability despite the leaching of periodic leaching of **Fe** from the catchment soils. This cycle is dominated by the succession of **Si**, **K**, **P** and **Fe**.

The chemistry of the loch and the catchment soils approached a critical threshold in this chemizone. The marked contrast between Chemizone BP3 and BP4 suggests that a sudden and drastic environmental change occurred from which the loch and its catchment has so far been unable to recover.

Chemizone BP4. 28 - 3 cm.

Youngest

4 cm. Peak in Mg, Ti, Al.	Recovery in Ni.	Decline in P, Cl.
5 cm. Peak in Mn, S, P, Na, Cl, Cu.		Decline in Mg.
6 cm. Peak in Mg. Minor peak in K.		
7 cm. Peak in Si.		Decline in Mg.
8 cm. Peak in Mg, Fe.		Decline in Zn.

10 cm. Peak in Zn, Cu.	Recovery in Si.	Decline in Mn, S, P, Cl, Cu, Ca.
20 cm. Peak in Mn, Mg, S, P, Na, Cu. Cl, Cu, Ca.		Decline in Si.
28 cm. Peak in P, Fe.		Decline in Si.

Oldest

Summary.

In chemizone BP4 several minerals which are present in low proportions in chemizones 1 - 3 feature prominently. In particular the proportion of S, and **Mn**, increased by several hundred percent; S from <2% to 13.8% and **Mn** from 0.6% to 4.4%. Cl and Na also exhibit a similar trend, but these indicate the influence of oceanicity and rainfall on the catchment rather than autocthonous processes occurring within the catchment soils [Waterston *et al.* 1977]. This change occurs suddenly at 20 cm depth where peak proportions of S, **Mn**, P, Na, Cl, **Cu**, and Ca occur. These elements exhibit Dynamic Metastable equilibrium, and this sudden change in the proportions of the minerals within the core suggests that a significant environmental change had occurred. A similar episode, but of lesser intensity occurred at 5 cm depth. Though a trace metal here, the peak relative abundance of **Cu**, approximately 1.2%, occurred at 20, 10, 5 and 3 cm. At 10 cm **Zn** rose to its highest value of the whole core, 0.98%. Mechanical erosion is indicated by a minor peak in K at 6 cm depth. Si proportions declined at 20cm to 21%, almost the lowest proportion of this mineral in the whole core, but was relatively stable between 7 and 4 cm.

Interpretation.

A significant change in the sediment chemistry occurred in this zone which suggests that the loch waters became acidified, and that this process occurred rapidly. Below this zone S and **Mn** are present at low ratios whilst within and above this zone both elements dominate the sediment chemistry. Minerals which peak at 20 cm can be divided into two groups, those which indicate an increase in the influence of the sea on the chemistry of the loch water's Na, Ca and Cl; and those which indicate an acid water chemistry **S**, and **Mn** and an abundant nutrient supply **P**. The range of minerals which peaked at 20 cm depth indicate that a significant threshold has been crossed. A similar event though on a smaller magnitude occurred at 5 cm depth. The most probable mechanism for this sudden environmental change is the onset of the Industrial Revolution and the deposition of acid materials in the catchment [Mitchell *et al.* 1985; Rippey *et al.* 1982].

The introduction of Chemizone BP5 into this sequence is caused by the need to consider the impact on sediment chemistry of Calcium bombing of the loch, which was carried out in the Spring of 1990. Studies of the sediment composition and morphology under a Scanning Electron Microscope revealed that calcium pellets were distributed to a depth of 3 cm in the core.

Chemizone BP5.

Youngest.

0.5 cm. Peak in Na, Ca.	Recovery in Mn, P, Al,. Cl, Si	Fall in Mg, Fe
1 cm. Rise in Mg, Fe, Zn.	Stable Na.	Steep fall in Mn, S, P, Cl.
2 cm. Peak in Ca, Mn, S, P, Al, Cl	Recovery in Na.	Decline Zn, Fe, Si, Cu.
3 cm. Peak in Ni, Zn, Fe, Cu.		Decline Mg, Ti, Al, Na, Ca.

Oldest.

Summary.

Pellets of introduced Calcium could be observed when the sediments were studied under the electron microscope and care was taken to focus the electron beam away from these to avoid artificially weighting the sediment chemistry. This zone is introduced at 3 cm depth by a decline in the proportions of **Na**, **Ca**, **Mg**, **Al**, and **P**; and peaks in the proportions of **Fe**, **Cu**, **Ni**, and **Zn**. At 2cm depth all these minerals plus **Mn**, **Cl** and **S** recover while **Fe**, **Cu**, **Ni** and **Ti** decline. All the elements which rose in ratio at 2cm stabilise or fall slightly at 1 cm, but **Mn**, **Fe**, **Ni**, **Zn** and **Ti** record increases in ratio. At 0.5 cm depth **Na**, **Ca**, **Al**, **P**, **Mn**, **Cl**, **S**, **Si**, and **Ti** increase in proportion, while **Mg**, **Cu**, **Fe**, **Ni** and **Zn** decline. At 0.5 cm **Ca** reached, 11% the highest proportion of this mineral in the entire core, as did **Na** at 5%.

Interpretation.

There are two peak values and one decline of **Ca** in this Chemizone. Are any or all of these in response to the deliberate introduction of this carbonate mineral into the loch. If these proportions are the result of deliberate introduction what, if any was the response of these on the sediment chemistry?

The **Ca** was introduced in an attempt to raise the pH of the loch and lower the **Al** intake of Salmon farmed in the loch; to what extent was this successful? In tandem with the rise in ratio of **Ca** at 2 cm depth **Zn**, **Fe**, **Cu** and **Si** are suppressed but **Mn**, **S**, **P** and **Al** ratios increase. These responses do not produce unequivocal evidence for a reduction in the acidity of the waters. **Mn**, **S** and **P** ratios in particular, which commonly indicate acid, eutrophic waters, increase in tandem with **Ca**. **Fe** is the only mineral, commonly taken to indicate a tendency towards acidity, which declines at this point. Could the rise in **P** to 1.4% at 2cm depth indicate increased nutrient availability in the loch brought about by the faecal input of farmed fish and the decomposition of unconsumed food? At 1 cm depth the value of **Ca** declines, as do the values of those minerals which rose in tandem with **Ca** at 2 cm. The proportion of **Fe** rose at 1 cm, but again this trend does not present equivocal evidence for a clear response to the introduction of allocthonous **Ca**, particularly since the increase in the acid indicator **Fe**, is accompanied by an increase in the base indicator **Mg**. At 0.5 cm depth values of **Ca** and **Na** were the highest recorded in the whole core, and the relative abundance of **Mn**, **P** and **Al** also increased. At the same depth, proportions of **Fe** and **Mg** decreased. These responses of **Mn**, **P**, and **Al**, to the **Ca** peaks in this zone may imply that the "Calcium bombing" was a failure. The **Ca** peaks and

Fe declines do occur in tandem and may imply a recovery in the pH status of the loch. In Chemizone BP5, between 3 and 2 cm, when **Ca** climbed from 2% to 7 %, **Fe** declined from 40 to 26%. Between 1 and 0.5 cm **Ca** ratios rose from 5.5% to 11%, while **Fe** declined from 45% to 19%. Ostensibly this is a significant response to the deliberate anthropogenic introduction of **Ca**. However, greater variation in the **Fe** content of the core can be observed at other depths in the core, between 90 and 80 cm (65-25%), 70 and 60 cm (55-29%), 38 and 33.5 cm (44-23%). Nor do all the declines in ratio of **Fe** correspond to a peak in **Ca**. At 90 cm a peak in the proportion of both minerals occurred. Interpretation of the **Fe** profiles in the top few cm of a sediment profile is further complicated by the fact that oxidizing conditions, peculiar to the uppermost part of the sediment column, may result in the accumulation of **Fe** at this point [Carignan & Flett 1981]. The response of **Fe** may then have little to do with the introduction of **Ca** into the waters.

Discussion.

Calcium bombing, success or failure?

On this evidence it appears that the introduction of allocthonous **Ca** failed to have a marked effect on the acidity of the Loch A'Barpa. If the principal aim was to reduce the ratio of **Al** in the water column, it appears that this also failed, since it can be seen that **Al** proportions increase in chemizone BP5 in tandem with increases in the ratio of **Ca**. Calcium bombing is a controversial means by which to address problems of water acidity [**New Scientist 1990**]. The process relies on the dissolution of the introduced carbonate in the loch waters, but observations have suggested that the once the surface irregularities of the Calcium pellet have been smoothed by dissolution, processes all exchange between the loch water and the allocthonous calcium will cease. Once this occurs the introduced **Ca** will cease to have an impact on the chemistry of either the loch waters or deposited loch sediment. Studies of the calcium pellets in the loch sediments under a the loch sediments under Scanning Electron Microscope revealed that the their surfaces had been smoothed, and few surface irregularities were observed. A further problem arises if the peak ratio of **Ca** in Chemizone BP5 is ascribed to the anthropogenic introduction of allocthonous material; from 20 cm depth upwards peaks in **Ca**, **Na** and **Al**, are associated with peaks in the minerals **P**, **Mn**, **Cl** and **S**, which are indicators of acid conditions.

The artificial introduction of **Ca** to a water body and ultimately to a sediment column should be portrayed by a increase in proportion which suppresses the proportion of other minerals in the core. To what extent is the **Ca** observed in the core, and in particular in Chemizone BP5 the result of autocthonous or allocthonous **Ca**? The nature of the analytical technique used here is such that a genuine increase or decrease in the ratio of an element in the core will inevitably result in an apparent decrease or increase in the ratio of other elements within the core and in particular in the ratios of minerals which normally respond in tandem to the introduced material. It is for this reason that successful interpretation of EDMA results relies on the construction of a facies model. From 74 cm depth, in Chemizone BP2, to 0.5 cm depth in Chemizone BP5, variation in the ratio of **Ca** in the core is strongly paralleled by **Na** and **Al** [See Figure BP1]. This indicates either a similar source, or that these minerals respond to similar environmental conditions. The allocthonous introduction of **Ca** should then have resulted in the suppression of **Na** and **Al**, but this did not occur, which suggests that the peak ratio of **Ca** in Chemizone BP5 does not reflect the introduction of allocthonous **Ca**.

The proportions of S and **Zn**, good indicators of acid stress [Holdren *et al.* 1984] fluctuate and decline in the top 5cm of the core apparently in response to increase in the ratio of **Ca**. However, several studies have noted a decline in the deposition of these minerals at the top of sediment cores, and this has been taken elsewhere to indicate a genuine fall in the output of industrial contaminants [See Berge *et al.* 1990; Renberg *et al.* 1990; Rippey 1990]. The rise in **Ca** may therefore be a consequence of a decline in the deposition of S and **Zn** rather than the direct cause of the decline in the proportion of these minerals in the core. Evidence from two other Lochs from the Outer Hebrides also reveal an increase in **Ca** ratio at the top of the sediment column. These lochs [Discussed below] have not had calcium introduced artificially.

From the above discussion it is obvious that the impact of Calcium bombing on the pH of Loch A'Barpa is difficult to detect in this study of sediment geochemistry. It appears that processes which may reverse the acidification of the loch may already be occurring and that the introduction of Ca into the loch has had little impact on the progress of these processes.

Alternative Calcium sources. Influence of the sea? Erosion of sand dune and Machair?

Rainfall in the Outer Hebrides has been observed to be primarily dilute sea water [Waterston *et al.* 1979] containing dissolved substances acquired from the atmosphere and the ocean. There must therefore be a close relationship between such elements as Sodium, Chloride and Calcium. Maitland and Holden [1983] observed a clear correspondence between the ratio of Sodium and Calcium in the inland waters of the Outer Hebrides. The relationship in this core between Sodium and Calcium is clear, demonstrating the real influence of the sea on the chemistry of Loch A'Barpa. A correspondence with the trends in Cl can also be observed, but this is clearest above 20 cm in depth.

The close theoretical and observed relationship between Ca and Na allows us to suggest that where peaks in the proportion of either element occur in tandem these indicate the influence of the sea, but that where peaks in either element occur independently of the other, dilute sea water may not be the source.

The close correspondence between Na and Ca in Chemizone BP5 suggests the influence of the sea may be more important than the introduction of Ca by helicopter. At 90 cm a peak occurs in the ratio of Ca which is independent of Na. An alternative hypothesis to account for the presence of this element is from the soil improvement practise of liming via the introduction of shell sand. Since this rise in Calcium follows immediately after what appears to be a substantial disturbance of the landscape indicated by the high proportion of K at 90 cm, the latter hypothesis appears the most likely.

Finally and perhaps most significantly, similar peak ratios of **Ca** can be observed near the surface in the sediment chemistry of Lochs Druidibeg and Obisary, below, which have not been the subject of calcium bombing. The peak in the proportion ratio of **Ca** in Chemizones BP4 and BP5 may reflect the erosion of calcareous material from machair and dunes to the West and deposited in the loch. This would account for the disparity observed where high **Ca** proportions are not associated with other indicators of the influence of the sea.

Geochemical Trends.

A study of Figures 8.2a and 8.2b illustrates that few of the minerals in the sediment core behave independently of the other minerals present. A strong association can be observed between **Na**, **Ca**, and **Al**, and a slightly weaker association can be noted between those three and **P** and **Mg**. A strong association can also be observed between **Mn**, **P** and **S**. All seven minerals behave similarly in Chemizones BP4 and BP5, above 28 cm depth. Trends in the input of **Mg** are classically interpreted as indicating mechanical erosion and this can be seen at 92, 74, and 40 cm depth.

Dating the core.

Cu, and **Zn** do not respond in tandem to any other minerals, and the source of these may be allocthonous to the loch, the catchment or even the Outer Hebrides. As trace metals these may indicate the onset of atmospheric pollution brought about by industrial activity in Europe [Rippey 1990] and as such are a good means of dating that part of the core [Holdren *et al.* 1984]. Therefore in the Loch A'Barpa sediment core the peak ratios in these minerals at 20 cm may indicate a date of between 1820 and 1880.

Fe and **Mn** are commonly used to reconstruct palaeo-redox conditions of the catchment soils [Mackereth 1965,1966]. Here **Mn** is closely related to **Cl** and **S** rather than **Fe**. **Fe** proportions in the core rose after each episode of mechanical erosion and dominated the geochemistry in Chemizone BP3. Peaks in **Fe** suppress the biological activity of the loch, indicated by **Si** proportions. **Si** commonly has a biogenic source and the decline in concentration of this mineral in tandem with peaks in Fe suggest that the loch was periodically oligotrophic in Chemizones BP1 and BP2.

Throughout the length of the core Fe and Si are negatively related. The presence of **Fe** in the sediments may be the result of the leaching of **Fe** from sediments and their acid status. Since peaks in **Fe** are related to decreases in **Si** it seems clear that the trophic status of the water body has fluctuated throughout the time recorded by the sediment column. Hebridean lochs may fluctuate between a range of trophic states through time, or even concurrently across the loch itself [Boyd 1979; Glentworth 1979; Waterston *et al.* 1979] and the changes recorded in the sediment chemistry may record these processes.

Non-Anthropogenic environmental change.

In this discussion, non-anthropogenically induced environmental change is interpreted as events which are not directly attributed to the activity of people, but it is difficult to isolate environmental change in the Outer Hebrides which does not have an anthropogenic component. The environment of the Outer Hebrides, the soils, flora and fauna, have been subtly altered by human influences over thousands of years [Bennett *et al.* 1990; Boyd 1979; Glentworth 1979]. The geochemistry suggests that a significant environmental change occurred at 60 cm, where peak ratios in **Na**, **Ca**, and **Al**. These minerals primarily have an allocthonous source, in dilute sea water deposited as rainfall, and may indicate an episode of increased rainfall. Alternatively these minerals may have been leached from the catchment soils in response to growing acidity. Were this to be the case a rise in **S** should also be anticipated, since this did not occur an increase in rainfall would appear to be the most likely source for this episode.

Anthropogenic Impact?

The use of geochemical data to attempt the reconstruction of a detailed environmental history of a catchment is still in its infancy and in the absence of palynological or radiocarbon dating it is difficult to estimate the periodicity of anthropogenic inputs into the sediment core, or to estimate how long the material has been accumulating. However, the acidification of waters has been demonstrated to be a relatively recent event in many areas [Battarbee *et a*l. 1985; Holdren *et al.* 1984; Renberg 1990] so it would appear that 20% of the core has accumulated in the past 200 years. Comparison with Bennett *et al's* [1990] radiocarbon dated sediment core, from Loch Lang on South Uist, suggests that the material retrieved from Loch A'Barpa may have accumulated in the past 1500 years. Mechanical erosion is indicated by trends in the element potassium; three substantial increases in the proportion of this element occur at 92 cm, 74 cm and 40 cm, and a lesser increase can be observed at 6 cm. The trend in this element is one of declining input into the basin. Each successive peak is smaller than the preceding one. An anthropocentric interpretation of this trend would suggest three phases of clearance or landscape utilisation, each of which was either less intense, or generated less disturbance to the soils than the preceding event. These erosion episodes may be related to episodes of increased population pressure, rather than to new phases of settlement [Dodgshon 1988]. At Loch Lang Bennett *et al.* [1990] noted changes in the ratios of inorganic material at 2235 BP and again at 480 BP. This present analysis indicates that erosional episodes occurred more frequently in the Loch A'Barpa catchment, or that the analytical [EDMA] method used here is better able to identify such episodes than flame photometry or atomic absorption. An alternative hypothesis would suggest that the ratio of K available for erosion had diminished, but given the character of the Lewisian Gneiss (parent material) this seems unlikely.

Mg rises at 92 cm and stays at a high level until 70 cm. Mg is an important base element and its incorporation in the loch sediments at this point may point to increased soil erosion in response to cultivation.

Summary.

This analysis of lacustrine sediments from a remote Hebridean loch demonstrates that even in such isolated environments, human modification of the environment is one of the principal environmental determinants. Three clear phases of landscape disturbance are identified each of which has a distinct geochemical signature which suggests that intensification of anthropogenic exploitation rather than other environmental variables were responsible for these episodes.

Anthropogenic activity is also probably responsible for the sudden change in the acidity of the lacustrine sediments at 20cm. The influence of the sea is also identified as a major environmental determinant. At several points in the core the influence of the sea appears to be the major variable operating upon the environment of the loch. The deliberate introduction of carbonate material into the loch was detected, but this strategy does not appear to have had the desired effect. The application of EDMA to the study of this loch demonstrates that it is sensitive enough to identify phases of anthropogenic activity, rainfall intensity and the deposition of industrial contaminants. A further test of this technique will be the degree of replicability between this and the other lochs analysed below.

Loch Obisary.

Loch Obisary lies on the eastern side of North Uist, grid reference NF 896661 [Figure 8.1], sandwiched between undulating blanket peat to the west and the high ground of Eaval [347 metres] and Burrival [140 metres] to the east. The underlying bedrock is Lewisian Gneiss. Tills derived primarily from the gneiss material underlie the dominant soil type abutting the loch, the peaty podzols of the Lochinver series.

Three soil types are found around the loch:

1. Peaty podzols and peaty gleys, described as map unit 391 of the Lochinver series by the Soil Survey of Scotland [Hudson *et al.* 1982]. This soil is base poor and acidic and is only suitable for rough grazing.

2. Peaty gleys and peat, described by the Soil Survey of Scotland as map unit 394 [Hudson *et al.* 1982] which develop on stony, sandy loam colluvium. This is a minor soil type abutting Loch Obisary, but a major one on the islands as a whole. The soil is base poor and acidic and is only suitable for rough grazing.

3. Peaty gleys and podzols formed on very steep hillsides described as map unit 396 by the Soil Survey of Scotland [Hudson *et al.* 1982]. This soil develops on colluvium and is base poor and acidic and capable of supporting only limited amounts of rough grazing. In terms of area occupied, this is the least important of the soils around the loch, but in terms of the contribution of terrestrial material to the loch it may be the most important, as the steep slopes which support this soil drop straight into the loch, from the slopes of Eaval and Burrival.

Much of the peat to west of the loch has been cut for fuel, and Feannagean, evidence of former spade cultivation is common. Most of the islands in the loch are grazed by sheep. Several building structures of the prehistoric and historic age are located around the loch.

The loch is connected to the sea by an open channel into the sea loch, of Loch Eport. This channel ensures that the influence of the sea features strongly in the sediment chemistry, and acts as a strong counter to processes of loch acidification. As a result, surface waters are brackish, whilst at depth full-strength sea water can be found [Boyd & Boyd 1990]. There is evidence that fish farming has been practised in the loch until quite recently. The loch sediments were sampled because of its great depth. Loch Obisary is up to 45.3 metres deep [Waterston *et al.* 1979] which offered the potential for a considerable accumulation of Holocene sediments, unfortunately only 110 cm of material was recovered by the boat launched corer which was disappointing. The ingress of the sea under certain conditions appears to have set up currents which either prevents or disturbs the accumulation of lacustrine sediment. The core described below was retrieved from the deepest section of the loch at NF 897615, to the south-west of Eilean Fada.

Core Description.

The sediment retrieved consisted of featureless grey black gyttja. Contiguous 10 cm samples were taken down the core and prepared in the manner described above. Small quantities of tephra were observed [Figure 8.3] when this material was examined. Compared to the results obtained at the Strath of Kildonan, these figures are low and sub-sampling of the core between 0-10cm and 70-80cm failed to reveal any tephra at all. Despite the low tephra count the two areas with the largest tephra counts were sampled at 1cm intervals for the geochemical investigation.

To allow clearer interpretation of this material the core has been divided into 4 chemizones refer to Figure 8.4a & 8.4b.

Chemizone OB1. 110 - 80 cm.

Youngest.

80 cm. Peaks in Zn, Ni, Mn, Fe, Cu.	Decline in Si,
90 cm. Peak in Si, Al.	Decline in Cl.
100 cm. Peak in Na, Cl.	Decline in Si, Al.
110 cm. Peak in Si, S, Al.	

Oldest.

Summary.

At the base of the core peaks in **Si**, **S** and **Al** were observed. **S** with a proportion of 15%, is higher here than at any point in the whole of Loch A'Barpa. The rise in the proportion of **Na** and **Cl** at 100 cm suggest an episode where the influence of the sea dominated the sediment chemistry. At 80 cm peak ratios in **Zn** and **Cu** occurred which may indicate the deposition of industrial pollutants. The ratio of **Mn** also peaks at 80 cm and this may record the acidification of the loch waters.

Interpretation.

Although the whole core is of a similar length to the sediment accumulated at Loch A'Barpa, the geochemistry of Chemizone OB1 indicates that it is considerably younger. In this chemizone the value of S in the core falls from a peak of 14% to a background value of 6%. This is a similar sized peak, but a far higher background proportion, to those achieved in the top 28 cm of the Loch A'Barpa core. In Loch A'Barpa this ratio of S was taken to indicate the acidification of the waters concurrent with the onset of industrial pollution, if this is the case here then the whole core may have been accumulating for less than 200 years. Local conditions may influence the ratio of S in the core. However, the presence of **Zn** and **Cu** at 80 cm is another indicator that this material has accumulated in the industrial period [Nriagu & Coker 1983; Rippey *et al.* 1982]. Rippey [1990] suggested that significant quantities of **Zn** were not deposited at the equally remote Lochan Dubh, in the north-west Highlands of Scotland, until the 1880s which suggests that the sediments examined here may have accumulated rapidly over a short period of time. The influence of the open channel to the sea is graphically demonstrated by the background proportion of **Na** in this core, circa 4% and peak a ratio in Chemizone OB1 of 27%. Background values of **Na** at Loch A'Barpa were 0.5%, with a peak of 5%. The supply of **Na** to the loch reduced the tendency towards acidification which normally follows the onset of industrialisation elsewhere.

Chemizone OB2. 79 - 70 cm.

Youngest.

70 cm. Peak in Na, Cl, Al.	Decline continues.
71 cm. Peak in Mg, Na, Cl.	Decline continues.
72 cm. Peak in Si.	Decline in K, Ti, Ni, Fe Mn.
73 cm. Peak in K, Ti, P, Mn, Ni.	Decline in Fe.
74 cm. Peak in Fe. Rise in Ti, Ni.	Decline in Mg, Si.
75 cm. Peak in Mg, Al.	Decline in Zn, Ti, Ni, Mn, Fe, Cu.
76 cm. Peak in Zn, Ti, Mn, Fe, Cu.	Decline in Mg.
77 cm. No significant alteration.	No significant alteration.
78 cm. Peak in Cl, Si.	Decline in Fe, Al.
79 cm. Peak in Al, S. Rise in Si.	Decline in Ni, K, Fe, Cu..

Oldest.

Summary.

In this chemizone three episodes of environmental change occurred. At 76 cm peak values of **Zn, Cu, Ti** indicate an intensification of industrial pollution; while peak values in **Fe** and **Mn** suggest the acidification of the catchment soils and waters. At 75cm increases in the ratios of the base minerals **Mg, Na, Cl** occurred. An ingress of sea water into the loch is the most probable cause for this event. At 73 cm a peak in **K** occurred which was accompanied by a peak in **P** which suggests that soil erosion has occurred, accompanied by an inwash of organic material into the loch.

Interpretation.

In this Chemizone the high ratios of minerals which were probably generated by industrial pollution [Holdren *et al.* 1984] is further evidence that the entire core has been accumulating for a relatively short period of time. S proportions remained constant, around 10%, but the influence of this mineral was countered by the influence of bases supplied by the sea, in particular at 75 cm. The peak in the value of K, at 8.7%, indicates an episode of soil erosion. Such episodes may be the result of a direct anthropogenic modification of the catchment soils. In the case of Loch Obisary, the steep slopes of Burrival, which supports the peaty gleys of soil map unit 396, slope directly into the loch and erosion from these may have occurred naturally rather than have been prompted by the activities of people. No geochemical changes are observed in this chemizone which might be attributed to the influence of tephra on the catchment soils and waters.

Chemizone 3. 70 - 20 cm.

Youngest.

30 cm. Rise in Fe begins. Decline in P, Mg, .
40 cm. Peak in P, Mg.
50 cm. Peak in Si.
60 cm. Peak in Ti, S, Fe.

Oldest.

Summary

In this Chemizone the indicators of industrial pollution and loch acidification decline while the indicators of biological productivity, nutrient supply and base availability, all increase.

Interpretation.

The decline in indicators of industrial pollution and acidification is related to an increase in the ratios of minerals which indicate a recovery in base status and biological productivity, P, Mg,

Al, Cl and **Ca.** This pattern has been noted at Loch Tinker, in the Trossachs, and at the Round Loch of Glenhead, in Galloway [Rippey 1990]. The explanation advanced is that the accumulation of **Mg, Al** and **P** in this zone indicates the rapid accumulation of sediment in the loch [Rippey 1990]. This explanation fails to account for the mechanisms which have prompted the increase in sediment accumulation. The peak in **P** at 40 cm suggests that the level of biological productivity within the loch was greatly enhanced, which implies a change in the trophic status of the loch from oligotrophic to mesotrophic. This may have been brought about by natural mechanisms operating within the loch to counter acidification the existence of which has been speculated upon [Jones *et al.* 1986; Battarbee 1990] or by ingress of base rich material from the sea, or by a combination of both.

Chemizone OB4. 20 - 1 cm.

Youngest.

1 cm. Peak in Cu, Ni, Fe,	Rise in Ca.	Fall in K, Zn, P, Na, Mg.
2 cm. Peak in K, Zn, P, Na, Mg, Cl.		Fall in Ca.
3 cm. Peak in Ca.		Decline in S, Fe, Mn.
4 cm. Peak in S, Mn, Fe.		Fall in Ca.
5 cm. Recovery in Si.		Decline in S.
6 cm. Peak in S, Ca.		Fall in Si.
7 cm. Peak in Si.	Rise in Ca begins.	Fall in S.
8 cm. Peak in S.		Fall in Fe, Mn.
9 cm. Peak in Fe, Mn. Rise in S.		Decline in Zn, Cu.
10 cm. Peak in Zn, Cu,		Decline in P.
20 cm.		Decline in P.

Oldest.

Summary,

In this chemizone the ratio of minerals which are indicative of acidification, **Fe**, **Mn** and S increased substantially. S rose to 26%, **Fe** rose to 35% and **Mn** to 0.8%. Peaks in all three minerals occurred at 9cm and 4cm, and between **Mn** and S at 9cm, 6cm and 4 cm. **Zn** and **Cu**, indicators of pollution, peaked at 10 cm, and **Cu** also peaked to 3.9% at 1cm. **Si** values vary in response to the performance of acid indicators. Peaks in S, **Mn** and **Fe** inevitably result in a decline in the ratio of **Si** in the core. Two substantial increases in the proportion of **Ca**, to over 19%, occurred in this chemizone, at 6cm and 3 cm. The first of these, at 6 cm, coincides with a peak in acid indicators, while the second, at 3cm, coincides with a decline.

Interpretation.

In this zone between 20 cm and 4 cm the indicators of acidification, S, **Mn** and **Fe** dominated the sediment chemistry , which suggests that the acidity of the loch rose to its highest level. In Chemizone OB4 the acidity of the loch water rose to the point where biological productivity was diminished. This is indicated by the behaviour of **Si** and S. There are two main sources for S in lake sediments:

1. As a by product of the decomposition of lake flora and fauna [Rudd 1986].
2. From the deposition of industrial pollution [Jones *et al.* 1986].

Si in lake sediments is primarily the result of biological productivity within the lake [Battarbee 1986]. If this is so indicators of biological productivity and decomposition by-products should be in accordance, and this is the case throughout much of the core. In Chemizone OB4 however, the relationship between **Si** and S is a negative one, peaks in S are related to minima of **Si**. The source of S in this chemizone may be industrial pollution rather than the decomposition of lake flora and fauna. On this evidence the waters of Loch Obisary did not become acid and oligotrophic until quite recently, perhaps within the last 120 years, if the evidence of **Cu** and **Zn** at 76 cm is interpreted correctly.

Above 4 cm the proportions of indicators of acidification decline, apparently in response to the presence in the core of a high value of **Ca** 6 and 3 cm. For much of the core, the proportion of **Ca** rarely climbed above 6%, but in this chemizone it rises to over 19%. There has been no suggestion to date that **Ca** was artificially introduced to the loch, in a deliberate attempt to reduce acidity, nor were calcium pellets observed when the samples were studied in the Scanning Electron Microscope.

Two hypotheses are proposed to account for the peak ratios of Ca:

1. Autocthonous production of Ca within the loch.
2. The introduction of calcareous material into the loch.

If production of **Ca** at these points was autocthonous to the loch, any increase in its relative abundance should persist across more than one contiguous sample. The peak ratios of **Ca** were confined to samples taken from 6cm and 3 cm and if autocthonous internal productivity was the source it occurred during a relatively brief periods when the loch environment became less acid. There is no evidence in the sediment chemistry that the peak in **Ca** at 6 cm occurred in response to a fall in acidity. At this depth, a peak in **Ca** corresponds with peaks in **S** and **Mn** and a fall in **Si** and **Mg**. This does **not** suggest the return of neutral pH conditions. At 3cm the peak in **Ca** proportion 20%, does coincide with a decline in the ratios of acid indicators, and a limited recovery in the ratio of **Si** occurred. However, minerals which indicate a rejuvenated base status, **Na**, and **Cl**, perhaps via the influence of the sea, also decline. In the face of this argument, the internal productivity of **Ca** within the loch appears unlikely.

Any "natural" introduction of calcareous material to the loch requires a recognisable source. The correspondence of peaks in the ratio of **Ca** with minima in the ratio of minerals which indicate the influence of the sea, suggests that the **Ca** was not introduced in sea water; or produced in the loch following a modification of its trophic status following an ingress of sea water. An alternative source of calcareous material exists in the shell sands of the extensive machair and dune systems on the western side of the island. The sand dunes of Baleshare are only 10 kilometres to the west of the loch and the environmental disturbance episode which saw the formation of the dunes, could have resulted in the transport of calcareous material to the loch. Work in progress [Gilbertson *et al.* in press] indicates that the machair and dune systems have been disturbed and eroded several times in their history, and that the most recent episode occurred within the past 100 years. This hypothesis accounts for the limited duration of the **Ca** peaks, and for the fact that no other mineral which indicates a base rich environment rises increases its ratio at these points, as would have been the case had the **Ca** peaks recorded a change in the productivity of the loch.

Indicators of the influence of the sea, **Mg**, **Na**, **Cl** remain relatively constant in this chemizone, but **Al** proportions are much lower than in the two preceding chemizones, from a mean of 9% in zones 2 and 3 to a mean of 5% in zone 4. However, there are no peaks which might indicate the ingress of substantial volumes of sea water into the loch basin. Perhaps the direct influence of the sea has diminished in recent years facilitating the acidification of the loch?

Discussion.

The argument presented above suggests that the material retrieved in this study from Loch Obisary has accumulated within the past 200 years. Considerable depth of sediments would be expected to have accumulated in a loch of this depth [45.3 metres] and the fact that they have not suggests that a mechanism acts within the loch to prevent accumulation, or to periodically scour the basin clear. The probable source of this mechanism is the ingress of the sea during extreme storm conditions. Minerals which indicate industrial activity in Europe, **Cu** and **Zn**, are present from 80 cm depth and the sediment accumulated in Loch Obisary may well have accumulated post the industrial revolution. The loch is open to the sea via a narrow inlet and the influence of the sea on the sediment geochemistry can be seen throughout the sediment record. This acted to prevent the acidification of the loch until the top 10 cm of the sediment record. The acidification of the loch is indicated between 10 cm and 3 cm by peak proportions of in **Cu** and **Zn** followed by consistently high values of **Fe**, **Mn** and **S**. This trend is interrupted by the introduction of **Ca** into the basin, the most probable source of which is from dune blowout from the links and machair to the west. The trophic status of the loch is currently in a state of flux. Some acid indicators, **S** and **Zn** have declined in the top 3 cm, while others, **Fe** and **Mn** have recorded an increase. Unfortunately for the loch the main counter to the processes of acidification, the contribution of bases by sea water entering via the small open channel, declines at the top of the core.

Anthropogenic influences.

The deposition of industrial pollutants in this environment is clearly seen in Chemizone OB4. This is unquestionably an anthropogenic modification of the environment. The direct impact of the people of the island on the physical environment of the loch and its catchment is less easy to detect. Only one episode of physical erosion, marked by a peak in the proportion of **K** at 73 cm can be observed and this may be the result of natural erosion from the slopes of Eaval and Burrival. This erosion may have occurred in response to the overgrazing of the slopes and subsequent destabilization of the thin soils, but in the absence of further evidence this suggestion must remain tentative.

Summary.

Despite the different locations a clear similarity can be observed between the environmental history of Loch Obisary and Loch A'Barpa. In both case the sediment appears to have been accumulating for a short period of time. In both there is clear evidence for the onset of the industrial revolution with the deposition of contaminants such as **Cu** and **Zn**. In both the acidification of the loch waters is demonstrated to be a relatively recent event and both Lochs are demonstrated to be sensitive to the introduction of allocthonous acid materials, this may be significant for any consideration of the likely response of the Hebridean environment to the deposition of acid materials emitted by an Icelandic volcanic eruption. Both environments also demonstrate the importance of identifying the range of allocthonous influences on an ecosystem. We have already discussed the role of industrial contaminants, but in both ecosystems the influence of the sea is seen to be important; in Loch A'Barpa this is exerted via the chemistry of sea water, while in Loch Obisary this is via the direct ingress of the sea. A second allocthonous influence is detected in the introduction of Ca into both lochs. In the discussion of Loch A'Barpa the question was raised as to whether the deliberate introduction of Ca had played any role in modifying the lacustrine environment, particularly in the face of other, larger peaks in the values of Ca. The analysis of Loch Obisary demonstrates that the erosion of machair and shell sands from the west has played a constant role in returning the loch waters to a neutral pH. The use of EDMA is seen to be sensitive enough to identify such macro-scale influences but also to reconstruct the environmental response of each loch to the imbalances caused by the introduction of allocthonous material.

A third loch was selected for examination Loch Druidibeg, on South Uist.

Loch Druidibeg.

Loch Druidibeg, NF795375 [Figure 8.1], lies on South Uist, in a shallow basin "scoured" from the Lewisian Gneiss by glacial activity. The loch is fed by streams from the east which drain acid peats, and from the west by brackish water which drains from lochans which have formed in the lee of the machair. The loch was selected for coring as the size of its catchment ought to have ensured the transport and deposition of tephra in the loch sediment. However, the loch is shallow, exposed to the wind and in many areas was found to have a rocky bed, but sheltered bays do contain an accumulation of silt. A core was retrieved from one of these, NF795385, but the maximum depth of sediment recovered was 106 cm. The shallow nature of this core makes it unlikely that sediment has been accumulating since Late-Glacial, but the presence of sedimentary structures in laminations suggests that the accumulation is undisturbed. The shallow nature of the loch and its sediments ensures that anaerobic conditions will not have occurred and hence no significant movement of minerals in the core should have happened.

In comparison to material retrieved from the Strath of Kildonan, the tephra content of the core was very low [Figure 8.5]. The tephra count was obtained by sampling contiguous 10 cm slices of the core (see above for methodology). The highest count was 6 grains retrieved from between 20 - 30 cm, but when this area was sub-sampled no tephra was identified and no geochemical trace was identified during analysis on the Scanning Electron Microscope.

Three main soil types abut the loch. These are mainly on hummocky moraine, derived primarily from the Lewisian Gneiss, or on steep rocky slopes.

1. Peaty podzols and peaty gleys formed on hummocky moraine, described as map unit 391 of the Lochinver series by the Soil Survey of Scotland [Hudson *et al.* 1982]. This soil is base poor and acidic and is only suitable for rough grazing.

2. Peaty gleys, peat and some peaty podzols formed on dissected rocky terrain, described as map unit 395 of the Lochinver Series by the Soil Survey of Scotland [Hudson *et al.* 1982]. This soil is base poor and acidic and will only support poor grazing. This soil can be improved by liming with shell sand.

3. Humus-iron podzols and non-calcareous gleys formed on hummocky, "bouldery" moraine; described as map unit 388 of the Lochinver series by the Soil Survey of Scotland [Hudson *et al.* 1982]. The parent material for this soil unit is normally loamy sand. This soil unit is cultivated where relief allows but land use is commonly restricted to grazing.

In addition to the three main soil units, soils formed on calcareous shell sands can be found in close proximity. These are described as map units 259 and 262, brown calcareous soils and calcareous gleys by the Soil Survey of Scotland {Hudson *et al.* 1982]. These are base rich and are an abundant source of calcium. The transport of shell sand by people or by aeolian action must inevitably have an impact on the chemistry of the loch waters and sediments.

The loch chemistry is therefore influenced by a wide range of contrasting environments; acid peats and waters to the north, south and east, and calcareous sands and the sea to the east. As a result the pH and chemical content of the water varies considerably. A study of water chemistry [Waterston & Lyster 1979] found that pH varied from 7.23 in the east to 6.30 in the west, that sodium varied between 18.7 % - 12.8%, and calcium varied from 10.9% - 4.4%; this variety inevitably complicates the interpretation of the sediment chemistry.

To allow a clearer interpretation the geochemical data has been divided into three chemizones [See Figures 8.6a and 8.6b for detail]..

Chemizone DR1. 106 - 30 cm.

Youngest.

30 cm. Peak in Cl.	Decline in Zn, Ni.
40 cm. Peak in Zn.	Minima in Cu
60 cm. Peak in Si, Zn, Cu.	Decline in Fe, Ni.
70 cm. Peak in Fe.	Minima in P, K, Ti, Si.
80 cm. Peak in P.	Decline in Si.
90 cm. Rise in P, Fe.	No significant alteration.
100 cm. Peak in Si.	Decline in P,S,Ti,Al,Ca,Cl,K,Mg.
106 cm. Peak in P, S, Ti, K, Al, Ca, Cl, K, Mg.	

Oldest.

Summary.

At the base of the core high values were observed in a wide range of minerals, the majority of which declined consistently until 70 cm. At 60 cm and 40 cm depth peaks occurred in the relative abundance of **Cu** and **Zn**. **Na** barely features in the sediment chemistry, which is surprising given the vicinity of the sea. The value of S at the base of the core, 3.4 %, is the highest achieved in the whole sediment column, but falls to 0.5 % at 100 cm and rarely climbs above this ratio. Conversely **Mn** an indicator of acid conditions which usually responds in tandem with S barely registered a presence in Chemizone DR1. **Mg** has two potential sources: it can accompany **K** during episodes of mechanical erosion, or it can be deposited in tandem with **Na** and **Cl** in rainwater. In this Chemizone it is clearly associated with **K**. The proportion of **Fe** in the core rises steadily from 20 % at 100 cm to 75 % at 70 cm. This increase is initially associated with a rise in the proportion of **P** between 100 and 80 cm.

Interpretation.

This is a shallow core and it is unlikely that the sediment has been accumulating over millennia. What changed in the environment of the loch that resulted in the accumulation of sediment in this small bay? The minerals which peak at the base of the core may indicate the nature of these changes. At 106 cm the highest ratios of **K**, **Mg**, **Ti**, **Al**, **Ca**, **Cl**, and **S** occurred. The values of **P** were the highest until 27 cm. Taken together **K**, **Mg** and **Ti** can be used to indicate an episode of landscape disturbance which resulted in soil erosion into the loch [Engstrom & Wright 1984; Mackereth 1965, 1966]. The high values of **P** may be the result of the input of detrital organic matter, this is in accordance with the occurrence of an episode of soil erosion. A nutrient input should result in an increase in biological productivity and the peak in **S** may record the subsequent decomposition of flora and fauna which bloomed in this episode. If a general landscape disturbance occurred in the region, the machair and dunes to the west may have been destabilised. The episodic destabilization of the dune systems of South Uist has been demonstrated by Gilbertson *et al.* [in press]. Such an event would account for the peak in **Ca** at this depth. The most obvious source of **Cl** and **Al** is sea water or the brackish water of lochs which lie between the machair and the blacklands. Taken together, the elements which peak at 106 cm can be taken to indicate a phase of landscape disturbance.

Between 100 cm and 70 cm the proportion of **Fe** in the core rose from 20 % to 70 %. Whereas **Si** fell from 75 % to 20%. **Fe** is an indicator of the rate of leaching from catchment soils and subsequent acidification of waters [Engstrom & Wright 1984]. The values of **Mn** in this core are very low, but this element is a good indicator of increasing acidification and peaks do occur in tandem with peaks of **Fe**. **Si** is a good indicator of the biological productivity of the loch which again is closely tied to the acidity of the water. In this chemizone, indeed throughout the entire core, trends in these minerals are in almost exact opposition [Figure 8.6b]. In this chemizone, the trends in **Fe** and **Si** suggest that the pH of the loch fell between 100 cm and 70 cm, and then recovered between 70 and 30 cm.

The sediment accumulation appears to have been initiated by an episode of soil erosion. The enclosed nature of the bay sampled may have protected the accumulated sediment from the action of wind and current and encouraged the creation of a benthic micro-environment in the bay which allowed the creation and accumulation of sediment. The values of **Cu** and **Zn** at 60 cm and 40 cm indicate that the material at this point has probably been deposited since the onset of the industrial revolution.

Chemizone DR2. 29 - 22 cm.

Youngest

22 cm. Peak in K, Ti, Si, P, Al,		Decline in Mg,
23 cm. Peak in Mg.	Increase in Si.	Decline in Ti, K, P.
24 cm. Peak in Ti, Cu, Zn, Fe.		Decline in P, S, K, Al, Mn.
25 cm. Peak in Mn, K, Cl, Ca, Al, S, P.		Decline in Fe,
26 cm. Peak in Fe.		Decline in P,Ti,Zn,K,Si,Al,Cu.
27 cm. Peak in P, Zn, Cu.		Decline in Ti, K
28 cm. Peak in K, Ti, Si, Al, Ca, P		Decline in Fe, Cl.
29 cm. Peak in Ti.		Decline in Cu, Zn.

Oldest.

The close sampling ratio in this chemizone is the result of the detection of tephra located between 20cm and 30cm [Figure 8.5]

Summary.

The proportion of **Na** in this chemizone remained extremely low. S recorded only one minor increase, at 25 cm to 1.4 %. Peaks in **K** occurred at 28 cm, 25 cm and 22 cm, These corresponded with peaks in **Si**, **Ti**, **Al**, **Ca** and **P**. Values of **Cl** and **Mn** also peaked at 25cm. Peak ratios in **Zn** and **Cu** occurred at 27 and 24 cm. Minima in the ratio of **Fe** occurred in tandem with peaks in the ratio of **Si**, peaks in **Fe** at 26 cm and 24 cm are associated with minima in **Si**.

Interpretation.

Three episodes of mechanical erosion are indicated here by peaks in the ratio of **K**. Associated with the high ratio of **K** Are peaks in **Ca**, **Cl**, **Al** and **P**. These relationships suggest that some soils around the loch may have been disturbed. The peaks in **Ca** and **Cl** do not correspond with a peak in **Na**. A direct impact of the sea or intensification of rainfall is therefore unlikely. To the west of the loch, calcareous Brown Earths and Gleys, which are suitable for cultivation, are found. The parent material for these soil units is calcareous shell sand, which if eroded may have provided the geochemical traces identified at 28 cm, 25 cm and 22 cm. If the source of the eroded material was the podzols and peats, which lie to the north, south and east of the loch, then the peaks in **Ca** and **Cl** are difficult to account for. Equally if organic, base poor material, had been eroded into the loch, evidence for an increase in acidity, peaks in **Fe**, **Mn** and **S** and a decline in **Si** should be expected. But these predictions did not occur.

At 27 cm and 24 cm peaks occur in the proportions of **Zn** and **Cu** in the core. The deposition of these minerals is primarily associated with industrial pollution [Holdren 1984; Rippey 1990] and is further evidence that the sediment in the core has accumulated since the onset of the industrial revolution.

Chemizone Dr2. 21-1 cm.

Youngest.

1 cm. Peak in Si, Na, Ca.	Decline in Ti, Fe, Mn,
10 cm. Peak in Ni, Mn.	Decline in Si.
20 cm. Peak in Si.	Decline in Zn, Cu, Fe,
21 cm. Peak in Zn, Cu, Fe.	Decline in K, Ti, Si, P, Al,

Oldest.

Summary.

This chemizone is introduced at 21 cm by high values of **Zn** and **Cu**, which are associated with an Fe ratio of 78%. At 20 cm the highest ratio of **Si**, 88%, in the entire core was recorded; at the same time **Fe** fell to the lowest ratio recorded, 5%. At 10 cm **Fe** and **Mn** ratios rose. **Mn** rose to 34%, a significant increase compared to a mean for the core of 2%. At 1 cm peak ratios of **Si**, **Ca** and **Na** occurred.

Interpretation.

The core was sampled to investigate tephra impacts, not the history of acidification, hence the upper part of the core was not sampled in detail for geochemical analysis. The peaks in **Cu** and **Zn** at 21 cm are the highest in the core and indicate an intensification in the deposition of industrial pollution. An intensification of acid deposition may intensify the leaching of **Fe** from the base depleted soils which abut the loch and this would be indicted in geochemistry by a peak in **Fe**. At 21 cm, the indicators of industrial pollution are accompanied by an increase in the ratio of **Fe**. The acidification of the loch, in recent times, is indicated at 10 cm by a rise in the ratio of **Mn**, from 1% to 34%. The trend towards acidification appears to have been halted at the surface of the core where peaks in the ratio of **Si**, **Na** and **Ca** occurred. These elements do not indicate the persistence of acid conditions, rather the opposite. The high proportion of **Na**, (2.6%), coupled with high values of **Ca** and **Si** and an extremely high value of **Fe**, (4%) suggests that the loch sediments record the onset of neutral/alkaline conditions after a period of acidification which was probably brought about by the deposition of acid contaminants in industrial pollution.

Summary

The analysis of the geochemistry of Loch Druidibeg has further demonstrated the vulnerability of Hebridean lochs to the deposition of industrial contaminants. This subtle means of anthropogenic modification can be seen to have had a profound effect on the lacustrine environment. The role of the sea can also be seen to be of importance, particularly in the modification of any trends towards acidification. This continuous nature of this influence may be nearly undetectable in the geochemistry but EDMA clearly identifies major episodes where quantities of calcareous material is introduced into the loch. Only low concentrations of volcanic tephra were identified in this sediment, which may have accumulated within the past

200 years, but nonetheless the geochemistry demonstrates the sensitivity of Hebridean lacustrine environments to the input of acidifying material.

Discussion, Geochemical signals for environmental change in three Hebridean lochs.

A clear similarity can be observed between the environmental trends evident in Loch Druidibeg and Loch A'Barpa and Loch Obisary. In all three cases episodes of landscape disturbance are indicated; the influence of the sea can be seen to have played a major role in maintaining the lacustrine environment despite the acidification of terrestrial sediments, and the deposition of industrial contaminants can be seen to have played a major role in the creation of the lacustrine environments which we observe today.

Anthropogenic influences can be identified at two levels.

The first is direct, indicated by episodes of mechanical erosion in the soils of both the loch catchments and also of the calcareous soil of the dune systems and machair which lie downwind to the west. The disturbance of catchment and more distant soil is evidenced in each loch and the episodic nature of these events may be related to phases of human exploitation, or environmental degradation. In all three lochs the deposition of calcareous material is clearly indicated by the geochemistry, and this appears to have been more effective at maintaining a neutral pH than the deliberate introduction of carbonate material into Loch A'Barpa.

The second means by which people appear to have modified the environment is less obvious on the landscape, but clearly capable of bringing about a major change in the lacustrine environment. This is indicated by the recent acidification of all three lochs which is typical of environmental changes which have been noted in other remote bodies of water in northern Europe. Three hypotheses may account for this change:

1, That the acidification of the waters is the natural consequence of gradually falling pH [Renberg & Hellberg 1982; Atkinson *et al.* 1990].

2. Changes in land use resulted in an increase in the transport of ions from the catchment soils to the loch [Rosenqvist 1978, 1979].

3. The deposition of sulphate ions in rainfall intensified following the industrial revolution and it is this deposition which acidified the loch [Mitchell *et al.* 1985; Rippey *et al.* 1982; Rippey 1990]

The first hypothesis finds little support in contemporary literature. Many studies have noted a gradual acidification of European water bodies since the Late-Glacial, but these changes were very slow, <0.1 pH unit per 1000 years [Renberg & Hellberg 1982; Atkinson *et al.* 1990]. In none of these studies was a rapid change in pH status noted in the absence of evidence for an external forcing mechanism. The lower chemizones exhibit no evidence for a consistent fall in pH and this hypothesis appears unlikely.

The second hypothesis was advanced by Rosenqvist [1978. 1979], who suggested that a decline in farming intensity would lead to the regeneration of acid heathland or forest. This in turn would lead to the accumulation of an acid humus and the release of protons into the water body. This argument does not account for acidification where there has been no abandonment, nor where farming practises have been intensified [Renberg *et al.* 1990]. There is currently no evidence for acidification of waters in areas where the archaeological record attests to land abandonment [Anderson & Korsman 1990; Patrick *et al.* 1990; Renberg *et al.* 1990; Timberlid 1980]. Nor does Rosenqvist's hypothesis account for the recent nature of the acidification which has been observed in many remote European locations [Jones *et al.* 1990]. In the case of the Outer Hebrides there have undoubtedly been significant changes in landuse in the past 200 years [Boyd & Boyd 1990; Caird 1979] which may account for the change in chemistry evident at 20 cm depth. However, studies by the University of Sheffield, Department of Archaeology and Prehistory, suggest that such changes may have occurred on several occasions since prehistoric times, why then is the most recent set of changes the only one associated with the acidification of the island waters? Rosenqvist's hypothesis also fails to account for the increase in the presence of **Cu** and **Zn** noted at the onset of lake acidification, which are unlikely to be allocthonous to the loch catchment but are likely to have a distant industrial source [Rippey *et al.* 1982; Rippey 1990]. therefore the second hypothesis is also unsatisfactory.

The third hypothesis links the sudden change in sediment chemistry to the onset of the industrial revolution and the subsequent transport and deposition of contaminants. Similar changes in chemical profiles have been dated to circa 1800 AD [Appleby *et al.* 1990; Atkinson & Haworth 1990; El-Daoushy 1990; Jones *et al.* 1990; Nriagu & Coker 1983; Renberg *et al.* 1990]. The Outer Hebrides currently receive between 0.4 - 0.8 grams S-m2 a-1 [Derwent *et al.* 1988]. The acidification of Scottish mainland lochs with similar profiles have been clearly associated with industrial pollution [Kreiser *et al.* 1990; Rippey 1990; Wik & Natkanski 1990] The acidification of Loch A'Barpa is also Marked by an increase in the concentration of **Zn** and **Cu** which are primarily deposited in industrial pollution [Clymo *et al.* 1990; Holdren et al. 1984; Kreiser *et al.* 1990; Renberg *et al.* 1990]. Industrial pollution is therefore the most probable cause of the rapid change in sediment chemistry at 20cm depth.

The behaviour of the minerals in the core demonstrates the vulnerability of the Hebridean ecosystem to the deposition of acid generated at a distant source. The impact of a major Icelandic volcanic eruption on the environment may have been similar to the events which occur at 10 cm depth in this core.

This study has demonstrated a clear potential for the application of EDMA to the examination of palaeoenvironmental change in a lacustrine environment. The broad range of elements studied chosen after the pilot study of Loch Hellisdale clearly provides a wide range of interpretable environmental data. The fluctuation and balance between autocthonous environmental variables operating within the loch catchment and allocthonous variables from without, is clearly identified, which is a further demonstration of the sensitivity and potential of the technique.

Chapter nine.
Geochemical investigations of the Borve bog, Barra.

Summary of Chapter.

This chapter presents the results of the geochemical analysis of sediments which had accumulated in a basin mire on the Hebridean island of Barra. No tephra related response is noted, but the Late-Glacial / Holocene transition is clearly illustrated, as is the evolution and degradation of the soil resource through the Holocene. Anthropogenic modification of the environment is seen to be operating at a number of levels.

Borve Bog, Barra.

With the exception of Loch Hellisdale, the cores retrieved from North and South Uist were very short and only recent environmental change could be inferred from an interpretation of the sediment geochemistry. It also proved difficult to isolate volcanic tephra from the diatomaceous material which was the main constituent of the lake core sediments. This is a problem which has been encountered by other workers [A. Dugmore *pers comm*], and is in contrast to the relative ease with which tephra has been isolated from peats [Dugmore 1989; Pilcher & Hall 1992]. In response to this problem a core was retrieved from a basin peat which lay at an altitude of 65m O.D. at the head of the Borve valley [NF 677 009], on the Hebridean island of Barra [Figure 9.1]. The landscape in which the mire was set has been explored during extensive archaeological exploration of the Borve valley by the University of Sheffield [Branigan 1988; 1990] and it was known that up to 5 metres depth of sediment had accumulated in the basin.

The valley has a long history of land use, dating back to the Neolithic [Branigan 1988] and irrespective of whether volcanic forcing of the environment occurred at this location, the use of EDMA to investigate the environmental history of the upper Borve valley was an interesting application of the technique. The sediment geochemistry was also complemented by a palynological study of the core by K. Pratt [1992]. Reference will be made to the palynology of the core and this material will be presented here in outline form.

The valley itself is open to the west and is exposed to the influence of the sea. The mire is set below Grianan [294m] and Hartaval [353m].

A wide range of environmental influences are brought to bear on the mire at the head of the Borve valley. The valley itself is short, it is only 3.6 km from the mire to the sea at Borve point and encompasses a wide range of soil types; from brown calcareous soils and brown earths to peats and podzols. The landscape is also varied; dune, machair, moor and mountainside are all nearby and these include a wide range of environmental conditions. The machair and dune soils of the west coast are a base rich environment capable of sustaining arable and pasture and exposed to the influence of the sea, whilst the soils of the upper valley are characteristically base poor and acidic; and this has exposed the mire to a wide range of conflicting influences. The mire itself is bounded by acid soils of the Lochinver Association, fed by streams draining acid soils and lies below the steep northern flanks of Hartaval. Overgrown talus slopes extend from the slope of Hartaval into the mire which suggests that active physical processes took place in the past. No estimate could be made of the age of the talus slopes. However, in 1993 a mass movement of peat and mud reached the mire from a starting point on Hartaval, 0.5km distant and 200 metres above the mire.

Soil Morphology.

The underlying solid geology is Lewisian Gneiss and the soils of the upper valley are formed of drift derived from this material. The valley itself was probably glacial in origin, but little detail is known of the glacial history of the region [Whittington & Ritchie 1988].

Soil Units.

Three soil units are found at the head of the Borve valley.

Unit 392. The mire at the head of the Borve valley lies within soil map unit 392, and consists of Peaty gleys, podzols and rankers formed on Lewisian gneiss.

Unit 394. The hill slopes to the north of the mire are dominated by soil map unit 394, which develops on gentle to strong slopes and which consists of Peaty gleys, peat and some podzols and rankers.

Unit 396. The steep hillside to the south of the mire are dominated by Peaty gleys, podzols and rankers of soil map unit 396, which develops on steep rocky hillsides.

The immediate influences on the mire geochemistry therefore are those of organic, acid, base poor sediments. However, the physical and chemical characteristics of the calcareous soils of the Frazerburgh Series which lie down the valley to the west, the direction of the prevailing wind, must also be taken into account as these represent a potentially moderating influence on the mire environment. The soils of the Frazerburgh series consist of three soil map units, 259, 260 and 261 the component soils of which are Brown Calcareous Soils, Calcareous Regosols and Calcareous Gleys. When disturbed the component materials of these soils may be easily eroded and transported by wind. Human disturbance of the coastal soils may therefore be recorded in the geochemistry of the valley head mire.

Core description.

A 5.00 metre core was retrieved from the deepest area of the mire using a Russian peat corer. Two complete cores were taken using a 25 cm overlap between each sample. Each core was wrapped in a polythene sheet, labelled and placed in plastic guttering for protection. The base of the mire was reached but the auger was unable to retrieve the basal 15 cm of sediment.

0-15 cm. Active root zone of surface vegetation. Plant macro fossils of *Eriophorum*, *Molinia* and *Sphagnum*.

Clear transition.

15-27 cm. Highly organic, abundant fine - medium roots. plant macro-fossils *Eriophorum*, *Molinia* and *Sphagnum*. Poorly humified. Low mineral content.

Gradual transition.

27-60 cm. Highly organic, poorly humified, but highly comminuted organic matter. Common roots, low mineral content. *Ericaceous* plant macro-fossils.

Gradual transition.

60-64 cm. Highly organic, poorly humified but highly comminuted, common medium roots. Shell sand.

Gradual transition.

64-80 cm. Highly organic, poorly humified. Common fine-coarse roots. Shell sand.

Gradual transition.

80-175 cm. Highly organic, well humified. Rare roots.

Gradual transition.

175-206 cm. Highly humified organic material, stones and shell sand. Woody macro- fossils.

Gradual transition.

206-215 cm. Laminated peat . Highly organic, low mineral content. Rare roots. Rare plant macro-fossils. Low mineral content.

Sharp transition.

215-275 cm. Well humified peat. No mineral content.

Gradual transition.

275-380 cm. Well humified organic matter. *Phragmites* roots

Sharp transition marked by *Erica* roots.

380-440 cm. Organic lake mud. Gyttja. Common tree roots and bark.

Sharp boundary

440-469 cm. Poorly sorted inorganic sand and occasional organic laminae.

Gradual transition.

469-480 cm. Well sorted sand/silt. Low organic content.

Sharp transition.

480 488 cm. Poorly sorted coarse sand, low organic content.

Sharp transition.

488-496 cm. Fine silty sand. Organic laminae

Gradual transition.

496-500 cm. Organic silty clay. Fine plant macro- fossils.

Tephra distribution. [Figure 9.2]

Samples were prepared and tephra extracted from the core following the method outlined above. Tephra concentration throughout the core was low [See Figure 9.2]. The peak concentration, 13 grains, was located between 370-380 cm. A second peak, of six grains, was identified between 70-80 cm. These levels were sub sampled, but no tephra was identified in any of the sub samples. Insufficient tephra was isolated to allow geochemical analysis of the shards or and attempt tephrochronology [Westgate & Gorton 1981], a problem which has been encountered by other workers [Hall *et al.* 1993]. The distribution of the tephra within the core is too low to allow a reconstruction of depositional processes involved [Thompson & Bradshaw 1986].

Sediment Geochemistry.

The geochemical history for the entire core is presented in Figure 9.3a & b. However for ease of analysis the core has been broken down into a series of Chemizones, each of which has an accompanying figure which allows detailed examination of the trends and associations in each chemizone.

Chemizone BV1 380-500 cms [Figure 9.4a & 9.4b].

Summary.

This chemizone can be subdivided into two sections. Section A, between 460 - 500 cms, is dominated by elements which indicate mechanical erosion, **K**, **Al**, and **Si**. Whilst Section B between 450 - 390 cms is dominated by elements which indicate the chemical weathering of a soil profile, **Ca**, **Mn**, **Fe**, **S** and the influence of the sea **Al**, **Cl** and **Na**. Elements which feature little in this zone are **Cu**, **Zn**. The division between the two sections corresponds precisely to a sharp change in the nature of the material in the core from inorganic sands, clays and silts to organic lake mud. Most of the elements in this chemizone exhibit Dynamic Metastable Equilibrium, in which long-term trends are separated by a threshold to a new equilibrium. This threshold represents a significant change in the environment in the Borve Valley.

Interpretation.

Chemizone BV1 records two distinct environments which are sharply divided at 450 cms. The lower is characterised by minerals which indicate episodic mechanical erosion and an unstable landscape; and the upper is characterised by an increase in the proportion of elements which indicate chemical weathering processes.

Chemizone BV1A. Glacial / Post Glacial conditions.

Peaks in **K**, the principal indicator of mechanical erosion, suggests that two phases of mechanical erosion occurred; the first at the base of the core at 500 cm, 23 %, and the second at 470 cm 27 %, which had ceased by 460 cms. These are the highest proportions of **K** in the entire core and are separated at 480 cm by a low proportion, 5 %. This depositional pattern has been observed in other studies, most notably those of Mackereth [1965, 1966] and Pennington [1972] and has been interpreted as the consequence of the climatic oscillations which marked the Late-Glacial/Holocene transition.

Further evidence of climatic fluctuation is provided by the behaviour of **Na** and **Mg**. These elements can be used an indicator of the oceanicity of climate [Waterston *et al.* 1977]. The proportion of these elements in the core can be seen to increase steadily from the base of the core upwards and this may reflect a change in the pattern of atmospheric circulation, from one where atmospheric circulation originated in the continental interior to one where the atmospheric circulation originated over the oceans.

Peaks in the proportion of **K** which occur at the base of long cores extracted from northern or western basins in Britain are conventionally interpreted as indicating cold conditions and intense solifluction [Atkinson & Haworth 1990; Engstrom & Wright 1984; Pennington 1981 a & b]. The pattern of **K** presented in Chemizone BV1 would therefore represent two cold periods separated by a episode of warmer climate when processes of solifluction are reduced In immediately post-glacial periods, with immature soil development and little soil stability or vegetation the sediments are easily transported by aeolian and fluvial processes. The proportion of **K** in the core therefore, declines as soils and vegetation cover develop. As soils and vegetation develop the erosion of sediments becomes less likely and the thresholds at which erosion will occur are raised. If this hypothesis is accepted, the pattern of **K** at the base of Borve bog indicates two periods of recovery from glacial/periglacial conditions. The lowest was ended by a return to cold conditions, the second was ended by the evolution of soils and the raising of the threshold at which mechanical erosion of catchment sediments occurred.

Aluminium has several sources and may suggest mechanical erosion, the influence of the sea, or the paludification of catchment soils. The interpretation of **Al** therefore relies on the nature of the associated elements. In this chemizone **Al** is initially associated with peaks and troughs in **K**, but when the influence of **K** on the sediment chemistry diminished at 450 cm, the proportion of **Al** in the core remained high. The behaviour of **Al** above 360 cm may be associated with an increasing influence of the sea, indicated by the pattern of deposition of **Na**, . However, **Al** is also associated with the proportion of **Si**, which is an indicator of mechanical erosion. The behaviour of **Al** in this chemizone is therefore slightly ambiguous.

Silicon may also have several sources; either as a product of mechanical erosion, or from the skeleton of diatoms and hence related to biological productivity. A decline in **K** in post-glacial lake sediments has been noted by Mackereth [1965] and Engstrom [1983] and is thought to be the result of the dilution of the base metal proportion of the core by an increase in biogenic production of **Si**. Alternatively, the peak in Si at 480 cm may be an artefact of the analytical technique and be the result of the decline in **K**, **Al** and **Na** rather than an increase in biological activity or erosion.

The pattern of elements in this zone may record the Windermere Interstadial and Loch Lomond re-advance, as experienced in the Outer Hebrides. The pattern of elements identified in this zone is strikingly similar to the pattern observed at Loch Hellisdale, above, and by Bennett *et al.* [1990].

Chemizone BV1B. Full Holocene conditions.

The transition between the two chemizones is distinct occurring at 460 cm. The elements which feature prominently in this zone indicate the operation of chemical processes in a developing soil rather than physical processes operating in an immature landscape.

There is a sharp decline in the proportion of **K** at 460 cm from 27 % to 2 %, and an equally sharp decline in **Al** and **Si**, at 460 cms. The physical processes which are characteristic of the environment in chemizone BV1A are no longer indicated by the geochemistry above 460 centimetres; instead there is a increase in the proportion of **Ca**, **Na**, **Mg** **Fe**, **Mn** and S. These elements are not precipitated under cold conditions, nor are they commonly associated with the physical erosion of soils, or the chemical weathering of immature soils [Engstrom & Wright 1984]. They are however precipitated from organic soils under relatively warm, moist conditions. It is interesting in this respect that calcium was deposited in the basin at 460 cm, twenty centimetres before **Fe** proportions in the core increased and thirty centimetres before the proportions of S proportions increased. Calcium is a base which is selectively leached from a soil as acidity increases and before mobilisation of **Fe**, **Mn** and S occurs. The mobilisation of **Fe**, **Mn** and S at 440 cm depth implies the existence of organic acid soils early in the Holocene history of the Outer Hebrides.

The proportion of **Cl** in the core increases at 430 cm from 0.2 % To 1.4 %. The principal source of this element in sediments is sea water. In the case of Borve bog this must indicate rainfall patterns or intensity and is closely associated with the proportion of **Na** and **Mg** in the sediment which are also deposited as dilute rainfall in sea water [Waterston *et al.* 1977; Maitland & Holden 1983].

Pollen analysis

The pollen analysis corresponds with the geochemistry in that two distinct environments are represented. The lower zone is characterised by Polypodiaceae, Caryophyllaceae, Rumex and Salix spp. and by low pollen concentrations. This is a suite which has been ascribed to the early Flandrian in other studies of the Hebridean environment [Birks 1991] and is in broad agreement with the interpretation of the sediment geochemistry in chemizone BV1A.

The geochemical evidence indicates the existence of a sharp boundary between Late-Glacial and Holocene environments, which is outlined in Chemizones BV1A and BV1B. This change is also apparent in the palynology. Pollen concentrations rose dramatically in the sediments associated with chemizone BV1B, and the pollen suite was dominated by Cyperaceae, Gramineae, Ericaceae and Sphagnum. This suite suggests the onset of a mire environment and base poor sediments, which is entirely in accord with the geochemistry.

Summary Chemizone BV1

This chemizone records the climatic fluctuations at the end of the Late-Glacial, the rapid start of the Holocene, the formation of soils and soil acidification and the increasing influence of the sea on sediment chemistry.

Chemizone BV2. Tephra impact?

This chemizone was delineated by the tephra concentration identified between 370 and 380 cm. No tephra was identified when sub samples were examined under either an optical or Scanning Electron Microscope, and tephra could not be concentrated sufficiently to attempt tephrochronology, a problem which has recently been encountered by other workers [Hall *et al.* 1993]. The geochemistry of the sub-samples was ascertained in an attempt to identify any environmental disturbance which may have occurred in this zone.

Summary. [Figure 9.5a & b]

The proportions of **Ca**, and **Mg** declined throughout this zone from 380 to 371 cm before increasing at 370 cm. Between 371 and 370 cm **Mg** rose from 3% to 17%, and **Ca** from 4.5% to 12.8%.

The proportions of **Mn**, **Zn**, **Cl** and **Na** behave in tandem in this chemizone, peaking at 379 and 377 cm. With the exception of **Zn** these elements also peak at 370 cm. High proportions of S and **Fe** dominate the sediment chemistry between 375 and 372 cm. **Cu** is present at very low concentration and remained below 0.5% until 370 cm, when it climbed to 1.6%. **Ni** does not exhibit any interpretable trend. **K, P, Ti,** and **Si** also behave in tandem in this chemizone peaking at 378 and 376 cm. **Al** parallels this trend but the peaks are not as pronounced. With the exception of **Al** most of the elements in this zone exhibit Steady State Equilibrium, and although peaks in the proportion of several elements are evident, no long-term change in trend occurs and the environmental forcing which the peaks represent was short lived. The exception in this zone, **Al**, crossed a threshold at 376 cm and fell to a new, lower, equilibrium.

Interpretation.

There is no evidence of environmental change in response to the deposition of tephra in this chemizone and much of the geochemistry is difficult to interpret. The lower half of this chemizone is dominated by indicators of physical erosion and the upper by indicators of the chemical reduction of soils and acid conditions in the mire.

The geochemistry indicates episodes of soil erosion at 378 and 376 cm with peaks in **K**, **Si**, **Ti**, **P** and **Al**, but these are minor episodes compared to those which occur in chemizones 3 and 5 and which are not associated with tephra deposition. Could an episode of acid deposition, associated with the tephra concentration, have brought about the episodes of soil erosion in this chemizone?

The highest proportions of **Mn** in the entire core occurred before each of the soil erosion episodes. At 379 cm the proportion of **Mn** rose to 2.7% and at 377 cm to 2.8%. However, while the proportion of **Mn** may indicate acid conditions it is not the only element which may do so. Both **S** and **Fe** also indicate the acid status of the mire and are present in far higher proportions than **Mn**. In this chemizone the proportion of **Fe** twice reached 70%, at 374 and 372 cm; the proportion of **S** reached 47% at 375 and 373. **Mn** is the only indicator of acidity which is associated with these episodes of soil erosion, and in the context of this mire the proportions of **Mn** identified cannot be considered to be a major indicator of acid status and acid deposition. A significant change in the acidity of the mire did not occur before the episodes of soil erosion. However, the relative abundance of **Fe** and **S** do indicate that acid conditions returned to the mire following the episodes of soil erosion.

Alternative hypotheses for the episodes of soil erosion are that they were anthropogenic or that they occurred in response to a natural change in the environment. Either of these interpretations is in accord with the palynology described by Pratt [1992] who noted a decrease in *Betula* and *Erica* across this zone and an increase in Gramineae.

In this zone the proportions of **Mn**, **Zn**, **Cl**, **Mg** and **Na** are closely associated. The presence of **Cl**, **Mg** and **Na** indicates that this association is related to rainfall intensity. With the exception of occasional peaks [*i.e.* at 80 cm] the proportion of **Zn** in the core is very low, typically below 0.7% and may have been either deposited as a trace element in rainfall or leached from sediments.

The peak in the relative abundance of **Cu** at 370 cm appears significant when viewed within the limited context of this chemizone, but when seen in the context of the whole core [Figure 9.3a & b.] it is not significant.

The top of this zone, at 370 cm is marked by peaks in the proportions of all the elements which may be used to infer rainfall or the oceanicity of climate; **Na**, **Mg**, **Al**, **Cl**, and **Ca** [Maitland & Holden 1983; Waterston *et al.* 1979]. The proportions of **Mg** and **Al** at 370 cm are the highest achieved by these elements in the entire core and may indicate a short-lived intensification of rainfall or an increase in the oceanicity of the climate.

There is no evidence in this chemizone for any environmental change which may have been forced by the deposition of acid gases and/or aerosols generated in an Icelandic volcanic eruption. However, as only 13 tephra grains were counted from a 10cc sample of material and none in any of the 1cc sub-samples this result was not unexpected. Limited environmental change is indicated by the geochemistry, but this may have occurred in response to an anthropogenic disturbance or to a naturally occurring change in vegetation.

Chemizone BV3. 360-80 cms [Figure Borve 9.6a & b].

This the largest chemizone in the core and incorporates three bands of sediment, identified largely on the degree of humification, but which largely correspond to the geochemistry.

Summary.

This chemizone incorporates two peaks in the proportion of **K**, at 310 cm and 150 cm. The proportion of **K** at 150 cm was the greatest Holocene concentration of this element. **Si** peaked at 310 cm in correspondence with the peak in **K**, but a substantial increase in the proportion of **Si** in the core occurred between 210 and 150 cms, which was not associated with any increase in n K. The behaviour of **Si** in this chemizone was mirrored by **Fe**, and between 210 and 150 cm increases in **Si** correspond with decreases in **Fe**. **Ti** is often used to indicate erosion and here it parallels the trends in **Si** precisely.

The proportions of **Fe** and **S** were high between 360 and 220 cm. Peak proportions of **P** in this zone occurred at 360, 230 and 140-130 cms. The proportion of **P** in the core between 130 and 140 cms was the highest reached in the entire core. The highest proportion of Na, 12 %, in the entire core occurred in this chemizone at 110 cm, but this was not accompanied by rises in **Mg**. Despite this peak consistent changes in the nature of Na did not occur. Peaks in the proportion of **Cu** and **Zn** feature prominently in this chemizone, at 300, 270, 140 and 80 cm, and may be used to suggest a dating framework for this part of the core [Farmer *et al.* 1980; Rippey *et al.* 1982].

Interpretation. Mid Holocene. Anthropogenic land-use intensification.
In this chemizone, most of the elements studied exhibit steady state equilibrium with no net change in equilibrium level. This chemizone therefore is one in which no major environmental change is indicated by the sediment geochemistry. Indicators of the oceanicity of climate, **Na**, **Ca**, **Cl** and **Mg** do not exhibit a consistent change in trend and climatic change cannot be inferred from these elements.

The proportion of **Ca** in Borve bog may not indicate oceanicity but may instead indicate periods when the stability of the dunes and machair of the Frazerburgh series, 3 km to the west on the Atlantic coast, had been disturbed. Two such episodes can be identified; one which begins at 300 cm, peaks at 290 cm, 12%, and returns to a low proportion by 220 cm; and a second shorter lived episode which begins and peaks at 200 cm and returns to a low proportion at 180 cm. This episode is matched by the physical characteristics of the core, fine mineral material, interpreted as sand blow from the coast was noted between 200 and 183 cm. The organic content of the core fell at this point to the lowest of the Holocene [Figure 9.7]. There is no relationship between high proportions of **Ca** in this zone and **S**, **Fe** and **Mn**. The deposition of **Ca** in this zone, does not appear to have had an impact on the mire environment as reflected by the proportions of **Mn**, **Fe**, **S** which indicate acidity.

The changing environment of the mire is indicated by **Mn**, **Fe**, **S** and **Si**. A rise in pH levels between 210 -150 cms is indicated by a consistent increase in the proportion of **Si** in the core and fall in the proportion of **S** and **Fe**. The cause of this recovery is not evident in the geochemistry. The physical characteristics of the core are in accord with the interpretation of the geochemistry and between 207 and 150 cm wood macro fossils were identified. Trees growing on the mire surface would indicate that the mire environment was drier and that pH had risen sufficiently for trees to grow.

Between 150 - 140 cms the proportion of **Si** in the core fell from 50% to 15% while the proportion of **S** rose from 2% at 160 cm to 48% suggesting a return of acid conditions. There is no evidence that this episode is linked to increased rainfall. However, the increase in the proportion of geochemical indicators for acid conditions in the core is associated with the greatest Flandrian peak in the proportion of **K** at 150 cm, (17.8%) and an inwash of clay sediment into the core. **Si**, **Ti**, and **K** exhibit Dynamic Metastable Equilibrium; a threshold was crossed at 210 cm and a higher, dynamic equilibrium achieved. A second threshold was crossed at 150 cm, above which a new, lower dynamic Equilibrium was achieved. The proportion of **K** changes dramatically at this point, falling from a proportion of 17% at 150 cm to 0.4% at 160 cm.

All three elements which exhibit dynamic metastable equilibrium indicate a significant disturbance of the local landscape, which began at 230 cms, intensified, peaked at 150 cms and ceased suddenly by 140 cm. In the context of the Borve valley this episode may indicate an anthropogenic disturbance of the environment which gradually grew in intensity but ceased over a relatively short period of time.

If the increase in the proportion of **K** is interpreted as the result of anthropogenic disturbance of the landscape, the major peak in the proportion of **P** which occurred between 150 - 120 cms may be reflect the utilisation of the landscape by people. The increase in the geochemical indicators for acid conditions in the mire may therefore be the result of increased water run-off following a clearance episode. If the anthropogenic interpretation is pursued, the decline in the relative abundance of **P** at 170 cm may indicate a reduction in land use intensity. The palynology of this zone appears to support this interpretation (see below).

Several peaks in **Cu** and **Zn** occurred in this zone. These elements are allocthonous to the mire and the conventional interpretation for increases in the concentration of **Cu** and **Zn** in sediment cores is that they indicate the onset of industrial activity in Europe [Rippey *et al.* 1982]. In remote western and northern parts of Scotland such deposition has been dated to the 1880's, but these episodes occurred at relatively shallow depths [Rippey 1990] whereas in Borve bog a prominent peak in **Cu** and **Zn** occurred at 270 cm, which is very deep to be ascribed such a recent date. Peaks in these elements suggest a source which is allocthonous to the mire. They must considerably predate the industrial revolution. In this respect it is worth noting here that a similar peak in **Cu** occurred at 270 cm in the core retrieved from the Strath of Kildonan, in Caithness [Discussed below]. Both elements achieved their highest proportion at 80 cm depth.

Palynology.

In Pratt [1992] an increase in the proportion of Gramineae pollen in a core was interpreted as the result of anthropogenic modification of the environment. A Gramineae peak at 140 cms corresponds with a major increase in the proportion of **P** in the core, from 0.5 to 9 %. Although the interpretation of P in sediment geochemistry is problematic it is often interpreted, when in tandem with other evidence, as evidence for human activity and an increase in the inwash of nutrients into a mire. Thus the peak in **P** between 130-140 cms and the corresponding increase in Gramineae may indicate anthropogenic of the upper Borve valley.

Chemizone BV4.

This chemizone is delineated because of the concentration of tephra noted in the analysis of a bulk sample taken between 70-80 cm. When sub-sampled no tephra was noted in any of the samples examined under either optical or scanning electron microscope.

Summary. [Figure Borve 9.8a & b]

No significant changes in the environment are indicated in this chemizone. Indicators of soil erosion and stability **K** and **Ti**, fell to below 1% at 79 cm and throughout this zone they exhibit stable equilibrium. Proportions of **Si** are also low, below 2% with the exception of 7% reached at 76 cm and 22% reached at 72 cm. The peak of 22% which occurred at 76 cm is low compared to the proportions achieved in chemizones 1, 3 and 5; In this zone **Si** exhibits dynamic steady-state equilibrium, and none of the peaks indicate the occurrence of long term environmental change.

Ca proportions between 79 and 74 cm are high and reached 13.6% at 79 cm, but slowly declined to a low proportion of 2% by 71 cm. Between 79-71 cm **Ca** exhibits dynamic metastable equilibrium with a declining trend, and this event may represent a long term environmental change.

The proportions of both **S** and **Fe** are consistently high in this chemizone and also exhibit dynamic metastable equilibrium, the proportions of both are maintained at the higher level until 70 cm. A minor increase in the proportion of **P**, 1.7% occurred at 76 cm. **Al** proportions rise throughout this zone. The proportions of **Cu** and **Zn** remain at background levels throughout. No trend is discernible in the proportions of **Na**, **Mg**, **Cl** or **Mn**.

Interpretation. No environmental response to tephra deposition.

There was no evidence in the sediment geochemistry that the deposition of six tephra grains was associated with a detectable disturbance of the environment. No soil erosion occurred, indeed the geochemistry suggests that the landscape remained stable throughout this zone. The mire environment appears to have returned to acid conditions, indicated by the high proportions of **Fe** and **S**, but there is no evidence that this is the result of the deposition of acid material from an Icelandic volcanic eruption. The increase in the proportion of **Ca** in this zone appears to have had no effect on the proportions of **S** and **Fe**. In the absence of indicators of rainfall, the most probable source for the trend in **Ca** is the calcareous soils of the Frazerburgh series. The higher equilibrium achieved by **Ca** in this zone may indicate a disturbance to these soils and subsequent erosion by wind. The deposition of **Ca** was not at a sufficiently high concentration to reduce the acidity of the mire as indicated by the proportions of **S** and **Fe**. There is a slight increase in the relative abundance of **Si** at 72 cm. This may be the result of a concentration of tephra in the core, but none was observed in this sample when studied under a Scanning Electron Microscope, and this increase may not be environmentally significant. The values of **S** and **Fe** peaked at 71 cm. This may indicate acid deposition associated with tephra deposition, but given the normal range of the proportions of these elements, significant environmental forcing by an external mechanism is unlikely. After peaking at 80 cm the proportion of **Cu** and **Zn** in the core indicates that the deposition of atmospheric contaminants, originating in industrial pollution, was not a significant external factor operating on the mire environment. An increase in the percentage content of **P** occurred at 76 cm. It is difficult to assign any significance to this peak given the slight nature of the increase when compared to the proportions of P in chemizones 3 and 5.

The geochemistry in this zone demonstrates that the presence of tephra in a sediment core is not sufficient evidence to imply the occurrence of an episode of environmental change.

Palynology.

The palynology fails to highlight any changes to the environment in this zone. Cyperaceae values remain constant, *Ericaceae* values fall and Gramineae rises slightly.

Chemizone BV5. 0-70cm [Figures 9.9a & B].

Summary.

The proportions of the indicators of rainfall, **Na** and **Mg**, decline consistently throughout this chemizone from 60 to 10 cm and exhibit dynamic equilibrium with a declining trend, before increasing at the mire surface. **Cl**, another element which may suggest rainfall remains relatively stable throughout this chemizone, but the percentage of this element also increases at the mire surface, from 0.1% at 10 cm depth, to 7% at the surface. The pattern of **Al** in this zone is paralleled by **Ca** which suggests that both elements had the same source.

The base status of the sediments and the stability of the catchment soils are indicated by **K**, **Ti** and **Si**. The percentage of **K** increases between 60 and 30 cm, rising to 5% at 30 cm, which suggests a slight but consistent disturbance of the landscape. The proportions of **Ti** and **Si** also increase between 60 and 20 cm. Above 20 cm the proportions of all three elements decline. The relative abundance of **P** increased at 60 cm, to 2.8%, and remained high until 10 cm. This increase represents a consistent change in the deposition of **P** in the core, rather than a short lived peak.

Acid conditions are indicated by **S**, **Fe** and **Mn**. The proportions of **S** and **Fe** are low in the bottom section of this zone, up to 24 cm and high in the upper section, from 24 cm to the top of the core. The proportion of **Mn** does not respond in tandem with **S** and **Fe**.

No peaks in the proportion of **Cu** and **Zn** occur in this zone.

Interpretation. Recent Anthropogenic exploitation.

Indicators of base input, soil erosion and anthropogenic activity, **K**, **Ti**, **Si** and **P** dominate this chemizone between 60 and 30 cm, above 30 cm the percentages of these elements decline, whereas the elements which indicate acid conditions, **S** and **Fe**, recover.

The increase in the relative abundance of **K**, **Si**, **Ti** and **P** between 60 and 30 cm suggests that a slight but significant disturbance of the upper Borve valley continued throughout the time represented by this sediment accumulation. All four elements exhibit Dynamic or Metastable equilibrium. In each case a threshold was crossed at 60 cm, which was followed by a period of stability, when the increased proportion of these elements was maintained. The percentages of **K**, **Si** and **Ti**, cross a second threshold at 30 cm and decline, **P** crossed a threshold at 20 cm, following which the proportion of this element also declined. Human use of the upper Borve valley may be the source of this episode. The lower Borve valley and the littoral zone at its mouth contains the most fertile soils on the island of Barra and the use of these may have been accompanied by a disturbance of the upper valley. The trend in the proportion of **Ca** in this zone does not suggest that the soils of the Frazerburgh series had been disturbed to any extent. A change in land-use strategy rather than an increase in population, or degradation of more fertile soils, may therefore have been the impetus for the exploitation of the valley head. The geochemistry suggests that the exploitation of the valley head has declined in recent years, this is in accord with the observations of Caird [1979] and Dodgshon [1988].

At 30 cm, indicators of acid conditions in the mire increase, this may be concomitant to the decline in the proportion of base indicators in the core or reflect a real increase in the acidity of the mire. The geochemical trends in the upper 20 cm of the core are difficult to interpret, the upper 15 cm of the core is obviously part of the active root zone of the current mire surface and the influence of present day conditions on the geochemical trends in the core must be considered.

The proportion of **Cu** and **Zn** suggests that the deposition of industrial pollutants has not played a significant role in the production of the acid status of the mire environment.

The obvious change in the trends of most elements in the core at 19 cm suggests that the acrotelm [Ingram 1978, 1987] lay between 10 and 20 cm. The **acrotelm** is the upper sedimentary zone, where depositional processes are ongoing, in contrast to the **catotelm** which is all the sediments below the acrotelm which are considered to be geochemically stable [Ingram 1978, 1987]. An analysis of the chemistry of the acrotelm cannot usefully be compared to the sediment chemistry of palaeo-sediments.

Discussion.

Sediment geochemistry, anthropogenic activity and environmental change in the Borve valley.

Geochemical trends in the core.

The analysis of the sediment geochemistry of Borve bog has shown that the application of EDMA to mire sediments, as opposed to lake sediments, allows the reconstruction of general environmental trends and specific episodes of environmental disturbance. **K, Ti, Si** and **Al**, can be seen to act in tandem and record short lived episodes of landscape disturbance, and also longer periods when these elements achieved a new equilibrium indicative of persistent disturbance. The geochemical trends also help to highlight the nature of the forcing mechanisms responsible. Episodes associated with the establishment of new equilibria may indicate climatic change, vegetational change, soil evolution or human activity. Anthropogenic disturbance is most clearly suggested between 260 and 140 cm. Landscape disturbance of the coastal zone may be indicated by the proportion of **Ca** in the core. **Ca** exhibits dynamic metastable equilibrium, and episodes of high or low equilibria may represent the long term stability of the soils of the Frazerburgh series.

Peaks in the proportion of **P** are difficult to interpret as this element may be co-precipitated with other elements. However, there are episodes where peaks in **P** are associated with other indicators of anthropogenic disturbance, between 150 - 120 cm and 60 - 20 cm. In these cases **P** may be associated with the activities of people in the landscape.

The indicators of acid conditions and soil reduction, **S**, **Fe** and **Mn**, exhibit dynamic metastable equilibrium. **S** in particular has a high proportion between 430 - 230 cm and 100 - 71 cms, decreasing to lower equilibria outside these zones. The high abundance of **S** in the core from 430 cm onwards suggests that the soils of the upper Borve valley were acidic very early in the Holocene, an observation which is supported by the palynological evidence [see Pratt 1992 and Figure 9.10].

Trends in rainfall are more difficult to reconstruct than episodes of landscape disturbance. **Na**, **Mg** and **Cl** largely exhibit steady state equilibrium, however, some trends are discernible. The Late-glacial/Holocene transition is clearly indicated by an increase in **Cl**, which is the only element which is unequivocally associated with rainfall, and which may indicate a distinct change in the degree of oceanicity of climate.

Episodes of landscape stability and instability are clearly identified at the base of the core, which clearly correspond to the patterns of Late-glacial/Holocene transition previously identified by Mackereth [1966] and Pennington *et al.* [1972] on the British mainland. These trends were also identified in the pilot study conducted on material retrieved from Loch Hellisdale on South Uist, but here the wider range of elements studied allows a more detailed appraisal of this climatic episode.

Industrial activity?

The proportions of **Cu** and **Zn** in the core are typically regarded as useful indicators of industrial pollution, and may therefore be used as isochrones [Holdren *et al.* 1984; Rippey 1990]. Peaks in the proportion of both elements occurred at 300 cm, 270 cm, 140 cm and 80 cm. There is a constant background concentration of both elements and at these concentrations there is little association between the two elements [See Chemizone BV2]. However, the correspondence between peak proportions of these elements suggest that when the proportions of both rise above background concentrations they have the same origin, and this is most probably anthropogenic in origin; this interpretation does however present problems of dating. Conventional dating of concentrations of either elements would ascribe a date in the 19th century AD [Rippey *et al.* 1982], but it would seem unrealistic to assume that 3 metres of sediment had accumulated in the last 200 years and only 2 metres in the preceding 10 000. The palynological study by Pratt [1992] also suggests that the sediments were laid down in the mid-Flandrian Perhaps the peaks at 270 and 300 cm have their origin in the smelting of metals in the European Bronze age?. The source for these concentrations is an interesting research problem and in this respect it is interesting to note that the similar length core extracted from the Strath of Kildonan, Caithness, also has a substantial peak in **Cu** at, curiously and coincidentally, 270 cm. A study of other cores is obviously needed to address this problem., Irrespective of the dates ascribed to the peak proportions of these elements, the low proportions in the upper 80 cm of the core suggest that the deposition of industrial contaminants has not played a significant role in the modification of the environment at the head of the Borve valley.

Geochemistry and Palynology.

The relationship between the geochemical and palynological interpretations of environmental history of the Borve valley are complimentary. The summary presented by Pratt [1992], Figure 9.10 here, suggest that peaks in Gramineae occurred between 120-150 cms, 200-220 cms and at 320 cm. The Gramineae peaks correspond to episodes when the geochemical indicators of physical landscape disturbance exhibit dynamic metastable equilibrium, cross a threshold and achieve and attain a higher equilibrium expressed by a consistently higher proportion in the core [Figure 9.3a & b]. These episodes suggest a clear relationship between the vegetational and geochemical history and may indicate the modification of the landscape by people. A detailed comparison of the geochemical and palynological history is beyond the scope of this immediate project, but will be made at a later date.

Correlation Hellisdale and Borve.

A clear and striking relationship can be seen between the geochemical history of the Borve bog and Loch Hellisdale. Both cores illustrate the Late-Glacial/Holocene transition, record the chemical weathering of catchment soils and mid-Holocene episodes of soil erosion which may be anthropogenic. However a clear difference can be observed in the degree and timing of the acidification of both environments. Borve mire appears to become an acid environment very early in the Holocene, whereas Loch Hellisdale does not acidify until relatively recent times. However, these trends are in accordance with recent observations made of the timing and nature of lake and sediment acidification [Battarbee *et al.* 1985]. Many lakes set in the midst of catchments dominated by acid soils and peats which developed in the mid-Holocene, maintained a near neutral pH until the onset of the industrial revolution and the subsequent deposition of industrial contaminants, predominantly acid rain [Battarbee *et al.* 1985; Renberg 1990]. In both locations the EDMA has identified processes operating within the local environment such as soil erosion and soil development and identified processes which are allocthonous to the immediate environment, such as the deposition of industrial pollutants, and climatic change. The relationship between the two sets of analyses has been a further successful test of the application of EDMA to the reconstruction of palaeoenvironments and of the replicability of the technique.

Tephra.

Tephra concentrations identified throughout the core were very low and only identified in the analysis of bulk samples. No attempt has been made to interpret the tephra distribution in the core given the sparse concentration. It proved impossible to isolate sufficient under the Electron Beam of the Scanning Electron Microscope to attempt to establish the provenance of the eruption. Given the low numbers of tephra in the core it is not necessarily the case that the tephra identified here identified here originated in Iceland [Rietmejer 1988, 1990; Rose & Chesner 1990]. Despite the lack of tephra related environmental change in the sediment-geochemistry, some episodes of environmental change were identified at Borve and the technique has been shown capable of producing results which will allow meaningful interpretation. A core of similar length was extracted from a mire in the Strath Of Kildonan. Sufficient tephra was extracted from that core to allow a meaningful investigation of environmental responses to tephra deposition.

Chapter ten.
Geochemical investigations of the Strath of Kildonan.

Summary of chapter.

The palaeoenvironmental history of the Strath of Kildonan is reconstructed by an examination of the geochemistry of sediments which had accumulated in a basin, below a prehistoric settlement. The geochemistry suggests that the sediment has accumulated since the Late-Devensian Late-Glacial. A detailed reconstruction of the climatic oscillations which characterise this period is made. In the Strath of Kildonan, the climatic oscillations appear to be typical of continental rather than British models of this period. The geochemistry of the Holocene sediments suggest that most environmental change in this area has been of a gradual, rather than abrupt nature. The significance of this for models which draw sharp boundaries between palaeoenvironmental facies is considered. Three tephra concentrations were identified in the core, and these were examined in detail. Tephra concentration was established by a physical count, using an optical microscope. A striking correspondence was noted between the geochemical proportion of Si in the core, and the physical count of tephra. This is a further test of the replicability of the EDMA results. The geochemical analyses suggests that two of the tephra concentrations did not cause any environmental change. However, one tephra deposit does appear to have triggered an environmental disturbance. This episode is considered in detail. Human use of the landscape is suggested by increases in the phosphate content of the core and by episodes of soil erosion. An intriguing concentration of copper occurs at depth in the core, and a tentative suggestion is advanced that this may record smelting activities in pre-history. A regional environmental correlation between the Strath of Kildonan in Caithness, Borve bog on the island of Barra and Loch Hellisdale on the island of South Uist is established.

The Strath of Kildonan, which lies along the border between Caithness and Sutherland is central to the whole theory that an environmental catastrophe occurred in the late 2nd millennium B.C. Research conducted by **Historic Scotland** identified up to 2000 hut-circles along the Strath, which appeared, in the light of the historical evidence, to have been abandoned concurrently. The archaeological justification for this thesis has not been presented in peer reviewed press and may be open to challenge. How accurate is the archaeological evidence that simultaneous abandonment of settlement can be hypothesised? There is however no doubt that the Straths and Glens of northern Scotland were densely settled in the mid second millennium [Barclay 1985] and that an hiatus in settlement is apparent in the archaeological record across much of this area in the late second millennium B.C. and large areas of upland and northern Britain [Burgess 1985]. The archaeological interpretation of the upland settlement record led to several theories, most of which suggested a catastrophic event as the trigger for settlement abandonment [Burgess 1895]. The most recent of these has been the hypothesis that distant volcanic eruptions brought about sufficient environmental degradation that the abandonment of marginal settlements was inevitable [Burgess 1989; Baillie 1989 a & b] an hypothesis which has attracted the attention of the National press [Keys 1988] and television [BBC Television Programme **Horizon:** *A Time of Darkness;* Channel 4, Archaeological Magazine *Down to Earth*] and the funding which has supported this research.

To finally test the application of EDMA to the study of palaeoenvironmental change, and the hypothesis that the Icelandic Hekla 3 eruption was responsible for the postulated abandonment of the settlements along the Strath in the late Bronze Age, it was inevitable that at least one core should be extracted from a suitable location in the Strath of Kildonan [Figure 10.1]. A core was extracted from a basin mire on the south side of the Strath at National Grid Reference NC917194. The mire had formed in a basin created between a lateral moraine, of uncertain date, and the adjacent hillside. Hypothetically, therefore, the oldest basin sediments may have their origin in Devensian Late-Glacial and accumulated across the Late-Glacial/Holocene transition and throughout the Holocene. The mire site had the added attraction that it lay below a settlement of Bronze Age date [John Barber *pers. comm.*]. The sediments in the core extracted from this location may therefore cover the late-Glacial/Holocene transition, the evolution of the north Scottish environment through the Holocene, the impact of people upon this environment, and should record any "drastic" environmental change. The site of Altnabreac from which tephra had been extracted previously [Blackford 1993; Dugmore 1989] lay 15km to the north-west, and tephra may therefore have accumulated in this basin.

Method.

The mire was probed to establish the deepest point, and a 4.9 metre core was then extracted using a large chambered Russian peat corer. A 25 cm overlap was established between each sample and three sampling points used to ensure minimal disturbance of the sediment. Each sample was placed in a plastic gutter and then wrapped in heavy duty polythene.

The Physical Environment.

Parent Materials.

The geological structure of the Strath consists of faulted sandstones and conglomerates, of variously Middle Devonian and Moinian age, igneous rocks also occur [Phemister 1960]. More than 80% of the district is covered by surficial deposits associated with Pleistocene glacial activity, but the fabric of this material is largely reworked local bedrocks. The soils of the district then are formed on weathering-resistant, base-poor acid rocks, granites, granulites and schists, and sedimentary rocks which are more easily weathered but still base-poor [Futty & Towers 1982; Hudson 1988]. The district has been extensively modified by ice movement, and there is an extensive covering of drift and till. In the Strath of Kildonan, this process has introduced erratics of quartzite, sandstones and grits.

Climate.

The principal climatic variables controlling the sedimentary environment of the Strath are rainfall and temperature. Average annual rainfall is in the range of 1200 mm and although winter temperatures at low altitudes are mild, these are offset by cool summers [Birse 1970]. The environment of the glen itself has been assessed by Birse [1970] as Boreal and very humid.

Soil Map Units.

The geomorphology, land use, altitude and degree of exposure to wind all determine the distribution of soil types in the area. On morainic mounds peaty podzols are found, while deep peats occur where moraines and underlying relief have acted together to create deep basins. The soil associations of the valley are complex. Relief, drainage and parent material combine to produce a wide range of related soil types. These are mapped in Futty and Dry [1977] and Futty and Towers [1982]. A common denominator however, is that with the exception of some alluvial soils, all are base- deficient and acidic and support a limited range of moor land vegetation, heather, sedges, grasses and mosses. Cotton grass grows at the sample site. The limited range of modern vegetation probably presents a false impression of the vegetation which could grow here. In the valley of the Craggie Water, protected from grazing pressure, extensive birch woodland can be found. These trees grow within 200 metres of the sample location.

A. Well drained Brown Earth. Mapped as unit 71, of the Braemore/Kinsteary Associations, these are well-drained to imperfectly-drained soils on shallow drift and well-weathered parent material. The base status of this soil varies from moderate to good. This soil is found on gentle slopes and is associated with hummocky moraine. In intervening hollows gleys and peats formed. These soils are closely associated to Bronze Age settlements

B. Imperfectly drained Brown Forest Soils and Humus-iron podzols, mapped as unit 25 of the Arkaig Association. Formed on hummocky moraine, boulderiness and wetness restrict land use to rough grazing.

C. Peaty podzols and deep peat mapped as unit 26 of the Arkaig association. These are formed on hummocky moraine and in the basins formed between the moraines and hillsides of the Strath. This unit has extremely limited land-use potential and is largely limited to Deer Forest and Conifer Plantation. The core analysed below was extracted from a deep peat typical of this unit.

D. Humus iron podzols, gleys and rankers mapped as unit 125 of the Countesswells/Dalbeattie/Priestlaw associations. Formed on colluvium these soils are marginal for anything other than rough - moderate grazing and have a low to moderate base status.

E. Organic Soils form a part of most of the soil associations mapped in the Strath and the dates for the onset of peat growth are an interesting measure of the evolving environment of the Strath. An unpublished survey carried out by Historic Scotland, produced a wide range of Radio carbon dates for peat initiation, from 5370 ± 60 BP to 880 ± 90 BP. The location of these peats are located along the transect marked on Figure 1. [Table 1].

The range of dates for peat initiation along the Strath, demonstrates the need for caution, when using the date for onset of peat formation in one site, as indicative of palaeoenvironmental conditions existing across a wider area. Local micro-environmental conditions are demonstrably more important in the Strath of Kildonan, than macro-scale factors such as regional soil development, mean temperature and rainfall.

5370 ± 60 BP
4650 ± 50 BP
4320 ± 80 BP
4150 ± 50 BP
3600 ± 50 BP
2860 ± 150 BP
2630 ± 50 BP
1730 ± 50 BP
880 ± 80 BP

Table 10.1. Radio carbon dates for Peat initiation in the Strath Of Kildonan.

The sediment texture, organic content, degree of humification and plant macro-fossil type can be used to construct a model of climatic and environmental change. The environmental implications of the sedimentary succession can be interpreted and can be set against the geochemical history presented below.

Core description

	Youngest
0 - 10 cm.	Growing surface of the bog (Acrotelm). Abundant coarse roots, little humification.
	Clear boundary.
10 - 35 cm.	Organic sediment. Abundant fine roots, well humified peat.
	Diffuse boundary.
35 - 100 cm.	Organic sediment. Abundant tree macro fossils in well humified matrix *Betula* twigs. *Corylus* nut at 69 cm. At 90 cm Abundant large (3 cm - 1.5 cm) fragment of wood and bark.
	Sharp boundary.
100 - 130 cm.	Organic sediment. Well humified, rare wood macro fossils, *Betula* / *Pinus* twig.
130 - 215 cm.	Organic sediment. Well humified. Rare fine roots. No tree macro fossils.
	Diffuse boundary.
215 - 272 cm.	Poorly humified organic sediment. Abundant coarse roots. No tree roots, but abundant tree bark.
	Diffuse boundary
272 - 282 cm.	Organic Sediment. Common tree twigs or root (*Betula*)
	Diffuse boundary.
282 - 320 cm.	Organic sediment. Well humified, common fine roots. Rare plant macro-fossils.
	Diffuse boundary.
320 - 330 cm.	Organic sediment. Moderately humified common coarse roots.
	Sharp boundary.
330 - 340 cm.	Organic horizon. Abundant, poorly humified strong coarse roots (*Calluna*?)
	Sharp boundary.
340 - 348 cm.	Moderately well humified organic sediment. Common roots.
	Diffuse boundary.
348 - 377 cm.	Organic clay silt. Rare plant macro fossils. Common fine roots. Organic content declines with depth towards underlying strata. Lake sediment
	Sharp Boundary.
377 - 405 cm.	Grey plastic clay. Common coarse roots but these appear to penetrate from higher strata rather than form part of the fabric of this unit.
	Diffuse boundary, between underlying organic and overlying inorganic sediment. Clay silt. Drop stones, angular moderate - small quartz.
405 - 415 cm.	Organic sediment. Clay silt, very abundant fine roots.
	Clear boundary.
415 - 466 cm.	Organic clay silt. Rare plant macro fossils, some seeds. Lake sediment.
	Diffuse boundary
466 - 473 cm.	Organic band, rare plant macro fossils, rare common roots.
	Diffuse boundary
473 - 481 cm.	Inorganic. Grey, very plastic clay.
	Sharp Boundary.
482 - 490 cm.	Organic silt. Very rare fine roots.
	Oldest

Environmental interpretation.

Youngest.

20 - 35 cm.	Wet.
35 - 100 cm.	Drier bog surface.
100 - 282 cm.	Alternatively wet / Dry conditions.
282 - 340 cm.	Wet.
348 - 377 cm.	Warm. Holocene / Late-Glacial transition. Developing soils.
377 - 405 cm.	Cold Stadial.
405 - 415 cm.	Warm. Interstadial.
415 - 473 cm.	Warm. Periglacial / Interstadial.
473 - 481.cm.	Cold. Stadial.
482 - 490 cm.	Warm. Interstadial.

Oldest.

Tephra distribution.

The tephra content of the core was established using the method outlined in detail above. The initial coarse sampling identified three distinct tephra peaks [Figure10.2], between 10 - 20 cm, 50 - 60 cm and 180 - 190 cm. Fine resolution sampling of these areas established the distribution and concentration of tephra within these zones [Figure 10.3]. The tephra distribution within the core shall be discussed below when the geochemistry of the core is discussed.

Geochemistry.

Samples for geochemical analysis were taken at 10 centimetre intervals. In addition, distinct sedimentary units, areas of tephra concentration and the upper 30 centimetres of the core were sampled in greater detail. The outline geochemical history conforms to the pattern observed at Loch Hellisdale on South Uist and Borve mire on Barra, as well as, in outline, the work of Mackereth [1966] and Pennington *et al.* [1972]. In brief the core appears to outline the Devensian Late-Glacial / Holocene transition, the development of soils and the declining base status of the sediments once they had developed [Figure10.4]. The geochemical history of the mire is now considered in detail and to allow closer examination the core has been divided into distinct geochemical units.

Chemizone KL1A & KL1B 190 - 490 cm . [Figure 10.5].

Late-Glacial climatic oscillations, Late-Glacial / Holocene transition. Early Holocene.

This chemizone consists of the bottom 3 metres of sediment. It has been delineated to highlight the distinct contrast between the Late-Glacial and Holocene environments and the nature of the Late-Glacial / Holocene transition. This environmental change is apparent at 350 cm. Below this depth, the geochemistry is dominated by elements which are characteristic of the mechanical weathering of an unstable environment, **K** and **Si**; while above 350 cm the elements are characteristic of the chemical weathering of developed soils [Figure10.5]. This chemizone is considered in detail below. To allow a detailed interpretation chemizone KL1 has been sub-divided into two zones. KL1A and KL1B.

Chemizone KL1A. 330 - 490 cm. [Figure 10.6].

Late-Glacial climatic oscillations, Late-Glacial / Holocene transition.

Summary.

All of the elements which feature prominently in this zone typify mechanical erosion. Several elements which peak in this zone, such as **Fe** and **Mg** are open to several interpretations, here they are interpreted as indicating mechanical erosion.

High proportions of **K** occurred at 476 cm 6 % and 400 cm 5%. These values are the highest achieved by **K** in the entire core. Between 490 - 480 cm, and 470 - 410 cm the proportions of **K** declined to below 2 % and from 400 cm to 330 cm the proportion of **K** steadily declined to below 0.5 %. **Ti**, a trace element, but a consistent measure of mechanical erosion throughout this study follows the trend exhibited by **K**. **Mg, Fe** and **Al** also peak in this zone at 476 cm.

P is not detected in the core between 350 and 460 cm but is present between 490 and 476 cm. **P** may be co-precipitated with other elements or may reflect organic productivity of the environment. **Cu**

and **Zn** exhibit similar behaviour to P. Both are present in relatively percentages between 476 - 490 cm, but fall to a new, much lower equilibrium above 470 cm.

Si can indicate biogenic productivity and/or mechanical erosion, and has a consistently high relative abundance in chemizone KL1A, never falling below 65 %. The value of **Si** declined when the proportion of **K** increased at 476 and 400 cm, and increased when the proportion of **K** declined between 410 and 470 cm.. This relationship is not entirely conditioned by the way in which the ZAF program calculates the proportion of elements present in any sample. The percentage of **K** may rise by 3% at 476 cm, but the proportion of **Si** falls by 30%. A significant part of the abundance of **K** in this zone my reflect biogenic productivity. The value of Si remained high until 340 cm. This was associated with a distinct change in the nature of the sediment.

S and **Mn** peaked at 410 cm and between 466 - 476 cm. These elements conventionally indicate chemical weathering of sediments and it is interesting to note that these peaks coincide with organic bands in relatively inorganic sediments.

Interpretation.

Between 490 cm and 380 cm most of the elements analysed exhibit dynamic metastable equilibrium. Sharp changes occur in the proportion of elements which indicate opposing climatic conditions, and new, stable, equilibria are established at higher or lower proportions. Environmental change is rapid but having occurred, stability is achieved and maintained until a significant change occurs in the controlling environmental variables.

High percentages of **K** and **Ti** are conventionally interpreted as indicating periods of soil erosion and instability typical of periglacial conditions [Mackereth 1966]. **Al** is closely associated with to **Ti** and **K** in this zone. Several interpretations may be advanced for high proportions of **Al** but when in close association with indicators of mechanical erosion, and in the absence of elements which would support alternative hypotheses such as rainfall or leaching, then it may also indicate mechanical erosion. The trends exhibited by **Na** also paralleled K. **Na** may indicate mechanical erosion, and in these circumstances the extensive association of elements which indicate mechanical erosion suggest that this is the most likely interpretation. If this interpretation is accepted, then chemizone KL1A is punctuated by two episodes of cold. All four elements exhibit dynamic metastable equilibrium, rising and falling steeply to new equilibria.

The initial cold episode, at 476 cm, is preceded by high values of **P**, **Mn**, **Cu** and **Zn**, and low proportions of **K** and **Ti**. The elements which peak in the bottom sediment are not typical of those which indicate warm conditions, but examination underneath a dissecting microscope showed that these sediments were an organic Gyttja. The elemental composition of sediments found at the base of similar cores have not previously been studied in the detail allowed by EDMA, and perhaps environments in immediately periglacial sediments have a geochemical signature which is different to that which characterises fully warm or cold conditions? This question will have to be addressed in future studies of other cores extracted from similar environments.

Between 476 cm and 400 cm the elements which indicate soil erosion fall to a lower equilibrium. Between these points the proportions of **Cl**, **S**, **Mn** and **Si** increase. These elements indicate chemical weathering of sediments, increased rainfall and an increase in biological activity and suggest a warmer, wetter climate. The geochemistry indicates that interstadial conditions came to an abrupt halt at 400 cm with sharp rises in **K**, **Na**, **Al** and **Ti**, all elements which in association indicate mechanical erosion, and a fall in **Cl**, **S**, and **Si** which in association reflect warmer conditions. At this point in the core the sediment changes sharply from an organic clay silt to a stiff, plastic inorganic clay. Between 400 and 380 cm the elements which indicate cold conditions achieved a high equilibrium which indicates persistent cold conditions. The trends exhibited can be interpreted in the light of established climatic models, and record the Older and Younger Dryas and the Allerod and Loch Lomond Stadials. Above 380 cm the geochemical evidence suggests that environmental change occurs slowly and steadily rather than rapidly and abruptly as it did between 490 and 380 cm. This of itself may indicate a change in environment and climatic conditions.

A significant change in environment is indicated at 377 cm. From this depth most of the elements analysed exhibit dynamic equilibrium with a long term trend. However these trends are in opposition. The proportion of elements which indicate mechanical erosion and cold conditions decline steadily while the proportion of elements which indicate climatic amelioration, and the development of soils rise steadily. The percentages of **K**, **Al** and **Ti** decline from 380 to 350 cm, falling to near trace concentrations. Across the same depth the values of **Cl**, **Si**, **S** and **Mn** increase. This trend suggests a declining rate of soil erosion, developing soil structure and vegetation, which itself suggests a climatic recovery. The geochemical trends between 380 - 350 cm records the Loch Lomond stadial/Holocene transition.

Summary of Environmental trends in Chemizone KL1A.

Climatic oscillations in the Late Devensian period and the onset of the Holocene are clearly indicated in chemizone KL1A. The chemistry at the base of the core, between 480 and 490 cm indicates relatively warm conditions and stable sediments, which are interrupted by a sudden return to cold conditions at 476 cm. Cold conditions are maintained until 470 cm, following which warmer conditions are indicated until 400 cm. A return to cold climatic is indicated at 400 cm. From 380 cm to 350 cm indicators of mechanical erosion decline while indicators of an improving climate increase.

Chemizone KL1B [Figures 10.5 & 10.7].

Summary.

A distinct change in the sediment geochemistry and morphology occurred at 350 cm. This change can be seen clearly in Figure 10.5, and is characterised by a sharp rise in proportions of several elements, **S**, **Fe**, **Mn**, **Ca**, **Cl**, **Mg** and **Na**, which maintain equilibrium at the higher concentrations achieved. The suite of elements which dominate this chemizone are distinctly different from those which dominated chemizone KL1A, and the values of **K**, and **Si** fell to a very low percentage in this zone, <0.5 % and <1 % respectively. These changes suggest that distinctly different environmental conditions existed in this zone to those which were characteristic of the preceding. **Ni**, **Zn** and **Ti** exhibit steady state equilibrium and it is unlikely that changes in the relative abundance of any of these elements in this chemizone reflect the fluctuation of a variable which has an influence on environmental conditions. The percentage of **Ca** rose at 340 cm from 3 % to 40 %; **S** rose from 5 5 to 20%; **Fe**, from 2 % to 10 %; and **Mn** from 0.2 % to 1.6 %. **S** and **Ca** exhibit Dynamic Metastable Equilibrium, with long term trends separated by a threshold to a new level. The new long term trends established however, are different. The long term trend of **S** across this zone records an increasing representation, while that of **Ca** records a decreasing percentage. **Mn** and **Fe** exhibit similar behaviour to S. Interpreted together, these elements suggest that a significant environmental variable has altered, probably the acid status of the soils in the Strath or the nature of the mire environment. **Na**, **Mg**, and **Cl** also exhibit Dynamic Metastable Equilibrium, together the increase in the proportion of these elements indicates a distinct change in rainfall regime. The value of **Cu** in the sediment peaks between 290-280 cm, and between 260-200 cm, rising to 4.5 %. This behaviour can be interpreted as Metastable Equilibrium and indicates a major change in a source variable.

Interpretation.

This chemizone records changes to the immediate mire environment and the onset of full Holocene conditions. The sharp decline in the proportion of elements which indicate mechanical weathering of sediments associated with the sharp increase in the relative abundance of elements associated with the chemical weathering of soils supports this interpretation. The establishment of full Holocene climatic conditions is also indicated by the rise in the proportions of **Na**, **Mg** and **Cl**, which indicate rainfall [Waterston *et al.* 1979; Maitland & Holden 1983] and here may indicate the onset of oceanic climatic conditions. The distinct threshold crossed at 350 cm suggests that a significant change in rainfall regime occurred which may be associated with the chemical weathering of the catchment sediments.

A distinct change in the sediment morphology was recorded at 348 cm which is recorded by the geochemistry at 340 cm. The sediment changed from an organic clay silt, which may have been a lake sediment, to a moderately well humified sediment more typical of a palaeosol. The geochemical indication of this change is a steep fall in **Si** in the core from 90 % at 350 cm, to 15 % at 340, and <

10 % from 330 cm onwards. Given the decline in the proportions of other indicators of mechanical erosion, the principal source for **Si** in this zone is the siliceous skeletons of freshwater diatoms. The sediment morphology suggests that the mire infilled and a soil formed. It is probable that the local change from a benthic to a terrestrial sediment was responsible for the steep fall in the representation of **Si** in the core; but this change itself is indicative of evolving sediments across a far wider area. The steep rise to a new threshold at 340 cm recorded in the relative abundance of **S**, **Mn**, **Fe** and **Ca** in the sediment suggests that a significant variation in an environmental variable occurred at this depth. Locally this change is expressed by the formation of a soil on the mire, but in the context of the wider environment of the Strath it indicates the formation of acid soils which were relatively base deficient. The soil formed on the lake clay was organic, acid and base deficient. Despite a marked increase in the proportion of **Ca** in the core at 340 cm the long term trend of this element is one of decline. A declining trend can be identified in this chemizone, but a long term trend can also be observed throughout the entire core above 340 cm [Figure 10.5], which confirms the limited base status of the local environment.

The peaks in **Cu** in this zone are difficult to interpret. Conventionally they would be taken to indicate industrial activity [Rippey 1990] but in sediments which record the industrial revolution, peaks in the proportion of **Cu** are associated with peaks in **Zn**. This was the case with the sediments analysed from the Borve valley, Barra, discussed above. At this depth in the Strath of Kildonan core, it is difficult to propose an anthropogenic origin the high proportion of **Cu** but to hypothesise that it originates in the local environment is difficult. When present at trace levels **Cu** and **Zn** are commonly associated with soil erosion but other indicators of soil erosion are absent and this explanation seems unlikely. One explanation could be a simple error or anomaly, but as the electron beam is re-calibrated between each analysis it is unlikely that each of the samples which record a high proportion of **Cu** between 290 and 190 cm incorrect. A similar peak in **Cu** occurred at approximately the same depth in the core retrieved from the Borve Valley, Barra, and it is possible that both record the same event. Could the peak in **Cu** record the local smelting of copper? Obviously this question will need to be addressed in more detail than this present study allows, but the coincidence of high values of copper at the same depth in two cores may be more than coincidental.

Summary of environmental trends in Chemizone KL1B.

This zone indicates a distinct change in the weathering processes operating upon the sediments of the Strath, from physical to chemical processes. The long term trends of the elements which indicate chemical weathering suggest acidification and the reduction of base availability. An increase in rainfall intensity is indicated. The local environment of the mire altered significantly between 340-350 cm and a soil formed over the mire. The soil was succeeded by the accumulation of organic material. These trends are not typical of periglacial conditions and the range of evidence presented above suggests an early-mid Holocene date, perhaps the Atlantic period.

Chemizone KL2. [Figure 10.8].

This chemizone was delineated by the location of a concentration of tephra between 180-190 cm [Figure 10.2]. The detailed distribution of tephra at this depth was established by the analysis of contiguous 1 cm^3 samples [Figure 10.3]. Samples for geochemical analysis were taken at the same sampling interval.

Summary.

The tephra identified in this zone consisted of clear and sepia coloured glass shards which exhibited concoidal fractures. The location of tephra across this zone is typical of a near- normal pattern of distribution, which is slightly positively skewed downwards. The peak concentration of tephra occurred at 185 cm where 55 shards were counted. The proportion of several elements appear to respond to the concentration of tephra in this chemizone. The proportion of **K** through much of this chemizone was low, <1 %, but at 185 cm **K** rose to 1.7 %. The trend in the percentage of **Si** between 184 and 190 cm is almost exactly parallel to that exhibited by tephra. **Ti** also peaked at 185 cm and the trend in the proportion of this element is again similar to the distribution of tephra in the core. The percentage of **P** also appears to be related to the deposition of tephra in the core. Other elements analysed do not appear to respond to the deposition of tephra. **Na, Mg** and **Cl** exhibit stable equilibrium. Between 181-189 cms, **Al** exhibits Stable Equilibrium with a long-term rising trend. **S, Mn** and **Fe** exhibit stable equilibrium between 181-189 cm. **Ca** maintained a declining trend across this chemizone. **Cu, Zn** and **Ni** are all present at very low proportions, <0.8% and do not exhibit any trend which indicates change in an environmental variable. At the base of this chemizone an increase in the proportion of **K, P, Ti** and **Si**, and a decline in the value of **S** occurred. These changes were far greater than those associated with the tephra fall.

Interpretation.

Comparison between the distribution of tephra in this zone and tephra distribution observed in other studies [Persson 1971; Thompson & Bradshaw 1986] suggests that one episode of tephra deposition occurred which was turbated both up and down the core. There is no evidence that the deposition of this tephra resulted in a significant deterioration of the environment. The remarkable association between tephra distribution and the trends exhibited by **K, Si** and **Ti** may be a reflection of the chemistry of the tephra shards. Tephra is predominantly silica and the proportion of this element in this zone may be a direct result of the concentration of tephra shards in any one sample. The same interpretation is possible of the **K** and **Ti** in this zone. **K** and **Ti** are also common constituents of tephra grains [Devine *et al.* 1984; Dugmore 1989; Sigurdsson *et al.* 1985; Thorarinsson 1981]. An alternative hypothesis which may account for the response of elements to the tephra deposition is that **Si, Ti** and **K** record an episode of soil erosion which occurred in conjunction with the tephra deposition. The distribution of tephra across this chemizone and the very similar response of **K, Si, Ti** and **P** suggest that all five variables record the same episode. This distribution is only slightly skewed which suggests that little soil erosion occurred in response to the tephra deposition. The close association of **P** to the tephra is difficult to interpret. **P** has been noted as a constituent of basaltic volcanic eruptions, of the eastern Icelandic volcanic zone [Jakobsson 1979] and the proportion of **P** detected by the micro-probe may well be a chemical constituent of the tephra in the samples. Alternatively the proportion of **P** may indicate an environmental response to the tephra deposition. Could the tephra fall have been associated with the death of plants on the mire and hillside above and be responsible for **P** enrichment of the mire? A few papers have suggested that tephra deposition on mires can have a beneficial impact on their nutrient status [Martin 1913; Thorarinsson 1967] but these studies deal with the impact of heavy tephra falls, proximal to the source, which have significantly altered the hydrology of the mire environment, not a relatively light tephra fall at a considerable distance from the volcano.

The trend in the representation of **Ca** across this zone continues the decline exhibited in previous zones. There is no evidence that the tephra fall was responsible for an enhancement of base status which may have prompted an increase in organic productivity and hence of the proportion of **P**. A light dusting of tephra and a low level of sulphur deposition can act as a fertiliser in base rich sediments [Blong 1984], but the geochemistry of the mire and the nature of the sediment itself indicate that this was an acidic base poor environment.

There is no geochemical evidence for the deposition of acid volatiles associated with the tephra. The proportions of **S**, **Fe** and **Mn** do not appear to change in response to the tephra deposition. Nor is there a change in the trends exhibited by these elements, which would indicate fluctuation in any environmental variable which might have had an influence on the proportion of these elements in the core.

The scale of any environmental disruption associated with the volcanic event must be considered. Within the context of chemizone KL4, the response of **K**, **Si**, **Ti** and **P** to tephra deposition, indicates a significant enhancement of the proportion of these elements, and in the environmental variables which affect their concentration. However, in the wider context of the environmental changes recorded by the geochemistry throughout the entire core, the degree of environmental change which occurred in chemizone KL4 is minimal. This is illustrated by the sharp increase in the proportions of these elements at 180 cm which is not associated with any tephra fall.

Summary of environmental trends in Chemizone KL3.

A tephra deposit was identified in this zone which was closely associated with the changes in proportion of **K**, **Si**, **Ti** and **P**. An environmental response is indicated by the geochemistry, in particular by the concentration of **P**. The exact nature of this environmental impact is ambiguous but a nutrient enrichment of the mire appears to have occurred in response to the deposition of tephra. The degree of environmental change indicated however, was minimal compared to geochemical changes observed elsewhere in the core, which were not associated with tephra falls.

Chemizone KL4. 60-180cm [Figure 10.9].

The sampling interval across this chemizone was 10 cm. However, in order to test the relationships observed in the tephra zones where the sampling interval was much closer, and the relationship between the elements analysed potentially much closer, the sediments between 150 - 160 cm were sampled and analysed in the same manner as the tephra zones.

Summary.

Chemizone 4 is characterised by a considerable enhancement of the proportion of **P**. In chemizones 1, 2 and 3, **P** does not rise above 0.8 % and only approached this figure on two occasions; in chemizone 4 the proportions of **P** are consistently higher than 1 %. **P** exhibits Dynamic Metastable Equilibrium and maintains the higher equilibrium reached at 180 cm until 150 cm. This chemizone is introduced at 180 cm by a sharp increase in the proportion of **K**, **Si**, **Mg**, **Na**, and **P**. The association of these elements may indicate an episode of erosion. An equally steep decline in **Al**, **Cl** and **S** occurred at the same depth. From 181 - 180 cms, the proportion of **K** rose from 0.5 - 4 %, Si from 0 - 35 %, and **P** rose from 0.5 - 1.1 %. Between 182 and 180 cm, **Na** rose from 3.5 -5.8 % and **Mg** rose from 0.3 - 0.75 %. Between 181 - 180 cm the percentage of **Cl** fell from 8 - 2 %, **Al** from 36 - 2 % and S from 22 - 8 %. At 170 cm the proportion of **K**, **Si** and **Ti** had returned to the level concentration achieved at 181 cm and the proportion of **S** had recovered but **P** maintained the higher proportion it had achieved at 180 cm. The proportions of **K**, **Si** and **Ti** increased between 120 and 80 cms perhaps indicating a phase of erosion. Several elements, **Ni**, **Cu** and **Zn**, exhibit stable equilibrium and do not indicate long term change in their controlling variables. There is steady increase in the percentages of **Cl** and **Na** between 160 and 157 cm and a peak in both also occurred at 151 cm. The long term declining trend in the proportion of **Ca** does not continue across this chemizone and a cessation of base depletion is implied. After recovering from the decline which took place at 180 cm, **S** maintained relatively stable equilibrium across this chemizone. Greater fluctuations are observed in the proportion of **Mn** and **Fe** and the relative concentration of both elements is consistently higher between 155 - 110 cm as is the proportion of **Mg**.

Interpretation.

This chemizone is introduced by steep increase in a wide range of elements which taken together indicate a physical disturbance of the landscape. The proportion of **K** at 180 cm was the highest recorded in the entire Holocene record. When this is associated with equally steep increases in the proportion of **Ti**, and **Si**, and **Mg** and **Na**, the association can be interpreted as indicative of a greater degree of short term landscape disturbance than is indicated elsewhere in the core. The indicators of landscape disturbance return to the concentrations at which stability is maintained at 170 cm but the proportion of **P**, which also rose steeply at 180 cm, did not decline until 110 cm. The increase in the mean equilibrium of **P** may be best appreciated by referring to Figure 10.4, where the behaviour of this element through the entire core can be estimated. The relative enrichment of the sediments by **P** may be responsible for the stability in this zone of the base status indicator **Ca** and for the stability of the acid indicator S. The relationship of these elements suggest that processes of soil degradation, indicated by rising proportions of **S** and declining proportions of **Ca** in preceding chemizones, ceased in this chemizone.

Several hypotheses may account for these phenomena.

1. Anthropogenic.

The episode of landscape disturbance was associated with the activities of people. This may be the result of clearance, changing land-use strategy, or an intensification of land-use. Following the disturbance of the soils a new equilibrium was achieved and the soils ceased eroding. The continuing anthropogenic presence then maintained the phosphate enrichment of the bog.

2. Natural.

Soil erosion does not require an anthropogenic trigger. The acidification of the soils of the hill slope above the basin could have progressed to the point where they became unstable. Alternatively a natural change in the vegetation cover could have occurred. Such a change does not require dramatic climatic change and could have been the result of a gradually deteriorating soil resource or climatic change or a combination of both. As suggested above, once the bog has been enriched by an inwash of nutrients and bases the organic productivity of the bog may have been enhanced and led to the higher representation of **P**.

Discussion.

The enhanced proportion of **P** in the sediment does not appear to be reflected in acid status of the mire. Although the percentages of **S** and **Ca** remain stable, there is no evidence in the geochemistry to suggest that the acidity was ameliorated, only that it stabilised. The high percentages of **P** in this zone is not associated with any element with which it may commonly be sorbed or co-precipitated, such as **Fe**. The production and deposition of **P**, in this context does not appear to have been the result of autocthonous processes occurring within the bog. Nothing in the geochemistry suggests that a significant alteration of climatic variables coincides with either the inferred initial erosion episode or the later proportion of **P**. Significant changes in vegetation in the north-eastern highlands of Scotland are known to have occurred at about this general period. The "Pine decline" *ca.* 4000 BP being one such; however this decline is associated with deteriorating climate, acidifying soils and volcanic eruptions [Blackford *et al.* 1992] and it is difficult to conceive how any or all of these could be responsible for the relative enhancement of **P** in the core and the stability of **S** and **Ca**. If it is accepted that the source of **P** in this chemizone may be the result of allocthonous productivity then the anthropogenic hypothesis appears to be the most attractive. Human activity may have destabilised the soils which then returned to an state of equilibrium. The continued human presence and use of the land around the basin may then have led to the production and deposition of phosphate. In this interpretation it should be noted that a settlement of postulated Bronze Age date lay on the hillside 150 metres from and 50 metres higher than, the core extraction site. In the light of this discussion the most likely hypothesis for the phenomena described is that they occurred as the result of a disturbance of the landscape followed by a period of exploitation.

A second environmental change is indicated in this chemizone, beginning at 130 cm, which is associated with a change in sediment texture and the presence of tree macro-fossils. At this point the proportion of **P** declined to a low equilibrium, while the percentages of **Si**, **Ti** and **K** increased. If the hypothesis advanced for the high proportion of **P**, above, is accepted then the decline in the proportion of P may indicate a cessation, or change in anthropogenic modification of the environment. This may have been because of the episode of landscape instability indicated between 110 - 80 cm. Alternatively, exploitation of the soil resource may have resulted in its degradation, erosion and subsequent abandonment.

The trends indicated by **K**, **Ti** and **Si** between 130 - 80 cm, suggest an episode of landscape instability, which occurred between 130 - 100 cm, which was followed by a slow return to stability between 100 - 80 cm. These trends correspond to sedimentary units within the core. Between 130 - 100 cm the sediment was well humified but contained rare wood macro-fossils. At 100 cm there was a sharp division between two sedimentary units, largely delineated by abundant wood macro-fossils above 100 cms. The immediate environment of the basin does not however appear to have been degraded and hill slope processes and processes taking place within the mire must be separated from each other. The presence of tree macro-fossils in the sediment, including a Hazel nut at 69 cm suggests that the sediment within the basin was drier and that pH had risen. Between 130 - 90 cm the proportion of S was at a low equilibrium indicating a lower pH. The closely sampled sediments between 150 -160 cm did not exhibit the close association between elements noted in the tephra zone above, KL2, or in the tephra zones discussed below. KL4 and KL6.

Summary of environmental trends in chemizone KL4.

This chemizone is introduced by a short lived episode of landscape disturbance which was followed by an enhanced representation of **P**. The landscape disturbance and enhancement of **P** have been attributed to anthropogenic activity. The accelerating acidification of the sediments, indicated by the proportions of **Ca** and **S** in chemizones appears to have ceased and a balance between base availability and acidity achieved. The input of **P** declined and was followed by an episode of landscape instability. This episode of landscape instability was associated with, and succeeded by a distinct sedimentary change and the presence of abundant tree-macro fossils in the core. This evidence suggests that the mire was drier and less acid.

Chemizone KL5. [Figure 10.10]

This chemizone was delineated by the location of a concentration of tephra between 50-60 cm [Figure 10.2]. The detailed distribution of tephra at this depth was established by the analysis of contiguous 1 cm^3 samples [Figure 10.3]. Samples for geochemical analysis were taken at the same sampling interval. An extra variable is considered in this zone,. the distribution of tephra grains which show signs of erosion. This distribution is plotted on figure 10.3.

Summary.

As in Chemizone KL3 there is a close association between the distribution of tephra and the proportions of **Si** and **K**. All three variables exhibit Dynamic Metastable Equilibrium with a trend which rises from 55- 50 cm. From 57 and 56 cm the proportions of **Fe**, **Mn**, and **S** decline steadily to 50 cm. The distribution of tephra between 50 - 60 cms is skewed, with a steady decline in the number of tephra grains counted between 50 and 60 cm from 52 to 11. The behaviour of **Si** and **K** is similar to the tephra distribution. However, when interpreting these trends the provenance of both elements must be considered. Do these trends record an environmental response to tephra distribution? Or alternatively are these trends the result of the geochemistry of the tephra grains?

The highest proportion of **S** in the entire sediment record occurred in this zone at 58 cm (27.5%); and the highest proportion of **Fe** below the Acrotelm [Ingram 1978, 1987] occurred at 57 cm (33 %). This point coincides with a minima in the tephra distribution. However with the exception of these peaks the long term trend of **S**, **Fe** and Mn is one of decline from 60 to 50 cm. The proportion of Ca in the sediment increased considerably at 55 cm, to 41 % followed by a steady decline to 10% at 51 cm.

Cu, **Zn** and **Ni** do not exhibit any trend which may be interpreted as indicating fluctuation of an environmental variable and **P** exhibits stable equilibrium across the zone.

Interpretation.

Do any of the trends described above and presented in Figure 10.10 suggest an environmental response associated with the deposition of tephra. A series of hypotheses is presented below.

1. No environmental response to tephra deposition.

Hypothesis.

The trends exhibited by **Si** and **K** are a result of the influence of tephra geochemistry on the EDMA analysis, and do not indicate any landscape disturbance. The peaks in S and **Fe**, which indicate acidity, are the result of a short term fluctuation of an existing controlling variable and not the result of the influence of an extra-ordinary variable such as the deposition of acid material emitted in a volcanic eruption. The long tail of tephra extending down through the core is the result of bioturbation and the operation of settling mechanisms.

2. Environmental response to tephra deposition.

Hypotheses.

A. Tephra deposition occurred at 50 cm, this triggered a short phase of soil erosion which intensified a trend in the proportion of elements associated with mechanical erosion. The long tail of tephra extending down the core is the result of bioturbation.

B. Tephra deposition occurred at 58 cm and is associated with peaks in **Ti**, **Mg**, **Na** and an increase in **Al** and **Ca**. All of these elements are associated with the geochemistry of tephra grains emitted in the Hekla eruptions [Devine *et al.* 1984]. The associated peak in **S** is the result of sulphur deposition which occurred in tandem with the tephra fall. The tephra fall and acid deposition resulted in a destabilization of the catchment sediments and/or vegetation. This resulted in erosion into the basin indicated by the long term trend in tephra, **Si** and **K**.

To investigate the hypothesis advanced in (2.A) the microscope preparation slides from which the tephra counts were obtained were re-examined. Silica fragments which were ignored in the initial count as not satisfying the morphological criteria established above, were re-examined. Silica fragments which were clearly phytoliths, using the classifications established by Powers and Gilbertson [1987] and Powers *et al.* [1989] were rejected, but fragments were noted which may have been eroded tephra grains. These were silica fragments which had been abraded and damaged, but were similar in size to tephra grains. These were counted and plotted against the distribution of tephra which had been correctly identified earlier and a clear relationship between the two established [Figure 10.11]. Tephra grains which show signs of abrasion are interpreted here as having been deposited outside the basin, and then transported to the sediments by post-depositional processes which brought about the abrasion. The distribution of these across the zone suggests ongoing soil erosion, resulting in a peak input at 150cm.

Discussion.

The geochemical and physical evidence in chemizone KL4 suggests that there was an environmental response to the deposition of tephra. The nature of this response depends principally on the interpretation of the distribution of tephra across the zone. If tephra deposition took place at 58 cm depth then hypothesis (2.A) may be supported, if however tephra deposition took place at 50 cm then environmental disturbance was minimal. The distribution of abraded tephra shards in the core is critical to either argument. When the abraded shards and the trends in **K** and **Si** are viewed together, an episode of landscape disturbance is indicated.

Is there any geochemical evidence for the mechanism by which the eruption may have disrupted the environment? There are two models which explain the impact of volcanic eruptions on environments remote from the volcanic source. The first of these is climate change. This has been extensively examined in the preceding chapters and the assumption that volcanic eruptions may cause climatic deterioration on the scale necessary to bring about environmental degradation has been challenged and essentially dismissed. There is **no** evidence in the geochemistry, in particular in the relationship and behaviour of **Na, Mg** and **Cl** for any intensification of rainfall. Nor is there any evidence for an intensification of leaching which might be associated with a climatic deterioration, the trends of **S, Fe, Mn** and **Ca** do not change significantly. The second hypothesis advanced in this research is that tephra deposition may be accompanied by the deposition of acid volatiles. Acid deposition and plant damage on the scale which occurred in eastern England in 1783 may have occurred in the Strath of Kildonan in association with the tephra fall. If this interpretation is accepted, then the conjunction of tephra and the highest proportion of S in the entire core may be significant and record such an tephra event. The resultant plant death may have then resulted in the destabilization of the soils of the hill slope above. However, neither model is unequivocally supported by the geochemical evidence and further testing of this hypothesis and the examination of the geochemical response to tephra deposition is needed; ideally the research should be extended to other locations where there is no doubt as to the size and nature of the volcanic event [This is now underway, Grattan and Newnham, looking at the geochemical and palynological response to tephra deposition in Lake Taharoa, New Zealand].

Chemizone KL5. 50 - 20 cm. [Figure 10.12].

This chemizone was delineated by the tephra deposits between 50 - 60 cm and 10 - 20 cm. Between 20- 30 cm the sediment was sampled for geochemistry in contiguous 1 cm samples. This was to act as a blank against which the analysis of zones with tephra concentrations could be compared.

Summary.

This chemizone was introduced by a steep decline in the proportion of **K** and **Si** elements which had peaked in association with tephra at the top of chemizone KL4. Having declined to a lower equilibrium level at 40 cm neither element exhibits instability. **K** exhibits stable equilibrium and **Si** exhibits stable equilibrium with a long-term increasing trend. The long term increase in the proportion of **Si** is also exhibited by **P**, and **Ti**. **S**, **Mg** and **Ca** also exhibit similar trends but the proportion of these elements declines across the chemizone from 30 - 20 cm. **Cu**, **Zn** and **Ni** do not exhibit any interpretable trend and **Fe** and **Mn** exhibit metastable equilibrium, no significant fluctuation in an environmental variable can be inferred from their proportion. **Al** exhibits Dynamic Meta-Stable Equilibrium, rises to a higher equilibrium state between 30 and 24 cm before declining to a lower equilibrium at 22 cm.

Interpretation.

There is no geochemical evidence for sudden environmental change in this zone. Indictors of landscape instability **K**, **Si** and **Ti** exhibit stability or slow change. The proportion of indicators of acidity and base status in the sediment exhibit meta stable equilibrium with a steady long term fall in the proportion of both elements and in consequence can be used to indicate neither acidity nor alkalinity. The trends in both elements may be the result of the result of the normalisation of the data. Both elements are products of chemical weathering of the sediments, whilst **Ti** and **Si** indicate physical weathering. All four elements may therefore be interpreted in association to indicate the dominant weathering processes, in this zone it appears that physical weathering was the dominant process.

The close sampling interval between 20 - 30 centimetres is a blank against which the closely sampled tephra zones can be assessed. None of the geochemical associations noted in the tephra zones were repeated here, in particular the close association between **Si**, **K**, and to a lesser extent **Ti** and **P** were observed. These relationships will be discussed in detail below.

Summary of environmental trends in Chemizone KL5.

A gradual increase in landscape disturbance is indicated by the trends in **Si** and **Ti**, but **K** does not follow these trends and so any disturbance may have been minimal. Environmental disturbance is not indicated by any elements achieving a higher, or lower equilibrium following a period of instability.

Chemizone KL6. 10 - 20 cm. [Figure 10.13].

Chemizone KL6 was delineated by the concentration of tephra between these points in the core [Figure 10. 2 & 10.3]. The tephra shards were formed of clear and blue glass with concoidal fractures.

Summary.

As in other zones where a tephra concentration was identified there is a distinct association between the distribution of tephra across the zone and the representation of associated elements, in particular of **K** and **Si**. The proportion of **Fe** peaked at 17 cm, and it is interesting to note that this coincides with a minima in the tephra count. This phenomenon will be interpreted and discussed below. With the exception of the peak concentration at 17 cms, the long term trend in the proportion ρf **Fe** across this zone in one of decline. **Mn** exhibit meta-stable equilibrium and no environmental change can be interpreted from its proportion. **Cu**, **Zn** and **Ni** do not exhibit any interpretable trends. **Ca** and **S** continue the trend established in chemizone KL5, and the percentages of both elements decline across the chemizone. The proportion of **Al** rises gradually from 17 cm to a peak at 13 cms and then slowly declines. to the minimum proportion in the zone (10 %) at 11 cm. The percentages of **Ca**, **P**, **Cl**, **Mg**, **Na** and **Zn** peak at 11 cm. In the case of **Na** the peak representation at 11 cm is part of a rising trend through the core, but in the case of the other elements which peak at 11 cm, an environmental change is indicated.

Interpretation.

A limited environmental impact can be detected in response to the tephra deposition. The changing values of **Si**, **Al** and **K** run parallel to the distribution of tephra across the zone. However, as in other areas where tephra is concentrated in the core, the interpretation of Si and K, and in particular their provenance is open to question. **K**, **Al** and **Si** are component parts of tephra from Iceland [Devine *et al.* 1984; Dugmore *et al.* 1992; Jakobsson 1979]. These percentages may therefore reflect the distribution of tephra shards through the chemizone. An alternative hypothesis is that the tephra deposition has brought about an episode of landscape disturbance which is reflected in the input of **Si** and K from adjacent soils into the basin sediments.

The landscape disturbance hypothesis is difficult to test. The representation of **Ti**, which may also indicate landscape disturbance, does not closely follow the trends established by **K**, **Al** and **Si**, but this element is also a constituent of the geochemistry of tephra which originated in the Hekla volcano [Dugmore 1989] and as such its provenance in this chemizone is open to question. The proportions and trends of other elements in the core do not appear to have been significantly perturbed by the tephra fall. The trend of **Ca** and **S** is of a steady decline across the zone to 14 cm, followed by a steady increase from this depth to 11 cm, which is followed by a decline. The long term trends in the proportion of both elements began well outside chemizone KL6 and cannot be used to support a the hypothesis of tephra related landscape disturbance brought about either by acid deposition, or climate change.

The **Fe** peak at 17 cm is the second highest proportion of **Fe** below the acrotelm and it is interesting to note that both this and the highest proportion of **Fe** are related to tephra concentrations in the core. Is this peak related to tephra deposition or the deposition of acid volatiles and the subsequent mobilisation of iron? The peak in **Fe** at 17 cms coincided with a minima in the tephra concentration and this relationship may be related to the acidity of the sediments. Hodder *et al.* [1991 suggested that under acid conditions silicate glasses may be dissolved and this may explain the relationship between an **Fe** peak and a minimum tephra count. On balance it does not appear that this tephra fall brought about an environmental disturbance which can be detected or suggested by a geochemical response in the sediments. However, the general question of geochemical responses to tephra deposition will be considered in detail below. The proportions of **Ca**, **Cl**, **Mg**, **P**, **S** and **Zn** all peak at 11 cm. The association of **Ca**, **Cl**, **Mg** and **Na**, can be used to suggest rainfall intensity; the peak in S could then be interpreted as an increase in acidity in response to this. However, at 11 cm depth the active root zone of the bog is approached and the concentration of these elements may indicate the chemistry of recent rainfall rather than a palaoenvironmental change, or may indicate the current location of the water table.

Summary of Environmental trends in chemizone KL6.

A tephra deposit was identified in this zone but the geochemical response to the tephra fall did not indicate an episode of landscape disturbance. The interpretations of several elements are ambiguous, as the elements which are closely related to the tephra fall are both the principle geochemical indicators of landscape disturbance, and common constituents of Icelandic tephra. Trends in the representation of S and **Ca**, which were established much deeper in the core, continued across this zone. The peaks in the proportions of **Ca**, **Cl**, **Na**, **Mg** may indicate the position of the water table.

Chemizone KL7. 0 - 10 cm [Figure 10.14].

The upper 10 cm of the core are unlikely to contain geochemical evidence of palaeoenvironments and is the active root zone of the bog. This zone also forms the acrotelm of the sediment. The acrotelm has a fluctuating water table, is subject to periodic air entry, and contains peat forming anaerobic bacteria [Ingram 1978]. Elements deposited in this zone are not immobile and environmental trends cannot be reconstructed by the trends exhibited. An analysis was carried out, primarily to identify any increase in the proportion of environmental contaminants which may have their source in industrial pollution, the results are presented in Figure 10.14. The proportions of **Zn** and **Cu** are not enhanced in this zone and little deposition of industrial contaminants is indicated in this location.

Discussion: sediment geochemistry and environmental change in the Strath of Kildonan [Figure 4].

The geochemistry of the core has been investigated in detail and presented in individual chemizones, an overview is presented here.

Late-Glacial/Holocene transition.

Two clear zones can be identified which represent the climatic oscillations at the Devensian/Holocene transition and the Holocene. Within the Late-Devensian sediments several cold and warmer episodes can be identified. These do not conform to the accepted British model of Windermere interstadial / Loch Lomond re-advance / Holocene, but also indicate the presence of an extra warm phase more typical of the Older and Younger Dryas periods indicated in European sediments. The sediment morphology and geochemistry suggest that the climatic oscillations in the Late-Devensian / Holocene transition consist of subtle changes beyond the scope of the research of this paper. A detailed analysis of these changes will be the subject of future research.

Soil Evolution.

The development of the Holocene environment can be seen to be gradual. The proportion of **K** in the sediment declines gradually over nearly a metre of sediment, while the representation of elements indicative of the chemical weathering of developing soils, increase gradually across the same sediments. The development of an organic soil is clearly indicated by the geochemistry at 350 cm. The contrast between the two environments is clear. Below 350 cm the principle weathering process indicated is mechanical, above 350 cm the principal weathering process is chemical. The evolution and development of the Holocene sediment can also be reconstructed. A steady decline in base status, and by inference a fall in pH is indicated by the trends exhibited by **Ca**. The depletion of base status can also be inferred from the long term trend apparent in **Mg** and **Na**. Holocene landscape disturbance is indicated by **K, Si** and **Ti**. Short lived increases in the proportion of any element in the core are obvious, but the interpretation of short lived fluctuations in the representation of any element may be problematic. These may have been caused by the fluctuation of several variables not all of which are significant in environmental terms. However, episodes where the percentages of these elements achieve a higher equilibrium in the core, may indicate alteration in an environmentally significant variable. Such variables may be the interaction of people and the landscape, vegetation change, soil development, or climate.

Anthropogenic Influences.

Anthropogenic influences may be inferred where episodes of landscape disturbance are associated with indicators of nutrient enrichment. In several parts of the core it is apparent that a high representation of **P** is associated with episodes of landscape disturbance and these may reflect the activities of people within the landscape. These episodes appear to be episodic in nature and may indicate episodes of more and less intense anthropogenic exploitation of the Strath. Anthropogenic activity may also be indicated by the geochemistry of elements such as copper and zinc which can be deposited as the result of industrial activity. In the Strath of Kildonan, **Cu** may have two sources. It is a common constituent of metamorphic rocks [Berrow & Mitchell 1980] and may therefore originate in the granitic rocks of the region, or it may be deposited from industrial pollution. The scale of the increase in the proportion of **Cu** between 200 -330 cm is difficult to attribute to the erosion of granite clasts. A steady background presence of **Cu** deposition occurred across the core and was typically below 0.5 %. The peak concentration of **Cu** is not closely associated with any indicators of physical and chemical weathering, so deposition from either of these mechanisms appears unlikely. If an anthropogenic source is considered then industrial pollution is indicated far earlier than the 19th century date suggested by most workers [Rippey *et al.* 1982]. This question will be investigated in future research in sediments retrieved from other locations, but it is interesting to note that a similarly high proportion of **Cu** occurred in the Borve bog, on the Island of Barra [discussed above] at 270 and 300 cm. and some form of working of copper, bronze or copper-affected vegetation may be involved.

Tephra deposition: environmental impacts.

The tephra falls identified in the Strath of Kildonan were the only deposits which were able to be examined in detail and which had a detectable geochemical response. Tephras identified in other locations did not approach the numbers counted here. Three tephra falls were identified in the Kildonan core and the geochemical responses associated with these were investigated [Chemizones KL2, 4 & 6; Figures 10.3, 10.8, 10.10 & 10.13]. A clear relationship could be observed between each of the tephra falls and several elements in each chemizone. The distribution of tephra within and across each chemizone is closely paralleled by the proportions of **K** and **Si**. In zone KL2 the proportions of **Si, K** and **P** are related to the distribution of tephra [Figure 10.3]. In zone KL4 **Si, K** and to a lesser extent **Al** are related to the distribution of tephra across the chemizone [Figure 10.10]. In chemizone KL6 the representation of **Si, K, Al** and to a lesser extent **Ti**, appear to change in response to the changing distribution of tephra. These relationships may have arisen because of the close sampling of sediments in the tephra zones. This possibility was tested by a similarly detailed examination of areas of the core where tephra concentrations had not been identified, between 20-30 cms and between 150-160 cms. In neither of these areas were the proportions of **K** and **Si** positively related to trends in **Al** or **P**. The values of **K** and **Si** were related but both elements may indicate landscape stability and a close degree of association is not to be unexpected.

All of the elements which are closely related to tephra distribution may be chemical constituents of the tephra shards themselves [Devine *et al.* 1984, Dugmore 1989; Jakobsson 1979] and this possibility must be considered when using geochemical trends to reconstruct environmental processes. When this research was instituted it was not anticipated that such a clear relationship would occur between tephra fall and the EDMA analysis of sediment geochemistry, but this is clearly the case. However, the distribution of tephra and associated elements across the zone may indicate the depositional processes involved and by extension, whether an episode of environmental disturbance is related to the tephra fall.

In chemizones KL2 and KL6, tephra and related elements have a "near normal distribution" and such distributions do not suggest that major environmental disturbances occurred. Nor in either case is there any evidence of acid deposition in association with these events. In chemizone KL4 however, the distribution of tephra is considerably skewed and indicates landscape disturbance and post-depositional mobility of tephra grains within the landscape [Figures 10.10 & 10.11]. Did the landscape disturbance occur because of the tephra deposition, or was it just chance coincidence? If the explanation for the distribution of tephra in this zone, advanced above, is accepted, then the tephra fall was associated with a the highest representation of **S** in the entire core, and the highest value of **Fe** in the entire core. These associations may, of course, be fortuitous, but in the light of the research presented in chapter six above, the possibility that these elements indicate the deposition of acid volatiles and associated landscape disturbance must be considered. Currently only one tephra horizon, identified as **Hekla 4**, has been associated with an environmental response, a decline in the pollen concentration of *Pinus sylvestris* in Scotland [Blackford *et al.* 1992]. But further examination of the material from the Strath of Kildonan is necessary before we can assume that these events are related. The second highest representation proportion of **Fe** in the core is also related to tephra deposition in KL6. The EDMA based examination of the geochemical response to tephra deposition clearly indicated which of the tephra falls may have been related to environmental change. In this respect it has proved a powerful tool. Its application in future studies would help to identify environmentally disruptive tephra falls and allow the focusing of other palaeoenvironmental tools to their investigation.

A common conclusion of this research has been the need to avoid the assumption that every volcanic event is environmentally disruptive. The geochemical evidence presented above suggests that only one of the three tephra horizons investigated in detail here was associated with environmental disruption. Caution must be exercised if the real value of tephra related palaoenvironmental studies, is not to be undermined by the casual application of volcanic forcing of environmental change to every palaeoenvironmental problem. It should also be remembered that 1783 was remembered as "The year of The Ashie", when the fields of Caithness were choked with ash fall from the Laki fissure eruption and crops were blighted as a result [Geikie 1893]. Yet no modern environmental scientist working in the field has found this relatively recent major ash fall.

It is apparent from a study of the geochemistry, that across the time scale of the Holocene that much environmental change occurs as the result of long term change. In this respect it is apparent that the climatic subdivisions employed in many studies such as 'Boreal, Sub-Boreal, Atlantic, and Sub-Atlantic' are not clearly defined by the geochemistry. To use the tools of facies modelling, the environmental sub-divisions employed in palaeoenvironmental reconstruction may have had a gradual conformable transition rather than the sharp boundaries drawn on pollen reconstructions.

Regional environmental correlations Borve bog, Strath of Kildonan, Loch Hellisdale.

The compositional changes in the geochemistry of the sediments examined in this study suggest that a series of changes in vegetation, climate, soils and land use have been clearly detected. All three cores record the Devensian Late-Glacial climatic oscillations in great detail. The climatic oscillations observed in the Loch Hellisdale and Borve bog sediments are in broad agreement with those noted elsewhere in Western Scotland and in England [Bennett *et al.* 1992; Mackereth 1966; Pennington *et al.* 1972]. The quality of the core retrieved from the Strath of Kildonan, allowed its examination in great detail and the Devensian Late-Glacial climatic oscillations appear to be mire complex in the north east of Scotland than in the West and south. This is a question which will be studied further by an examination of other material in the future.

The onset of full Holocene climatic conditions is clearly seen in the geochemical composition of the sediments. In Loch Hellisdale the Benthic environment appears to have maintained a near neutral pH, until relatively recent times, despite the early acidification of the terrestrial sediments. This is in accordance with the observations of lacustrine studies from elsewhere in the British Isles [Battarbee *et al.* 1985]. In contrast to Loch Hellisdale both the Borve, and Strath of Kildonan sediments indicate the acidification of the terrestrial sediments relatively early in the Holocene. Again this is in accordance with the observations made in other studies [Dimblebey 1962, 1965, Hudson, 1988, 1992; Hudson *et al.* 1982]. However, as well as identifying environmental processes operating at the macro-scale, environmental processes operating on a sub-regional, and perhaps smaller, catchment sized scale, have been identified and discussed. This demonstrates the ability of EDMA to produce results which contain evidence of the environmental variables operating within a landscape at the macro and micro scales.

Anthropogenic activity in the landscape is suggested in all three cores by the episodic soil instability and in the Borve and Kildonan cores by substantial increases in the representation of phosphate, which are frequently associated with soil instability. In addition to the direct impact of humans working within the immediate environment of the sediment basins there is also the suggestion of landscape disturbances outside the immediate catchment. The first of these is the deposition of sedimentary material which must have eroded and transported by aeolian activity from elsewhere. The second is the transport and deposition of metals which probably have their origin in the smelting of metals. In both the Borve and Kildonan cores there is a correspondence between the peaks and troughs recorded by copper. In addition, there is the suggestion of prehistoric metal working, with a substantial increase in copper in both cores, at depths which must indicate the pre-industrial revolution era.

Substantial concentrations of tephra were only identified in one core, from the Strath of Kildonan. Of three tephra falls identified in this core, only one is associated with any evidence for environmental change. This is very significant for any work which blindly assumes that any tephra fall will indicate an environmental disturbance. This study has identified the sparse nature of tephra fall across northern Scotland, in most locations it is very difficult to detect. Once it has been detected not all tephra falls are necessarily going to generate deleterious environmental change. We cannot therefore assume, that an environmental disturbance associated with any tephra in the Strath of Kildonan, or elsewhere, necessarily indicates that an environmental deterioration occurred across the north of Scotland. We may however incorporate the possibility into new hypotheses which must then be examined by future research.

Discussion.

The impact of Icelandic volcanic eruptions upon the ancient settlement and environment of northern Britain.

This work set out to consider the impact of Icelandic volcanic eruptions upon the environment of northern Britain. To do, so the theoretical and observed impact of volcanic eruptions were considered in detail.

The principal evidence that volcanic eruptions may have caused a deterioration in the environment of northern Britain, lies in the extremely narrow growth increments recorded by oak trees growing on raised mires in Ireland [Baillie & Munro 1988], which coincided with acidity peaks in the Greenland ice-core [Hammer *et al.* 1980]. The response of tree-rings from around the northern hemisphere to volcanic forcing was studied, and it was shown that the response of each chronology was conditioned by site specific environmental factors, rather than any reduction in hemispheric mean temperature. In the light of this discussion the "marginality" of the Irish Bog-oaks was considered. It was suggested that the acidity of the mires and their base status, may have played a significant role in conditioning the response of the Irish Bog-oaks to volcanic forcing of the environment.

Climatic forcing.

The mechanisms by which volcanic eruptions may cause environmental change were considered in great detail. The theories and models by which volcanic eruptions may cause a climatic deterioration were investigated and it was shown that there are no theoretical grounds to justify the suggestion that volcanic events of the magnitude of the Hekla eruptions of the Second Millenium B.C., wereresponsible for the volcanic and prehistoric equivalent of a "Nuclear Winter" in Northern Scotland [See Turco *et al.* 1982, 1983; & Rampino 1988]. The scale of any temperature response to the Hekla eruptions was considered and it was estimated that the maximum perturbation of hemispheric mean temperature would have been in the order of a reduction of 0.1°C. This is well within the normal deviation of mean temperature and it is difficult to conceive that a temperature reduction on this scale would have prompted the abandonment *en masse* of the Strath of Kildonan. The possibility that such a reduction in temperature may have set up a temperature and pressure gradient between the sea and land, with an associated disruption of atmospheric circulation was considered. It was shown that all the studies, to date, which propose such a response, are theoretically flawed, and are based on inadequate eruption chronologies and inadequate chronologies of the climatic events studied [See Nicholls 1988 & 1990 for a detailed criticism].

The consideration of the theoretical models by which it is proposed that volcanic eruptions may perturb climate, and prompt a response in affected societies was further studied by an analysis of the social and climatic impacts associated with two eruptions: those of the Laki fissure eruption in 1783 and the Tambora eruption in 1815. In both cases it was shown that the common perception of severe climatic deterioration in these years was inaccurate. In the case of the Laki fissure eruption, it was shown that the assumption that the summer of 1783 was cooler than normal, is mistaken. This assumption has been based on the account of Benjamin Franklin, which has gained a wide audience, rather than on the wealth of conflicting contemporary evidence unearthed by this study and on easily available temperature data [See Kington 1980; Manley 1974; Mossman 1896]. On the basis of this research a new model by which volcanic eruptions may cause regional warming was proposed. The winter of 1783-84 was shown to be unexceptional when viewed in the context of other, colder winters which occurred in the second half of the Eighteenth century, for which no volcanic prompting has been proposed. The failure of the Laki fissure eruption to generate an unambiguous climatic deterioration is significant for this thesis, since this eruption was one of the largest of the Holocene, and several orders of magnitude greater than the prehistoric eruptions of Hekla which are central to the archaeological debate in Scotland and Ireland[See Devine *et al.* 1984]. Despite the ambiguous climatic response, it is undeniable that the people of Iceland experienced a serious crisis in the years which followed. This crisis was examined and it was shown that the vulnerability of the Icelanders to the volcanic eruption, to poor weather, and the perception that this was a "**crisis**" year had been enhanced by several factors. These were:

1. The maladministration of the Danish colonial authorities.

2. Several harsh winters and poor summers preceding the volcanic eruption year.

3. The destruction of summer pasture and livestock by noxious volcanic gases.

4. The famine and epidemics which followed.

[See Ogilvie 1986 & Thórarinsson 1979, for detail].

Icelandic society was shown to be vulnerable to volcanic eruptions as the result of the combination of social, economic, climatic and volcanic factors, rather than to the eruption of the volcano alone. We must discuss the responses of Bronze Age society in northern Britain to volcanic forcing in a similar light, and consider the possibility that a range of factors must be considered for the proposed abandonment of the Strath of Kildonan, rather than seek to blame a "convenient" volcanic eruption alone. The responsibility of the volcano Tambora for "the year without a summer" was also investigated". It was shown that the common perception of this year as exceptional is a myth, and that in fact 1816 has come to represent a harsh decade in popular mythology. Temperature records suggest that temperature trends had been declining for several years prior to 1816 and that 1816 was not universally cold in Europe and North America. As in 1783-84 it was shown that in 1816 a specific range of social and economic factors conspired to present 1816 as a year of particular climatic stress.

Studies of both eruptions highlighted the fact that not all areas experienced climatic or economic stress, despite the common perception that harsh climatic conditions were associated with both events. We must consider the Bronze Age abandonment of northern Britain in the light of both events. Despite the magnitude of the eruptions, the temperature and climatic responses they produced must be considered, at best, to be minimal. In the case of both eruptions, regions which remember the years as being of particular crisis were already experiencing, social, economic and/or climatic stress. We cannot assume therefore, that the climatic or other forcing caused by the Second millennium eruptions B.C. eruptions of Hekla, were of themselves **sufficient** to bring about the abandonment of settlement in northern Britain.

Volatile dispersal and impacts.

The marginality of the Irish Bog-oaks was considered, and the possibility was raised that the deposition of quantities of acid volatiles, emitted in Icelandic volcanic eruptions, had lowered the pH of the mires on which the trees were growing, and that it was these hydrological and pedological effects which resulted in the narrow growth increments recorded by the Irish oaks. Perhaps the deposition of such volatiles in the Strath of Kildonan may have prompted the ancient abandonment abandonment?

The Laki fissure eruption of 1783, was again used as an analogue and extensive documentary investigation of its impacts was conducted. It was demonstrated that extensive evidence exists for widespread and severe acid damage across Europe in 1783. The probable source for these acid volatiles was the Laki fissure eruption. A model was proposed by which the deposition of such volatiles may have severe and long-lasting effects on particular ecosystems. The Strath of Kildonan is today mapped as extremely sensitive to acid deposition [Bull 1991], as are large areas of northern Scotland [Skiba *et al.* 1988]. The events of 1783 demonstrate that Icelandic volcanic eruptions may emit large quantities of acid volatiles and that these may be transported to Europe. The Irish Bog-oaks may therefore be experiencing stress in response to the deposition of acid volatiles on an acid sensitive, base deficient environment. Such events may be of greater significance in the palaeoenvironmental record than the assumption of a severe response to demonstrably minor temperature fluctuations. in this context we may consider again, the account presented in the forethought.

> "While the Saint was living in the island of Io ... he saw a heavy rain cloud that had risen from the sea to the north, on a clear day. Watching it as it rose, the saint said to one of his monks ... 'This cloud will be very hurtful to men and beasts; and on this day it will ... drop pestiferous rain upon Ireland ... and it will cause severe and festering sores to form on human bodies and on the udders of animals. Men and cattle who suffer from them, afflicted with that poisonous disease

> will be sick, even to death'. ... Silnan arrived ... at the place aforesaid; and found the people of that district ... devastated by the pestiferous rain falling upon them from the cloud"

[*Adomnan's Life of Columba.* From the translation by Anderson & Anderson 1961]

The events of 1783 and the response of the Irish Bog-oaks to distant volcanic events, suggest that the description above of a "pestiferous rain" falling from a cloud, " which had risen from the sea to the north" may record the impact of an Icelandic volcanic eruption.

Geochemical analysis.

If the hypothesis presented above is correct, or if Icelandic volcanic eruptions are capable of causing any degree of environmental stress, then this may be recorded in the geochemical history of sediments, associated with tephra concentrations, which have accumulated in suitable basins.

The technique adopted, to study the geochemistry of sediments retrieved from the Highlands and Islands of Scotland was Energy Dispersive X-ray Micro Analysis [EDMA]. The use of EDMA to study palaeoenvironmental change is a relatively new application of the technology, which is not without controversy, since the data produced is in the form of the relative proportion of each element in the sample, rather than in conventional formats such as milligrammes/gramme, ppm etc. Part of this study has been to develop and investigate the suitability of EDMA for the study of environmental change. A theoretical framework was proposed within which the data produced by EDMA can be interpreted in a meaningful manner. This framework involves the interpretation of the curves produced by each element and the construction of geochemical facies composed of associated elements, which together may indicate particular environments or influences.

A pilot study was conducted. Sediments retrieved from Loch Hellisdale, on South Uist, were studied by a variety of palaeoenvironmental techniques. It was seen that environmental reconstructions based on a study of the palynology and the changing frequency and abundance of diatom species, were compatible with the interpretation of the geochemistry of the laoch sediments. However, it was established that the range of elements studied was limited and as a result these were extended to incorporate copper and zinc.

Lacustrine sediments on North and South Uist.

Sediment cores were retrieved from three further lochs on North and South Uist. These were disappointingly short. Minimaal quantities of tephra were detected and no other "environmental" response to tephra deposition was observed. However, the geochemical investigation of these loch sediments demonstrated the value of EDMA to the investigation of environmental change. In all three cores, the influence of environmental variables specific to each catchment were identified, as were a range of environmental variables which operated upon the catchment but which originated outside. In each loch, episodes of soil erosion were noted, which suggests the anthropogenic disturbance of catchment soils. In each loch the influence of the machair environments, which lie to the west, is demonstrated to be of importance in maintaining the equilibrium of the lacustrine environments in the face of the progressive acidification of catchment soils. In this respect, it is interesting to note that the deliberate introduction of calcium into Loch A'Barpa, was less effective than the natural ability of calcareous material eroded from the dunes and machair of Baleshare, to reduce or reverse the acidity of the loch waters. It was demonstrated that the environment of all three lochs was sensitive to the deposition of acid materials, in all three the deposition of copper and zinc coincided with a deterioration in the lacustrine environment. Thus although no response to tephra deposition was observed, it was demonstrated that the lacustrine environment of these remote lochs was sensitive to the deposition of acid material, which is significant to any consideration of the impact of volcanically generated acid volatile material.

Borve Bog.

A core was retrieved from Borve Bog which lies at the head of the Borve valley on the Hebridean island of Barra. This bog lies within an archaeologically-rich landscape [Branigan 1988, 1990], and offered the potential to study the geochemical history of the mire throughout the Devensian Late-Glacial and Holocene, the impact of people upon the environment throughout that period. and the impact, if any, of volcanic tephra deposition. Although minimal quantities of tephra were located within the core, and no geochemical response to this was observed, environmental changes could be observed and interpreted in a meaningful manner using EDMA studies of the sediment core.

The nature of the Late-Glacial / Holocene transition was investigated through a study of the geochemistry of the sediments. The climatic fluctuations which characterise this period were clearly illustrated by contrasting episodes of mechanical erosion and stability. The slow evolution of soils during the Holocene could also be suggested by increasing stability and an increase in the proportion of elements which typify chemical rather than physical erosion. A prehistoric episode of atmospheric contamination is suggested by a peak in the proportion of copper in the core at 270 cm. The provenance of this peak will have to be studied further before an equivocal statement as to the question of Bronze age smelting can be made. However, other episodes of anthropogenic soil disturbance were clearly indicated by a consistent increase in the proportion of elements which indicate mechanical erosion and of elements such as P which might indicate the presence of people and or livestock. The anthropogenic exploitation of the upper Borve valley can be seen to have been episodic, and may have coincided with episodic exhaustion of the richer soil resources further down the valley, indicated by an increase in the proportion of calcium in the sediment. As in all the studies discussed above the onset and environmental impact of the industrial revolution is clearly indicated. The study of the sediments retrieved from the Borve bog demonstrated that EDMA is capable of producing information which will allow the reconstruction of environmentally determinant variables operating both within, and from outside the immediate catchment of the basin.

The Strath of Kildonan.

The geochemical analysis of the core retrieved from the Strath of Kildonan presented clear evidence for an environmental response to tephra deposition, as well as a evidence for a broad range of environmental change and evolution. The broad reconstruction of environmental history was similar to that presented in the analysis of the sediments analysed from Loch Hellisdale and Borve bog. The Late-Glacial / Holocene transition was very clearly illustrated, as was the evolution and degradation of the soil resource throughout the Holocene. The impact of people upon the sediment chemistry was again very clearly illustrated, with a rise in the proportion of phosphate in the core being associated with indicators for the physical disturbance of the landscape. The response of the geochemistry to tephra deposition is interesting. Three tephra concentrations were identified. For two of these both the geochemistry and the distribution of tephra through the sediment suggests that environmental disturbance was minimal. For one however, both the geochemistry and tephra distribution suggests that an episode of landscape disturbance occurred. This episode is associated with the highest proportions of sulphur and iron reached in the entire core which may be significant for the hypothesis advanced in this thesis, that the principal mechanism by which volcanic eruptions may disrupt the environment in northern Britain is via the transport and deposition of acid volatiles. However, caution must be urged when suggesting that all tephra horizons located in British sediments may be associated with a phase of environmental degradation, only one of the three tephras identified in the Strath of Kildonan, will support an hypothesis that environmental degradation ensued.

The application of EDMA to the investigation of environmental change.

This thesis has demonstrated that EDMA is a powerful research tool capable of isolating and identifying the operation of environmental variables within a variety of environments. The careful formulation of research strategies and methodologies should overcome the resistance to the wider adoption of this technique.

Icelandic volcanic eruptions and environmental change in northern Britain.

This thesis has investigated the question of the possible environmental impact of volcanic eruptions upon the environment in great detail. It has concluded that there is no evidence which would suggest that the Hekla eruptions of the Second Millennium B.C. were of the magnitude from which significant climatic deterioration can be reliably inferred. It has also demonstrated, by a study of the two largest volcanic eruptions of the Holocene, that volcanic eruptions may not be the sole agent of stress either climatically or socially. It is the environmental and social conditions which exist before the eruption which conditions the degree of response to the eruption. An environmentally specific model has been advanced by which the volatile acid emissions of an Icelandic volcano may bring about environmental change, but it must be emphasised that the sensitivity of the environment to such deposition, is as important as the scale of volatile deposition.

This study has also highlighted the possibility that a mechanism exists by which volcanic eruptions may bring about warming of the lower atmosphere on a local / regional scale.

It is unlikely, except in exceptional circumstances, that a volcanic eruption alone may act as an agent of environmental change. The Hekla eruptions of the Second Millenium B.C. were not, on the basis of current estimates of magnitude, on the scale where they may be considered likely to have been the sole agents of social or environmental change. This thesis has demonstrated that the criteria by which an environment or society may be considered to be marginal must be estimated before any assumption of the degree of volcanic forcing may be made.

Throughout this work, Renfrew's [1979] warning, against the assumption of causality based on a loose temporal association has been applied. It is hoped that this work has not itself fallen into that pitfall, and that it may act to move the debate on the impact of volcanic eruptions in prehistory onto a more critical and scientific level.

Did the Hekla 3 eruption cause the abandonment of the Strath of Kildonan?.

This thesis has not been able to prove or disprove this hypothesis. It has rejected the hypothesis that the Hekla 3 eruption may have brought about a severe and long lasting climatic deterioration. But in its place an explanatory model has been advanced by which the acid volatiles emitted in some Icelandic volcanic eruptions may have a severe impact on the acid sensitive environments, which the Strath of Kildonan may be considered to be.

John Grattan Plymouth. December 1993.

Bibliography.

Aber, J.D., Hendry, G.R., Francis, A.J., Botkin, D.B., & Mellio, J.M. 1982. Potential effects of acid precipitation on soil nitrogen and productivity of forest ecosystems. In D'Itri, F.M. (ed) *Acid precipitation Effects on ecological systems*. Ann Arbor.

Adriano, D.C., & Johnson A.H. (eds) 1989. *Acidic Precipitation. Volume 2: Biological and ecological effects*:61-80. London. Springer-Verlag.

Alt, B.T., Fisher, D.A. & Koerner, R.M. 1992. Climatic conditions for the period surrounding the Tambora signal in Ice cores from the Canadian Hgh Arctic Islands. In Harington, C.R. (ed) *The year without a summer*. Ottawa. Canadian Museum of Nature.

Alvarez, W, & Asaro F. 1990. An extra terrestrial impact. *Scientific American*. 163:44-52.

Allard, P., Carbonelle, J., Dajlevic, D., Le Bronec, J., Morel, P., Robe, M.C., Maurenas, J.M., Faivre-Pierret, R., Martin, D., Sabroux, J.C., And Zettwoog, P. 1991. Eruptive and diffuse emissions of CO2 from Mt Etna. *Nature* 351:387-391

Anderson, A.O., & Anderson, M.O. 1961. *Adomnan's Life of Columba*. London. Thomas Nelson.

Anderson, D.L. 1974. Earthquakes and the rotation of the earth. *Science* 186:49-50.

Anderson, N.J, & Korsman, T. 1990. Land use change and lake acidification: Iron Age de-settlement in northern Sweden as a pre-industrial analogue. In Battarbee, R.W., Mason, Sir John, Renberg, I. & Talling, J.F. (eds). *Palaeolimnology and Lake Acidification*. London. The Royal Society. pp147-150.

Anderson, R.Y. 1992. Possible Connection between surface winds, solar activity and the Earth's magnetic field. *Nature* 358:51-53.

Anderson, R.Y., Nuhfer, E.B. and Dean, W.E. 1984. Sinking of volcanic ash in uncompacted sediment in Williams Lake, Washington. *Science* 225:505-508.

Andresson, S.H. 1984. Athstoth Einokunarverslunarinnar.In Gunnlaugsson, G.A., Gudbergsson, G.M., Thorarinsson, S., Raffnson, S. & Einarsson, T. 1984. *Skáftareldar 1783-1784*. Rekyavik. Mal Og Menning. (In Icelandic with English summaries.)

Angus, S. 1987. Lost woodlands of the Western Isles. *Hebridean Naturalist 9*, 24 - 30.

Angus, S. 1991. Climate and vegetation of the Outer Hebrides. In Pankhurst, R.J. and Mullin, J.M. (eds.). *Flora of the Outer Hebrides*. London, Natural History Museum Publications, 28 - 31.

Annable, R. 1987. The later prehistory of Northern England. *British Archaeological Reports*. 160.

Angell, J.K. & Korshover,J. 1985. Surface temperature changes following the six major volcanic episodes between 1780 and 1980. *Journal of Climate and Applied Meteorology* 24:937-951.

Angell, J.K. 1988. Impact of El Niño on the delineation of tropospheric cooling due to volcanic eruptions. *Journal of Geophysical Research* 93 (d4): 3697-3704.

Appleby, P.G., Richardson, N., Nolan, P.J. & Oldfield, F. 1990. Radiometric dating of United Kingdom SWAP sites. In Battarbee, R.W., Mason, Sir John, Renberg, I. & Talling, J.F. (eds). *Palaeolimnology and Lake Acidification.* London. The Royal Society. pp7-12.

Ardanuy, P.E., Lee Kyle, H. & Hoyt, D. 1992. Global Relationships among the Earth's Radiation Budget, Cloudiness, Volcanic Aerosols and Surface Temperature. *Journal of Climate* 5:1120-1139.

Arnold, F. & Bürke. Th. 1983. New H2SO4 and HSO3 vapour measurements in the stratosphere - evidence for a volcanic influence. *Nature* 301:293-295.

Ashmore, M., Bell, N., & Garretty, C. (eds) 1988. *Acid rain and Britain's natural ecosystems.* ICCET.

Atkinson, K.M. & Haworth, E.Y. 1990. Devoke Water and Loch Scionascaig: recent environmental changes and the post-glacial overview. In Battarbee, R.W., Mason, Sir John, Renberg, I. & Talling, J.F. (eds). *Palaeolimnology and Lake Acidification.* London. The Royal Society. pp123-130.

Axelrod, D.I. 1981. Role of volcanism in Climate and Evolution. *Geological society of America Special paper,185.*

Bache, B.W. 1986. Aluminium mobilization in soils and Waters. *J. Geol. Soc. London.* 143:699-706.

Baes, C.F. & McLaughlin, S.B. 1988. Trace metal uptake and accumulation in treees as affected by environmental pollution. In Hutchinson, T.C. & Meema, K.M. (eds) *Effects of atmospheric pollutants on forests, wetlands and agricultural ecosystems.* London. Springer-Verlag.

Baillie, M.G.L. 1988. *Tree-ring dating and Archaeology.* Croom Helm, Canberra.

Baillie, M.G.L. 1988. Irish Oaks Record Volcanic Dust Veils Drama. *Archaeol. Ireland* 2(2):71-74.

Baillie, M.G.L. and Munro, M.A.R. 1988. Irish tree rings, santorini and volcanic dust veils. *Nature.* 322:344-346.

Baillie, M.G.L. 1989a. Do Irish bog oaks date the Shang Dynasty. *Current Archaeology* 117:310-313.

Baillie, M.G.L. 1989b. Hekla 3: how big was it? *Endeavour. New Series.* 13(2):78-81.

Baillie, M.G.L. 1991a. Marking in marker dates: towards an archaeology with an historical precision. *World Archaeology.* 23(2):233-243.

Baillie, M.G.L. 1991b. Suck in and smear, two related chronological problems for the 90's. *J. Theoretical Archaeology.* 2:12-16.

Baldwin, P., Pollack, J.B., Summers, A., Toon, O.B., Sagan, C. & Van Camp, W. 1976. Stratospheric aerosols and Climatic Change. *Nature.*,263:551-555.

Ball, D.F. 1966. Brown podzolic soils and their status in Britain. *Journal of Soil Science.*,17.

Ball, D.F. 1975. Processes of soil degradation. In Evans, J.G. & Limbrey, S. (eds) *The effect of man on the Highland zone.* C.B.A.

Ball, T. 1992. Climatic change, droughts and their social impact: Central Canada, 1811-20, a classic example. In Harington, C.R. (ed) *The year without a summer? World climate in 1816.* Ottawa. Canadian Museum of Nature.

Barber, H.G, and Haworth, E.Y. 1981. *A guide to the morphology of the diatom frustule.* Ambleside, Freshwater Biological Research Association Scientific Publication *44*, 1-112.

Barberi, F., Macedonio, G., Pareschi, M.T. & Santacroce, R. 1990. Mapping the Tephra fallout risk: an example from Vesuvius, Italy. *Nature.* 344:142-144.

Barclay, G.J., Andrews, M.V., Blackham, A.M., Gilbertson, D.D., Lee, J.A., & van der Veen, M. 1985. Excavations at Upper Suisgill, Sutherland. *Proc. Soc Antiq. Scot.* 115:159-198.

Barker, T. *Meteorological Register made at Lyndon hall, Rutland.* Unpublished Manuscript: available in National meteorological Library and Archive. Bracknell U.K. (1777-1789)

Baron, W.R. 1992. 1816 in perspective: the view from the Northeastern United States. In Harington, C.R. (ed) *The year without a summer? World climate in 1816.* Ottawa. Canadian Museum of Nature.

Barrett, C.F., Atkins, D.H.F., Cape,J.N., Fowler, D., Irwin, J.G., Kallend, A.S., Martin, A., Pitman, J.I., Scriven, R.A. & Tuck, A.F. 1983. *Acid deposition in the United Kingdom.* Warren Spring laboratory.

Barrett, T.W. & Benedict, H.M. 1970. Sulphur dioxide. In Jacobsen, J.S. & Hill, A.C. (eds) *Recognition of air pollution injury to vegetation.* Air Pollution Control Association. Pittsburgh U.S.A.

Barrett, C.F. *et al.*, 1987. *Acid deposition in the United Kingdom 1981-1985.* Stevenage. Warren Spring Lboratory.

Battarbee, R.W., Flower, R.J., Stevenson, A.C., and Rippey, B. 1985. Lake acidification in Galloway: a palaeoecological test of competing hypotheses. *Nature 314*, 350-352.

Battarbee, R.W. 1986. Diatom Analysis. In Berglund, B.E. (ed) *Handbook of Holocene Palaeoecology and Palaeohydrology.* Chichester. John Wiley.

Battarbee, R.W. 1990. The causes of lake acidification, with special reference to the role of acid deposition. In Battarbee, R.W., Mason, Sir John, Renberg, I. & Talling, J.F. (eds). *Palaeolimnology and Lake Acidification.* London. The Royal Society. pp113-118.

Bednarz, Z. & Trepinka, J. Climatic conditions of 1815 and 1816 from tree-ring analysis in the tatra mountains. In Harington, C.R. (ed) *The year without a summer.* Ottawa. Canadian Museum of Nature.

Becker, B. Kromer, B. & Trimborn, P. 1991. A stable-isotope tree-ring timescale of the Late Glacial/Holocene boundary. *Nature.* 353:647-649.

Beget, J., Mason, O. & Anderson, P. 1992. Age, Extent and climatic significance of the c.3400 BP Aniakchak Tephra, western Alaska. USA. *The Holocene* 2(1):51-56.

Bellinger, E.G. 1974. A key to the identification of the more common algae found in British Waters. *Water Treatment and Examination 23* (1):76-131.

Bengstsson, L. and Enell, M. 1986. Chemical Analysis. In Berglund, B.E. (ed.). *Handbook of Holocene Palaeoecology and Palaeohydrology.* Chichester, John Wiley: 423 - 451.

Bennett, K.D. and Fossitt, J. 1989. A stand of birch by Loch Eynort, South Uist, Outer Hebrides. *Transactions of the Botanical Society of Edinburgh 45*, 245 - 252.

Bennett, K.D., Fossitt, J.A., Sharp, M.J. & Switsur, V.R. 1990. Holocene vegetational and environmental history at Loch Lang, South Uist, Western Isles, Scotland. *New Phytologist* 114:281-298.

Bennett, K.D., Boreham, S., Sharp, M.J. & Switsur, V.R. 1992. Holocene history of environment, vegetation and human settlement of Catta Ness, Lunnasting, Shetland. *Journal of Ecology* 80:241-73.

Berge, F., Brodin, Y.-W., Cronberg, G., El-Daoushy, F., Høeg, H.I., Nilssen< J.P. Renberg, I., Rippey, B., Sandøy, S., Wallin, J.E. & Wik, M. 1990. Recent acidification and biological changes in Lilla Öresjön, south-west Swedenand the relation to atmospheric pollution and land-use history. In Battarbee, R.W., Mason, Sir John, Renberg, I. & Talling, J.F. (eds). *Palaeolimnology and Lake Acidification.* London. The Royal Society. pp165-170.

Bernard, A., Demaiffe, D., Matielli, N, Punongbayan, R.S. 1991. Anhydrite bearing pumices from Mt. Pinatubo: Further evidence for the existence of sulphur-rich silicic eruptions. *Nature* 354:139-140.

Berrow, M.L. & Mitchell, R.L. 1980. Location of Trace elements in soil profiles: total extractable contents of individual horizons. *Transactions of the Royal Society of Edinburgh.* Series B 71:103-121.

Betzer, P.R., Carder, K.L., Duce, R.A., Merrill, J.T., Tindale, N.W., Uematsu, M., Costello, D.K., Young, R.W., Feely, A., Breland, J.A., Bernstein, R.E. & Greco, A.M. 1988. Long-range transport of giant mineral aerosol particles. *Nature.* 336:568-571.

Birks, H.J.B. 1991. Floristic and vegetational history of the Outer Hebrides. in Pankhurst, R.J. & Mullin, J.M. (eds) *Flora of the Outer Hebrides.* London. Natural History Museum.

Birks, H.J.B., Berge, F., & Boyle, J.F. 1990. A test of the land-use hypothesis for recent lake acidification by using hill-top lakes in southwest Norway: an extended summary. In Battarbee, R.W., Mason, Sir John, Renberg, I. & Talling, J.F. (eds). *Palaeolimnology and Lake Acidification.* London. The Royal Society. pp143-144.

Birks, H.J.B. and Madsen, B.J. 1979. Flandrian vegetational history of Little Loch Roag, Isle of Lewis, Scotland. *Journal of Ecology 67*, 825 - 842.

Birks, H.J.B. and Williams, W. 1983. Late Quaternary vegetational history of the Inner Hebrides. *Proceedings of the Royal Society of Edinburgh 83B*, 269 - 292.

Birse, E.L. 1971. *Assessment of climatic conditions in Scotland. The Bioclimatic Sub-Regions.* Macaulay institute for soil research, Aberdeen.

Björck, S., Sandgren, P. & Zale, R. 1991. Late Holocene tephrochronology of the northern Antarctic peninsula. *Quaternary Research.* 36:322-328.

Blackburn, K.B. 1946. On a peat from the island of Barra, Outer Hebrides. Data for the study of post-glacial history. *New Phytologist 45*, 44 - 49.

Blackford, J.J., Edwards, K.J., Dugmore, A.J., Cook, G.T. & Buckland, P. 1992. Hekla-4: Icelandic volcanic ash and the mid-holocene Scots Pine decline in northern Scotland. *The Holocene* 2(3):260-265.

Blong, R.J. 1984. *Volcanic Hazards: a source book on the effects of eruptions.* Sydney. Academic press.

Bohncke, S.J.P. 1988. Vegetation and habitation history of the Callanish area, Isle of Lewis, Sotland. In Birks, H.H., Birks, H.J.B., Kaland, P.E. and Moe, D. (eds.). *The Cultural Landscape: Past, Present and Future.* Cambridge, Cambridge University Press, 455 - 461.

Bolin, B., Aspling, G. Persson, C. 1974. Residence time of atmospheric polutants as dependent on source characteristics, atmospheric diffusion processes and sink mechanisms. *Tellus* 26:185-194.

Boyd, J.M. 1979. The natural environment of the Outer Hebrides. *Proc. Roy. Soc. Edinburgh* 77B:3-19.

Boyd, J.M. and Boyd, I.L. 1990. *The Hebrides: a natural history.* London. Collins,

Bradley, R.S. 1988. The explosive volcanic eruption signal in Northern Hemisphere continental temperature records. *Climatic Change.* 12:221-243.

Bradley, R.S.& England, J. 1978. Volcanic dust influence on glacier mass balance at high latitude. *Nature.* 271:736-738.

Bradley, R.S. & Jones, P.D. 1992. Records of explosive volcanic eruptions over the last 500 years. In Bradley, R.S. & Jones, P.D. (eds) *Climate since AD 1500.* Routledge, London.

Braitseva, O.A. & Meleketsev, I.V. 1990. Eruptve history of Karymsky volcano, Kamchatka, USSR, based on tephra stratigraphy and ^{14}C dating. *Bulletin Volcanologique* 53:195-206.

Branigan, K. 1988. *SEARCH interim report on the reconnaiscance survey of the Borve valley, Barra. June 1988.* Dept. Archaeology and Prehistory. University of Sheffield.

Branigan, K. 1990. *SEARCH interim report on the reconnaiscance survey of the Borve valley, Barra. 1990..* Dept. Archaeology and Prehistory. University of Sheffield.

Bray, J.R. 1974. Volcanism and glaciation during the past 40 millenia. *Nature* 252:679-680.

Bray, J.R. 1978. Volcanic eruptions and climate during the past 500 years. In Pittock, A.B. Frakes, L.A., Jennsen, D., Petersen, D.A. & Zillman, J.W. (eds) *Climatic change and variability.* Cambridge. C.U.P.

Bray, J.R. 1979. Surface albedo increase following massive Pleistocene explosive eruptions in Western North America. *Quaternary Research* 12:204-241.

Brayshay, B.A. 1992. *The vegetation and vegetational history of Barra and South Uist in the Outer Hebrides of Scotland.* Unpublished Ph.D. dissertation, University of Sheffield.

Bridge, M.C., Haggart, B.A. & Lowe, J.J. 1990. The history and palaeoclimatic significance of subfossil remains of Pinus Sylvestris in blanket peats from Scotland. *Journal of Ecology* 78:77-99.

Bridges, E.M. 1978. Interaction of soil and mankind in Britain. *Journal of Soil Science.* 29:125-139.

Briffa, K.R., Bartholin, T.S., Eckstein. D., Jones, P.D., Karlén, W., Schweingruber, F.H. & Zetterburg, P. 1990. A 1400-year tree-ring record of summer temperatures in Fennoscandia. *Nature* 346:434-439.

Briffa, K.R. & Jones, P.D. 1992. The climate of Europe during the 1810's with special reference to 1816. In Harington, C.R. (ed) *The year without a summer.* Ottawa. Canadian Museum of Nature.

Briffa, K.R., Jones, P.D., Wigley, T.M.L., Pilcher, J.R. and Baillie, M.G.L. 1986. Climate reconstruction from tree rings:part 2, spatial reconstruction of summer mean sea-level pressure patterns over Great Britain. *Journal of Climatology* 6:1-15.

Briffa, K.R., Jones, P.D. & Schweingruber, F.H. 1988. Summer temperatures over Europe: A reconstruction from 1750 AD based on maximum latewood density indices of conifers. *Quaternary Research.* 30:36-52.

Briffa, K.R. & Schweinguber, F.H. 1992. Recent dendroclimatic evidence of northern and central European summer temperatures. In Bradley, R.S. & Jones, P.D. (eds) *Climate since AD 1500.* London. Routledge, .

Brown, D.J.A., & Turnpenny, A.W.H. 1988. Effects on Fish. In Ashmore, M., Bell, N., & Garretty, C. (eds) *Acid rain and Britain's natural ecosystems.* ICCET.

Brown, W.H., Peczkis, J. 1984. Nuclear war - counting the cost. *Nature* 310:455.

Brun, J.N., 1786. *Johann Nordahl Bruns Prædikan paa Nytaars Dag 1786. i Adlening af Collection for Island.* Bergen. Rasmus H. Dahl.

Bryson, R.A., Lamb, H.H. and Donley, D.L. 1974. Drought and the decline of Mycenae. *Antiquity* 68:46-50.

Bryson, R.A. and Goodman, B.M. 1980. Volcanic Activity and climatic changes. *Science* 207:1041-1044.

Bryson, R. A. 1989. Late Quaternary volcanic modulation of Milankovitch climatic forcing. *Theoretical and applied climatology* 39:115-125.

Buckland, P.C., Foster, P., Perry, D.W. & Savory, D. 1981. Tephrochronology and palaeoecolgy: the value of isochrones. In Self, S. & Sparks, R.S.J. (eds) *Tephra studies.* Amsterdam. Reidel.

Bull, K. 1991. Critical load maps for the U.K. *NERC news July*:31-32.

Bullard, F.M. 1976. *Volcanoes of the Earth* University of Austin, Texas.

Burbank, D.W. 1981. A Chronology of late Holocene glacier fluctuations at Mt. Rainier, Washington. *Arctic and Alpine Research* 13:369-386.

Burbank, D.W. 1982. Correlations of Climate, Mass balances and glacier fluctuations at Mount Rainier, Washington, U.S.A. *Arctic and Alpine Research* 14:137-148

Burgess, C. 1985. Population, climate and upland settlement. In *Upland settlement in Northern Britain* BAR 143:195-229.

Burgess, C. 1989. Volcanoes, catastrophe and the global crisis of the late second millenium BC. *Current Archaeology* 117:325-329.

Burke, K. & Francis, P. 1985. Climatic effects of volcanic eruptions. *Nature* 314:136.

Burton, Captain. 1875. The Volcanic eruptions of Iceland in 1864 and 1865. *Proc. R. Soc. Edinburgh* Vol 10. 1875-76:44-58.

Butler, S. 1992. X-Radiography of Archaeological soil and sediment profiles. *J. Arch. Science* 19:151-191.

Butzer, K.W. 1982. *Archaeology as Human ecology.* Cambridge University Press. Cambridge.

Cadle, R.D., Kiang, C.S. & Louis, J.F. 1976. The global scale dispersion of the eruptión clouds from major Volcanic eruptions. *Journal of Geophysical Research* 81(18):3125-3132.

Cadogan, G. 1988. Dating the Santorini eruption. *Nature* 332:402.

Caird, J.B. 1979. Land use in the Uists since 1800. *Proceedings of the Royal Society of Edinburgh 77B*, 505 - 527.

Caldeira, K. & Rampino, M. 1992. Mt Etna CO_2 may affect climate. *Nature* 355:401-402.

Caput, C., Belot, Y., Auclair, D. & Decourt, N. 1978. Absorption of Sulphur Dioxide by Pine needles leading to acute injury. *Environmental Pollution* 16:3-15.

Carey, S.N. & Sigurdsson, H. 1982. Transport and deposition of distal tephra from the May 1980 eruption of Mt. St. Helens. *Journal of Geophysical Research* 87:7061-7072

Carignan, R. and Flett, R.J. 1981. Post-depositional mobility of phosphorous in lake sediments. *Limnology and Oceanography* 26: 361-366.

Castleman, A.W., Munkelwitz, H.R. & Manowitz, B. 1974. isotopic studies of the stratospheric aerosol layer. *Tellus* 26:222-234.

Catchpole, A.J.W. 1992a. River ice and sea ice in the Hudson Bay region during the second decade of the Nineteenth century. In Harington, C.R. (ed) *The year without a summer? World climate in 1816*. Ottawa. Canadian Museum of Nature.

Catchpole, A.J.W. 1992b. Hudson's bay Company ships' log books as sources of sea-ice data, 1751-1870. In Bradley, R.S. & Jones, P.D. (eds) *Climate since AD 1500*. London. Routledge.

Chia-hsi, W., Da-fu, Q., Zheng-fang, L., Xu-ping, G., Shu-yu, T. & Ru-gui, P. 1982. Selection of plants resistant, Absorptive and sensitive to air pollutants. In Unsworth, M.H. & Ormrod, D.P. (eds) *Effects of gaseous air pollution in agriculture and horticulture*. London. Butterworth.

Chester, D.K. 1988. Volcanoes and Climate: recent volcanological perspectives. *Progress in Physical Geography* 12(1):1-35.

Chou, M.-D., Peng,L. & Arking, A. 1984. Climate Studies with a multi-layer balance model. Part III: Climatic impact of Stratospheric Volcanic Aerosols. *J. Atmos. Sci.* 41:759-767.

Chuan, R.L., Woods, D.C. & McCormick, M.P. 1981. Characterization of aerosols from the eruptions of Mt. St. Helens. *Science* 211:830-382.

Clausen, H.B. & Hammer, C.U. 1988. The Laki and Tambora eruptions as revealed in Greenland Ice Cores from 11 locations. *Annals of Glaciology* 10:16-22.

Cleaveland. M.K. 1992. Volcanic effects on Colorado plateau douglas fir-tree rings. In Harington, C.R. (ed) *The year without a summer? World climate in 1816*. Ottawa. Canadian Museum of Nature.

Clymo, R.S., Oldfield, F., Appleby, P.G. Pearson, G.W., Ratnesar, P. & Richardson, N. 1990. The record of atmospheric deposition on a rainwater dependent peatland. In Battarbee, R.W., Mason, Sir John, Renberg, I. & Talling, J.F. (eds). *Palaeolimnology and Lake Acidification*. London. The Royal Society. pp105-112.

Cobb, F.W., Wood. A.L., Stark, R.W. Parameter, J.R. 1968. Photochemical oxidant injury and bark beetle (*Coleoptera Scolytidae*) infestation of ponderosa pine. *Hilgardia* 39:121-152.

Conkey, L.E. 1986. Red Spruce tree-ring widths and densities in Eastern North America as indicators of past climate. *Quaternary Research* 26:232-243.

Cook, E.R. 1988. The use and limitations of dendrochronology in studying effects of air pollution in forests. In Hutchinson, T.C. & Meema, K.M. (eds) *Effects of atmospheric pollutants on forests, wetlands and agricultural ecosystems*. London. Springer-Verlag,

Cook, E.R., Bird, T., Peterson, M., Barbetti, M., Buckley, B., D'Arrigo, R. & Francey, R. 1992. Climatic change over the last millennium in Tasmania reconstructed from tree-rings. *The Holocene* 2(3):205-217.

Cook, E.R., Stahle, D.W. & Cleaveland, M.K. 1992. Dendoclimatic evidence from eastern North America. In Bradley, R.S. & Jones, P.D. (eds) *Climate since AD 1500*. Routledge, London.

Cook, R.J., Barron, J.C., Papendick, R.I. & Williams, G.J. 1981. Impact on agriculture of the Mt.St. Helens eruptions. *Science* 211:16-22

Cormie, A.B., Nelson, D.E. and Huntley, D.J. 1981. X-Ray fluorescence analysis as a rapid method of identifying tephras discovered in archaeological sites. In, Self,S. and Sparks, R.S.J. (eds) *Tephra Studies.* Amsterdam. Reidel:103-107.

Courtillot, V.E. 1990. Deccan volcanism at the Cretaceous-Tertiary Boundary: past climatecrisis as a key to the future. *Palaeo', Palaeo', Palaeo'.* 189:291-299.

Courtillot, V.E. 1990. A volcanic eruption. *Scientific American.* 263:53-60.

Coward, M.P. 1972. The Eastern Gneisses of South Uist. *Scottish Journal of Geology* 8(1):1-12.

Cresser, M.S., Harriman, R. & Pugh, K. 1988. Processes of acidification in soils and freshwater. In Ashmore, M., Bell, N., & Garretty, C. (eds) *Acid rain and Britain's natural ecosystems.* ICCET.

Cresser, M.S., Pugh, K.B. & Edwards, A.C. 1987. Soils and surface water quality in northeast Scotland. *Trans. R. Soc. Edinburgh. Series B.* 78:399-404.

Craker, L.E. & Bernstein, D. 1984. Buffering of acid rain by leaf tissue of selected crop plants. *Environmental Pollution* A 36:375-382.

Cronin, J.F. 1971. Recent volcanism and the stratosphere. *Science.* 172:847-849.

Cruz-Renya, S. De La. 1991. Poisson-distributed patterns of explosive eruptive activity. *Bulletin Volcanologique* 54:57-67.

Currie, R.G. 1991. Deterministic signals in Tree-rings from North America. *International Journal of Climatology* 11(8):861-876.

Cullum, Rev. Sir John. 1783. Of a remarkable frost on the 23rd of June, 1783. *Philosophical Transactions of the Royal Society. Abridged volume (15)1781-1785*:604.

Cunningham, P. 1938. *The letters of HORACE WALPOLE. Volume VIII.* Richard Bentley, London.

Currie, A. 1979. The vegetation of the Outer Hebrides. *Proceedings of the Royal Society of Edinburgh 77B*, 219 - 265.

Dai, J., Mosley-Thompson, E., & Thompson, L.G. 1991. Ice core evidence for an explosive volcanic eruption 6 years preceding Tambora. *J. Geophysical Research.* 96 (D9):17361-17366.

Danielsen,E.F. 1981. Trajectories of the Mt. St. Helens eruption plume. *Science.* 211:819-821.

Danny Harvey, I.D. 1988. Climatic impact of ice age aerosols. *Nature.* 334:333-335.

D'Arrigo, R.D. & Jacoby, G.C. 1991. A 1000 year record of winter precipitation from northwestern New Mexico, USA: a reconstruction from tree-rings and its relation to El Niño and the Southern Oscillation. *The Holocene.* 1(2):95-101.

D'Arrigo, R.D. & Jacoby, G.C. 1992. Dendroclimatic evidence from northern North America. In Bradley, R.S. & Jones, P.D. (eds) *Climate since AD 1500.* London. Routledge.

Davies,T.D., Abrahams, P.W., Tranter, M., Blackwood, I., brimblecombe, P., Vincent, C.E. 1984. Black acidic snow in the remote Scottish Highlands. *Nature.* 312:58-61.

Davis, J.O. 1985. Correlation of Late Quaternary tephra Layers in a long pluvial sequence near Summer Lake, Oregon. *Quaternary Research.* 23:38-53.

De'er, Z. 1991. Historical records of climate change in China. *Quaternary Science Reviews.* 10:551-554.

Deepak, A. & Newell, R.E. (Eds).1982. *Mt. St. Helens eruptions of 1980.* (Atmospheric effects and potential climatic impact.) NASA. SP 458.

DeLuisi, J.J., Dutton, E.G., Coulson, K.L., DeFoor, T.E. & Mendonca, B.G. 1983. On some radiative features of the El Chichón volcanic stratospheric dust cloud and a cloud of unknown origin observed at Mauna Loa. *J. Geophys. Res.* 88:6789-6772.

Denton, G.H. & Karlén. W. 1977. Holocene glacial and tree-line variations in the White River Valley and Skolai pass, Alaska and Yukon Territory. *Quaternary Research* 7:63-111.

Derwent, R.G., Hopper, S., & Metcalfe, S.E. 1988. *Computer modelling studies of the origins of the acidity deposited in Scotland.* Harwell: Atomic Energy REsearch Establishment, report no. 13328.

Devine, J.D., Sigurdsson, H. Davis, A.N. & Self.S. 1984. Estimates of Sulfur and Chlorine yield to the Atmosphere from volcanic eruptions and potential climatic effects. *Journal of Geophysical Research.* 89:6309-6325.

Dimbleby, G.W. 1962. The development of British heathlands and their soils. *Forestry Memoir,* No.23.

Dimbleby, G.W. 1965. Post - Glacial changes in Soil Profiles. *Proc. R. Soc.* B161:355-362.

Dimbleby, G.W. 1976. Climate, Soil and Man. *Phil. Trans. R. Soc.* B275:197-208.

D'Itri, F.M. (ed) 1982 *Acid precipitation Effects on ecological systems.* Ann Arbor. Seven Seas.

Dittberner, G.J. 1978. Climatic Change: volcanoes, man-made pollution and Carbon Dioxide. *IEEE Trans. Geosci. Electron.* GE-16:50-61.

Dodgshon, R.A. 1988. The ecological basis of Highland peasant farming, 1500-1800AD. In Birks, H.H. Et al. (eds) 1988. *The cultural landscape: past, present and future.* Cambridge. C.U.P. :139-151.

Dugmore, A.J. 1989. Icelandic volcanic ash in Scotland. *Scottish geographical magazine.* 105.3.:168-172.

Dugmore, A.J., Buckland, P. 1991. Tephrochronology and Late Holocene Soil Erosion in South Iceland. In Maizels, J.K. & Caseldine, C. (eds) *Environmental Change in Iceland: Past and present.* Kluwer. Netherlands.

Dugmore, A.J., Newton, A.J. 1992. Thin tephra layers in Peat revealed by X-radiography. *J. Arch. Science.* 19:163-170.

Dugmore, A.J, Newton, A.J., Sugden, D.E., & Larsen, G. 1992. Geochemical stability of fine-grained silicic Holocene Tephra in Iceland and Scotland. *Journal of Quaternary Science.* 7(2):173-183.

Dutton, E.G. 1990. Comments on "Major volcanic eruptions and climate: a critical evaluation." *Journal of Climate.* 3:587-588.

Dyer, T.G.J. 1976. An Analysis of Manley's central England temperature data. *Quart. J. Royal Meteorological Society.* 102:153-155.

Eddy, J.A. 1977. Climate and the changing sun. *Climatic Change* 1:173-190.

Eddy, J.A. 1992. Before Tambora: the sun and climate. In Harington, C.R. (ed) *The year without a summer.* Ottawa. Canadian Museum of Nature.

Edmunds, W.M. & Coe, K. 1986. Geochemical aspects of Acid rain. *J. Geol. Soc. London.* 143:619-620.

Edwards, K.J. 1990. Fire and the Scottish Mesolithic: Evidence from Microscopic Charcoal. In Vermeersch, P.M. and Van Peer, P. (eds.). *Contributions to the Mesolithic in Europe.* Leuven, Leuven University Press, 71 - 79.

Edwards, K.J. & Rowntree, K.M. 1980. Radiocarbon and palaeoenvironmental evidence for changing rates of erosion at a Flandrian stage site in Scotland. In Cullingford, R.A., Davidson, D.A., and Lewin, J. (eds.) *Timescales in Geomorphology.* Chichester, John Wiley, 207 - 23.

Einarsson, T., Kjartansson, G. & Thórarinsson, S. 1957 *The eruption of Hekla 1947-1948.* H.F. Leiftur, Rekyavik.

Einarsson, T. 1986. Tephrochronology. In Berglund, B.E. (ed) Handbook of Holocene *Palaeoecology and Palaeohydrology.* Chichester. Wiley.

Eiriksson, J., Wigum, B.J. 1989. The morphometry of selected tephra samples from Icelandic volcanoes. *Jökull.* 39:57-73.

El-Daoushy, F. 1990. Lead-210 chronology of the Scandinavian SWAP sites. In Battarbee, R.W., Mason, Sir John, Renberg, I. & Talling, J.F. (eds). *Palaeolimnology and Lake Acidification.* London. The Royal Society.

Ellsaesser, H.W. 1986. Comments on "Surface temperature changes following the six major volcanic episodes between 1780 and 1980". *Journal of Climate and Applied Meteorology* 25:1184-1185.

Engstrom, D.R. 1983. *Chemical stratigraphy of lake sediments as a record of environmental change.* Unpublished PhD thesis. University of Minnesota.

Engstrom, D.R. and Wright, H.E. 1984. Chemical stratigraphy of lake sediments as a record of environmental change. In Haworth, E.Y. and Lund, J.W.G. *Lake Sediments and Environmental History.* Leicester, Leicester University Press, 11 - 67.

Epstein, S. & Krishnamurthy, R.V. 1990. Environmental information in the isotopic record in trees. *Phil. Trans. R. Soc. Lond.* A 330:427-439

Evans, L.S. 1984. Acidic precipitation effects on terrestrial vegetation. *Ann. Rev. Phytopath.* 22:397-442.

Evans, L.S. & Lewin, K.F. 1988. Perspectives on establishing the relationship between acidic deposition and vegetation response. In Hutchinson, T.C. & Meema, K.M. (eds) *Effects of atmospheric pollutants on forests, wetlands and agricultural ecosystems.* Springer-Verlag, London, Paris, Tokyo.

Farlow, N.H., Oberbeck, V.R., Sneitsinger, K.G, Ferry, G.V., Polowski, G. & Hayes, D.M. 1981. Size distributions and mineralogy of ash particles in the Stratosphere from the eruptions of Mt. St. Helens. *Science.* 211:832-834.

Farmer, J.G. 1991. The perturbation of historical pollution records in aquatic sediments. *Environmental Geochemistry and Health* 13(2):76-83.

Farmer, J.G., Swan, D.S., and Baxter, M.S. 1980. Records and sources of metal pollutants in a dated Loch Lomond Sediment. *Environmental Science and Technology 15*, 553-558

Fayle, D.C., Bentley, C.V. & Scott, P.A. 1992 How did treeline white spruce at Churchill Manitoba, respond to conditions around 1816? In Harington, C.R. (ed) *The year without a summer.* Ottawa. Canadian Museum of Nature.

Fernandez, I.J. 1989. Effects of acid precipitation on soil productivity. In Adriano, D.C., & Johnson A.H. (eds) *Acidic Precipitation. Volume 2: Biological and ecological effects.*:61-80. Springer-Verlag.

Filion, L., Payette, S., Gauthier, L. & Boutkin, Y. 1986. Light rings in subarctic conifers as a Dendroecological tool. *Quaternary Research* 26:272-279

Fisher, B. 1981. Acid rain - the long range transport of air pollutants. *Weather* 36:367-369.

Fitzharris, B.B., Hay, J.E. & Jones, P.D. 1992. Behaviour of New Zealand glaciers and atmospheric circulation changes over the past 130 years. *The Holocene* 2,2:97-106.

Fleming.A. 1983. The Prehistoric landscape of Dartmoor. *Proc Prehistoric soc.* 49.75-123.

Flohn, H. 1978. Abrupt events in climatic history. In Pittock, A.B. Frakes, L.A., Jennsen, D., Petersen, D.A. & Zillman, J.W. (eds) *Climatic change and variability.* Cambridge. C.U.P.

Flohn, H. 1979. On time scales and causes of abrupt palaeoclimatic events. *Quaternary Research* 12:135-149.

Flower, R.J. and Nicholson, A.J. 1987. Relationships between bathymetry, water quality and diatoms in some Hebridean lochs. *Freshwater Biology 18*, 71 - 85.

Fowler, P.D. 1984. Transfer to terrestrial surfaces. *Phil. Trans. R. Soc. Lond.* B 305:281-297.

Fox, W.F. 1985. The Adirondack black spruce. *Forest Commission, State of New York annual report 1984.* pp10-14

Franklin, B. 1784. Meteorological Imaginations and Conjectures. *Mem. Lit. Philos. Soc. Manchester.* 2:373-377.

Fraedrich, K & Müller, K. 1992. Climate anomalies in Europe associated with ENSO extremes. *International Journal of Climatology* 12(1):25-31.

Frenzel, B. 1966. *World climate from 8000-0 BC.*:99-123.

Fritts, H.C., Lofgren, R.G. & Gordon, G.A. 1979. Variations in climate since 1602 as reconstructed from tree-rings. *Quaternary Research* 12:18-46.

Fritts, H.C., Lofgren, R.G. & Gordon, G.A. 1981 Reconstructing seasonal to century time scale variations in climate from tree ring evidence. In Wigley, T.M.L., Ingram, M.J. & Farmer, G. (Eds) *Climate and History: Studies in past climates and their impact on man.* Cambridge. C.U.P.

Fritts, H.C & Shao, X.M. 1992. Mapping climate using tree-rings from western North America. In Bradley, R.S. & Jones, P.D. (eds) *Climate since AD 1500.* Routledge, London.

Fuge, R. & Andrews, M.J. 1988. Fluorine in the U.K. environment. *Environmental Geochemistry and Health* 10 (3/4):96-104.

Futty, D.W. & Dry, F.T. 1977. *The soils of the country around Wick.* Mem. Soil Survey Scotland. Aberdeen. Macauley Institute for Soil Research.

Futty, D.W. & Towers, W. 1982. *Soil and Land Capability for Agriculture. Northern Scotland.* Soil Survey of Scotland. Macaulay Institute.

Gagen, C. & Sharpe, W. 1987. Influences of acid run-off episodes on survival and new sodium balance of brook trout Salvelinus fontinalis confined in a mountain stream In Witters, H. & Vanderborght, O. (eds) Ecophysiology of acid stress in aquatic organisms. *Ann. Soc. R. Zool. Belg.* 117:219-230.

Gandrud, B.W. & Lazrus, A.L. 1981. Filter measurements of Stratospheric sulphate and chloride in the eruption plume of Mt. St. Helens. *Science.* 211:826-827.

Garrec, J.P., Lounowski, A. & Plebin, R. 1977. The influence of volcanic fluoride emissions on the surrounding vegetation. *Fluoride.* 10:153-156.

Gates, T. 1983. Upland agriculture in Northumberland. In Chapman, J.C. & Mytum, H.C. (eds) *Settlement in North Britain 1000 BC - 1000 AD. B.A.R.* 118:103-148.

Gearey, B. 1992. *Pollen taphonomy in a windy climate: Northbay, Barra.* Unpublished M.Sc. dissertation, University of Sheffield.

Gee, A.S., Stoner, J.H. 1988. The effects of afforestation and acid deposition on the Water quality and ecology of upland Wales. In Usher, M.B. & Thompson. D. B. A. *Ecological change in the Uplands.* Oxford. Blackwell..

Geikie, Sir A. 1893. *Text-Book of Geology.* London. Macmillan.

Gerlach, T.M. 1991. Etna's Greenhouse pump. *Nature.* 351:352-353.

Gerlach, T.M., Graeber, E.J. 1985. Volatile budget of Kilauea volcano. *Nature* 313:273-277.

Gerrard, J. 1991. An Assessment of some of the factors involved in recent landscape change in Iceland. In Maizels, J.K. & Caseldine, C. (eds) *Environmental Change in Iceland: Past and present.* Kluwer. Netherlands.

Giddings, J.L. 1941. Dendrochronology in northern Alaska. *University of Arizona Bulletin* 12(4):1-107

Gilbert,J.S., Lane, S.J., Sparks, R.S.J. & Koyaguchi, T. 1991. Charge measurements on particle fallout from a volcanic plume. *Nature* 349:598-600.

Gilbertson, D.D. & Pyatt, F.B. 1980. Tree crown foliage loss: a mapping survey on the Cumbrian coast. *Journal of Biological Education.* 14(40:311-317.

Gilbertson, D.D., Flenley, E.C., Fieller, N.R.J., Powers, A.H. & Padmore, J., 1991. The analogue approach in the reconstruction of ancient human environments: Statistical studies of opal phytoliths and grain size distributions. *Archeologia Del Paesaggio* 1:165-204.

Gilbertson, D.D., Kent, M, Scwenniger, J-L., Wathern, P.A., Weaver, R. & Brayshay,, B.A. In Press. The Machair vegetation of South Uist and Barra in the Outer Hebrides: Its ecological, Geomorphic and historical dimensions. *In* Roberts, N. (ed) *Ecological relations in Historical times.* London. Longmann

Gilliland, R.L. 1982. Solar, volcanic and CO_2 forcing of recent climatic changes. *Climatic change* 4:111-131.

Giordiadis, T., Strocchi, V., Fortezza, F., Lucialli, P., Bonasoni, P. & Giovanelli, G. 1993. Removal of sulphur dioxide and sulphates from the atmospheric surface layer during frost formation. *Water, Air, And Soil Pollution.* 66 (3/4):267-276.

Godwin, Sir H. 1975. *The history of British Flora.* C.U.P.

Goldstein, I., Newbury, E., Echlin, P., Joy, D.C., Fiori, C. and Lifshin, E. 1984. *Scanning electron microscopy and x-ray microanalysis.* Plenum Press. London

Glentworth, R. 1979. Observations on the soils of the Outer Hebrides. *Proc. Roy. Soc. Edinburgh* 77B:123-137.

Graumlich, L.J., Brubaker, L.B. 1986. Reconstruction of annual temperature (1590-1979) for Longmire, Washington, derived from tree-rings. *Quaternary research* 25:223-234.

Grace, J., Unsworth, M.H. 1988. Climate and Micro-climate of the uplands. In Usher, M.B. & Thompson. D. B. A. *Ecological change in the Uplands*. Blackwell. Oxford.

Grayson, D.K. & Sheets, P.D. 1979. Volcanic disasters and the archaeological record. In Grayson, D.K. & Sheets, P.D (eds) *Volcanic activity and human ecology*. Amsterdam. Reidel.

Griggs, R.F. 1922. *The Valley of Ten Thousand Smokes*. National Geographic Society.

Graybill, D.A. & Shiyatov, S.G. 1992. Dendroclimatic evidence from the northern Soviet Union. In Bradley, R.S. & Jones, P.D. (eds) *Climate since AD 1500*. London. Routledge,

Gronvold, K. & Johannesson, H. 1984. Eruption in Grímsvötn, 1983. *Jökull* 34:1-11.

Gudmundsson, A. Oskarsson, N., Gronvold, K., Saemundsson, K., Sigurdsson, O., Stafansson, R., Gislason, S.R., Einarsson, P., Brandsdottir, B., Larsen, G., Johannesson, H., & Thordarson, T. 1992. The 1991 eruption of Hekla, Iceland. *Bulletin Volcanologique* 54:238-246.

Gunnlaugsson, G.A. 1984. The population of Vestur -Skaftafellssysa and the Laki eruption. In Gunnlaugsson, G.A., Gudbergsson, G.M., Thorarinsson, S., Raffnson, S. & Einarsson, T. (eds) *Skáftareldar 1783-1784*. Rekyavik. Mal Og Menning. (In Icelandic with English summaries).

Gunnlaugsson, G.A., Gudbergsson, G.M., Thorarinsson, S., Raffnson, S. & Einarsson, T. 1984. *Skáftareldar 1783-1784*. Rekyavik. Mal Og Menning. (In Icelandic with English summaries.)

Guthbergsson, G.A. & Theodórsson, T. 1984. Effects of Lakagígar eruption on population and settlement in Leithvallar and Kleifa communes. In Gunnlaugsson, G.A., Gudbergsson, G.M., Thorarinsson, S., Raffnson, S. & Einarsson, T. (eds) *Skáftareldar 1783-1784*. Rekyavik. Mal Og Menning. (In Icelandic with English summaries).

Hálfdanarson, G. 1984. Loss of human lives following the Laki eruption. In Gunnlaugsson, G.A., Gudbergsson, G.M., Thorarinsson, S., Raffnson, S. & Einarsson, T. (eds) *Skáftareldar 1783-1784*. Rekyavik. Mal Og Menning. (In Icelandic with English summaries).

Hall, V.A., Pilcher, J.R. & McCormac, F.G. 1993. Tephra dated lowland landscape histroy of the north of Ireland, A.D. 750-1150. *New Phytologist* 125:193-202.

Halliday,S.P. 1982. Later pre-historic farming in S.E.Scotland. In,Harding,D.W.(ed)*Later pre-historic settlement in S.E.Scotland*. pp74-91.1

Hammer, C.U. 1984. Traces of Icelandic Eruptions in the Greenland Ice sheet. *Jökull*. 34:51-65.

Hammer, C.U. 1977. Past volcanism revealed by Greenland ice sheet impurities. *Nature*., 270:482-486.

Hammer, C.U., Clausen, H.B. & Dansgaard W. 1980. Greenland ice sheet evidence of post glacial volcanism and its climatic impact. *Nature*. 288:230-235.

Hammer, C.U., Clausen, H.B. & Dansgaard W. 1981. Past volcanism and climate revealed by Greenland ice cores. *J. Volcanol. Geotherm. Res.*, 11:3-10.

Hammer, C.U., Clausen, H.B.,Friedrich, W.L. & Taubert, H.H. 1987. A Minoan eruption of Santorini in Greece dated to 1645 BC. *Nature*. 328:517-519.

Hammer, C.U., Clausen, H.B.,Friedrich, W.L. & Taubert, H.H. 1988. Dating of the Santorini eruption. *Nature*. 332:401.

Handler, P. 1986a. Possible association between the climatic effects of stratospheric aerosols and sea surface temperatures in the eastern tropical Pacific Ocean. *Journal of Climatology* 6:31-41.

Handler, P. 1986b. Stratospheric Aerosols and the Indian monsoon. *Journal of Geophysical Research*, Vol 91(D13):14475-14490.

Handler, P. & Andsager, K. 1990. Volcanic Aerosols, El Niño and the Southern Oscillation. *International Journal of Climatology* 10:413-424. More of above. See Nicholls criticism.

Handler, P. & O'Neill, B. 1987. Simultaneity of response of Atlantic Ocean Tropical Cyclones and Indian Monsoons. *Journal of Geophysical Research*. Vol 92, No C13:14621-14630.

Handler, P. 1989. The effect of volcanic aerosols on the global climate. *J. Volcanol. Geotherm. Res.*, 37:233-249.

Hansen, J.E., Wang, W. and Lacis A.A. 1978. Mount Agung eruption provides test of a global climatic perturbation. *Science*. 199:1065-1068.

Hansen, J.E. & Lacis, A.A. 1990. Sun and dust versus greenhouse gases: an assessment of their relative roles in global climate change. *Nature* 346:713-719.

Harington, C.R. (ed) *The year without a summer*. Ottawa. Canadian Museum of Nature.

Harshvardhan, 1979. Perturbation of the Zonal radiation balance by a stratospheric aerosol layer. *J. Atmos. Sci.* 36:1274-1285.

Hays, J.D., Imbrie, J. and Shackleton, N.J. 1976. Variations in the Earth's orbit: Pacemaker of the ice ages. *Science*. 194:1121-1131.

Heidam, N.Z. 1986. The Greenland Aerosol: elemantal composition, seasonal variations and likely sources. In Stonehouse, B.(ed) *Arctic Air Pollution*. Cambridge. Cambridge University Press.

Herron, M.M. 1982. Impurity sources of F, Cl, NO and SO in Greenland and Antarctic precipitation. *Journal of geophysical research*, 87:3052-3060.

Heslop Harrison, J.W. and Blackburn, K.B. 1946. The occurence of a nut of *Trapa natans* L. in the Outer Hebrides, with some account of the peat-bogs adjoining the loch in which the discovery was made. *New Phytologist 45*, 124 - 131.

Hingane, L.S., Rupa Kumar, K. & Patil, S.D. 1990. Low-Latitude Volcanic Eruption Signal In Indian Surface Air Temperatures. *International Journal of Climatology* 10:703-709.

Hirschboek, K.K. 1979. A new worldwide chronology of volcanic eruptions. *Palaeogeography, Palaeoclimatology, Palaoecology.* 29:223-241.

Hobbs, P.V., Radki, L.F., Eltgroth, M.W., & Hegg, D.A. 1981. Airborne studies of the emissions from the volcanic eruptions of Mt. St. Helens. *Science.* 211:816-818.

Hodder, A.P.W., De Lange, P.J. & Lowe, D.J. 1991. Dissolution and depletion of ferromagnesian minerals from Holocene tephra layers in an acid bog, New Zealand, and implications for tephra correlation. *Journal of Quaternary Science* 6(3):195-208.

Hofmann, D.J. 1987. Perturbations to the global atmosphere associated with the El Chichon volcanic eruption of 1982. *Reviews of Geophysics.* 25(4):743-759.

Holdren, G.R. Brunelle, T.M. Matisoff, G. & Whalen, M. 1984. Timing the increase in atmospheric sulphur deposition in the Adirondack Mountains. *Nature* 311:245-248.

Hollstein, E. 1980. *MittelEuropaische Eichenchronologie.* Mainz am Rhein: Philip Von Zabern.

Holdsworth, G., Krouse, H.R., & Nosal, M. 1992. Ice core signals from Mount Logan, Yukon A.D. 1700-1897. In Bradley, R.S. & Jones, P.D. (eds) *Climate Since AD 1500.* London. Routledge.

Horstmeyer, S.L. 1989. In search of Cincinnati's weather. *Weatherwise* 42:320-327.

Hoyt, V.D. 1978. An explosive volcanic eruption in the southern hemisphere in 1928. *Nature.* 275:630-632.

Hoyt, D.V. & Siquig, R.A. 1982. Possible influences of Volcanic Dust Veils or changes in Solar Luminosity on Long-Term temperature Trends. *Journal of Atmospheric Science* 39:680-685

Hudson, G. 1988. Effects of latitude, oceanicity and geology on alpine and sub-alpine soils in Scotland. In Usher, M.B. & Thompson. D.B.A. *Ecological change in the Uplands.* Oxford. Blackwell.

Hudson, G. 1991. The geomorphology and soils of the Outer Hebrides. In Pankhurst, R.J. and Mullins, J. (*eds.*). *Flora of the Outer Hebrides.* London, Natural History Museum Publications :19 - 27.

Hudson, G. Towers, W. Bibby, J.S. & Henderson, D.J. 1982. *Soil and land capability for agriculture: The Outer Hebrides.* Macauley Institute for Soil Research. Aberdeen.

Hughes, M.K., Scweingruber, F.H., Cartwright, D. & Kelly, P.M. 1984. July-August temperature at Edinburgh between 1721 and 1975 from tree-ring density and width data. *Nature* 308:341-344.

Humphreys, W.J. 1920. *Physics of the Air.*, New York, McGraw-Hill; 2nd edn 1940.

Hunt, B.G. 1977. A simulation of the posiible consequences of a vlcanic eruption on the general circulation of the atmosphere. *Monthly Weather Review.*105:247-260.

Hunt,D. 1987. Early farming communities in Scotland. *British Archaeological Reports.* 159.

Hunt, J. 1993. Report on the 2nd U.K. tephra workshop. *Quaternary Newsletter* 63:41-44.

Ingram, H.A.P. 1978. Soil Layers in mires: Function and terminology. *J. Soil Science* 29:224-227.

Ingram, H.A.P. 1987. Ecohydrology of Scottish peatlands. *Trans. Roy. Soc. Edinburgh. Earth Sciences.* 78:287-296.

Inn, E.C.Y., Vedder, J.F., Condon, E.P. & O'Hara, D. 1981. Gaseous constituents in the plume from the eruptions of Mt. St. Helens. *Science.* 211:821-823.

Jackson, E.L. 1982. The Laki eruption Of 1783: impacts on population and settlement in Iceland. *Geography* 67(1):42-50.

Jacobsen, J.S. 1984. Effects of acidic aerosol, fog, mist, and rain on crops and trees. *.Phil. Trans. R. Soc. Lond.* B 305:327-338.

Jacobsen, S.P. 1979. Petrology of recent basalts of the eastern volcanic zone, Iceland. *Acta Naturalia Icelandica* 26:1-103.

Jacoby, G.C. & D'Arrigo, R. 1989. Reconstructed northern hemisphere annual temperature since 1671 based on high-latitude tree-ring data from North America. *Climatic Change* 14:35-59.

Jacoby, G.C. & D'Arrigo, R. 1992. Spatial patterns of tree-growth anomalies from the North American boreal treeline in the early 1800's, including the year 1816. In Harington, C.R. (ed) *The year without a summer? World climate in 1816.* Ottawa. Canadian Museum of Nature.

Jacoby, G.C., Ivanciu, I.S. & Ulan, L.D. 1985. Reconstructed summer degree-days in Central Alaska and Northwestern Canada since 1524. *Quaternary Research* 23:18-26.

Jacoby, G.C., Ivanciu, I.S. & Ulan, L.D. 1988. A 263- year record of summer temperature for Northern Qubec reconstructed from tree-ring data and evidence of a major climatic shift in the early 1800's. *Palaeogeography, Palaeoclimatology, Palaeoecology,* 64:69-78.

Jacoby, G.C. & Ulan, L.D. 1982. Reconstructions of past ice conditions in a Hudson Bay estuary using tree rings. 1982. *Nature* 298:637-639

Jakosky, B.M. 1986. Volcanoes, the Stratosphere and Climate. *J. Volcanol. Geotherm. Res.,* 28:247-255.

Jenkins, D.A. 1989. Trace element geochemistry in archaeological sites. *Environmental geochemistry and health* 11(2)57-62.

Jobey, G. 1980. Unenclosed platforms and settlements of the later 2nd Millenium. *Scottish Archaeological Forum.* 10.

Jobey, G. 1981. Groups of small cairns and the excavation of a cairnfield on Millstone Hill,Northumberland. *Archaeologia Aeliana.* (5) 9.

Jobey, G. 1983. Excavation of an unenclosed settlement on Standrop Rigg. *Archaeologia Aeliana.*(5) 11.

Jehu, T.J. and Craig, R.M. 1925. Geology of the Outer Hebrides. Part II. South UIst and Eriskay. *Transactions of the Royal Society of Edinburgh 53*, 615 - 641.

Jones, P.D. Briffa, K.R. 1992. Global surface air temperature variations during the twentieth century: Part 1, spatial, temporal and seasonal details. *The Holocene* 2(2):165-179.

Jones, V.J., Kreiser, A.M., Appleby, P.G., Bodin, Y.-W., DAyton, J., Natkanski, J,A., Richardson, N., Rippey, B., Sandøy, S. & Battarbee, R.W. 1990. The recent palaeolimnology of two sites with contrasting acid deposition histories. In Battarbee, R.W., Mason, Sir John, Renberg, I. & Talling, J.F. (eds). *Palaeolimnology and Lake Acidification.* London. The Royal Society. pp 171-176.

Jones V.J. Stevenson A.C. & Battarbee, R.W. 1986. Lake acidification and the land use hypothesis: a mid-post glacial analogue. *Nature* 322:157-158.

Jones V.J. Stevenson A.C. & Battarbee, R.W. 1989. Acidification of Lakes in Galloway, South West Scotland: A Diatom and Pollen Study of the Post Glacial History of the Round loch of Glenhead. *Journal of Ecology.* 77:1-23.

Keeley, H.C.M. 1982. Pedogenesis in Britain. In Harding A.F. (ed) *Climate change in later prehistory.*

Kelly P.M. 1977. Volcanic dust veils and North Atlantic Climate Change. *Nature* 268: 616-617.

Kelly, P.M. and Sear, C.B. 1984. Climatic impact of explosive volcanic eruptions. *Nature* 311: 740-743.

Kelly, P.M., Wigley, T.M.L. & Jones, P.D. 1984. European pressure maps for 1815-16, the time of the eruption of Tambora. *Climate Monitor* 13: 76-91.

Kennett, J.P. and Thunell, R.C. 1975. Global increase in quaternary explosive volcanism. *Science.* 187:497-503.

Kent, M., Brayshay, B.A., Gilbertson, D.D., Wathern, P. and Weaver, R. In press. The present and past vegetation of South Uist, Outer Hebrides of Scotland. *Scottish Geographical Magazine.*

Kerr, R.A. 1981. Mount St. Helens and a climatic quandary. *Science.* 211:371-374.

Keys, D. 1988. Cloud of Volcanic dust blighted north Britain 3000 years ago. *The Independent.* 16-08-88.

Kilham, P. 1971. A hypothesis concerning silica and the freshwater planktonic diatoms. *Limonology and Oceanography 16*, 10 - 16.

King, J. & Ryskamp, C. 1981. *The letters and prose writings of WILLIAM COWPER*. Vol II. Clarendon. Oxford.

Clarendon PressKington, J. A. 1980. July 1783: The warmest month in the Central England temperature series. *Climate Monitor* 9(3):69-73.

Kington, J.A. 1988. *The weather for the 1780s over Europe*. Cambridge. C.U.P.

Kington, J.A. 1992. Weather Patterns over Europe in 1816. In Harington, C.R. (ed) *The year without a summer*. Ottawa. Canadian Museum of Nature.

Koerner, R.M., Fisher, D. 1982. Acid snow in the Canadian high arctic. *Nature*. 295:137.

Kirchner, J.W., Dillon, P.J. & LaZerte, B.D. 1992. Predicted response of stream chemistry to acid loading tested in Canadian Catchments. *Nature* 358:478-482.

Kreiser, A.M., Appleby, P.G., Natkanski, J., Rippey, B. & Battarbee, R.W. 1990. Afforestation and Lake acidification: a comparison of four sites in Scotland. In Battarbee, R.W., Mason, Sir John, Renberg, I. & Talling, J.F. (eds). *Palaeolimnology and Lake Acidification*. London. The Royal Society. pp151-158.

Kristinsdóttir, K. The Laki eruption and its consequences in Sudur Múlasysla. *SKAFTAR ELDAR 1783-1784*. Mal Og Menning. Iceland. (In Icelandic with English summaries.)

Krug, E.C. & Frink, C.R. 1983. Acid rain on acid soil: a new perspective. *Science* 221.,:521-525.

Kukla, G. 1979. Missing link between Milankovitch and Climate. *Nature*. 253:600-603.

Kullman, L. 1992. Orbital Forcing and tree-limit history: hypothesis and preliminary interpretation of evidence from Swedish Lapland. *The Holocene* 2(2):131-137.

Kuniholm, P.I. 1990. Archaeological evidence and non evidence for climate change. *Transactions of the Royal society of London*. Series A 330:645-655.

Kyle, P.R., Jezek, P.A., Mosley-Thompson, E. & Thompson L.G.. 1981. Tephra layers in the Byrd station ice core and the Dome C ice core, Antarctica and their climatic significance. *J. Volcanol. Geotherm. Res.*, 11:29-39.

LaMarche,V.C. 1974. Palaeoclimatic inferences from long tree-ring records. *Science*. 183:1043-1048.

LaMarche, V.C., Graybill, D.A. Fritts, H.C. & Rose, M.R. 1984. Rising atmospheric CO2: Tree-ring evidence of growth enhancement in natural vegetation. *Science* 225:1019-1021

LaMarche, V.C. and Hirschboek, K. 1984. Frost rings in trees as records of major volcanic eruptions. *Nature*. 307:121-126.

LaMarche, V.C. and Hirschboek, K. 1985. Reply to Parker. *Nature*. 313:161.

LaMarche, V.C & Stockton, C.W. 1974. Chronologies from temperature sensitive bristlecone pines at upper treeline in western United States. *Tree-ring Bulletin* 34:21-45

Lamb, H.H. 1961. Climatic variation and observed changes in general circulation. *Geografiska Annaler.* 43:363-400.

Lamb, H.H. 1970. Volcanic dust in the atmosphere; with a chronology and assessment of its meteorological significance. In, *Phil. Trans. Roy. Soc. London.* Series A,266(1170),425-533.

Lamb, H.H. 1977. *Climate: Past, Present and Future.* Volume 2. London. Methuen.

Lamb, H.H. 1981. An approach to the study of the development of climate and its impact in human affairs. In Wigley, T.M.L., Ingram, M.J. & Farmer, G. (Eds) *Climate and History: Studies in past climates and their impact on man. C.U.P.*

Lamb, H.H. 1982. *Climate History and the Modern World.* London. Methuen.

Lamb, H.H. 1988. Volcanoes and climate: an updated assessment. In *Weather Climate and Human Affairs.* :301-328. London.

Lamb, H.H. 1992. First essay at reconstructing the general atmospheric circulation in 1816 and the Early Nineteenth Century. In Harington, C.R. (ed) *The year without a summer.* Ottawa. Canadian Museum of Nature.

Landsberg, H.E. & Albert, J.M. 1974. The summer of 1816 and volcanism. *Weatherwise.* 27(2):63-66.

Lang, D.S., Herzfeld, D. & Krupa, S.V. 1980. Reponses of plants to submicron acid aerosols. In Toribara, T.Y., Miller, M.W. & Morrow, P.E. (eds) *Polluted Rain.* New york and London. Plenum.

Langan. S.J. Episodic acidification of streams at Loch Dee, SW Scotland. *Trans. Roy. Soc. Edinburgh. Earth Sciences.* 78:393-397.

Langway, C.C., Clausen, H.B. & Hammer, C.U. 1988. An inter-hemispheric time-marker in ice cores from greenland and Antarctica. *Annals of Glaciology* 10:102-108.

Larsen, G. 1992. Hekla tephra layers from the period 2900-1800 BP: H-x, H-y and H-z. *Proceedings of the 1992 Nordic geologists Conference.* Rekyavik.

Larsen, G. 1992. The Hekla eruption of 1991 - The tephra fall. *Proceedings of the 1991 Nordic geologists Conference.* Rekyavik

Larsen, G. & Thórarinnson, S. 1977. H_4 and other Acid Hekla Tephra Layers. *Jökull* 27:28-49.

Larsen, G., Vilmudardóttir, E.G. & Thorkelsson. 1992. The Hekla eruption of 1991, the Tephra fall. *Náttúfræthingurinn* 61 (3-4):159-176.

Lascelles, B. 1993. Diatoms as reconstituted quaternary tephra. *Quaternary Newsletter* 69:10-16.

Latter, J.H. (ed) *Volcanic Hazards. Assessment and Monitoring.* Springer-Verlag. Berlin, London, New York.

Lazrus, A.L., Cadle, R.d., Gandrud, B.W., Greenberg, J.P., Huebert, B.J., & Rose, W, I. 1979. Sulfur and halogen chemistry of the statosphere and of volcanic eruption plumes. *J. Geophys. Res.* 84:7869-7875.

LeBlanc, D.C. Raynal, D.J. & White, E.H. 1988. Dendroecological analysis of acidic deposition effects on forest productivity. In Hutchinson, T.C. & Meema, K.M. (eds) *Effects of atmospheric pollutants on forests, wetlands and agricultural ecosystems.* Springer-Verlag, London, Paris, Tokyo.

Le Guern, F. Faivre-Pierret & Garrec J.P. 1988. Atmospheric contribution of volcanic sulphur vapour and its influence on the surrounding vegetation. *J. Volcanol. Geotherm. Res.* 35:173-178.

Leavey, M. & Sweeney, J. 1990. The influence of long range transport of air pollutants on summer visibility at Dublin. *International Journal of Climatology* 10(2):191-201.

Lee, J.A., Press, M.C., Studholme, C., & Woodin, S.J. 1988. Effects of acid deposition on Wetlands. In Ashmore *et al.*, (eds) *Acid Rain and Britain's Natural Ecosystems.* ICCET.

Lee, J.A., Press, M.C., Studholme, C., & Woodin, S.J. 1988. Responses to acid deposition in Ombotrophic mires in the U.K. In Hutchinson, T.C. & Meema, K.M. (eds) *Effects of atmospheric pollutants on forests, wetlands and agricultural ecosystems.* London. Springer-Verlag.

Lee, J.A. Tallis, J.H. & Woodin, S.J. 1988. Acidic deposition and British upland vegetaion. In Usher, M.B. & Thompson. D. B. A. *Ecological change in the Uplands.* Blackwell. Oxford.

Lee, J.J., Neely, G.E. Perrigan, S.C. & Grothaus, L.S. 1981. Effects of simulated acid rain on Yield, growth and foliar injury of several crops. *Environ. Exp. Bot.* 21:171-185.

Legrand, M. & Delmas, R.J. 1987. A 220 year continuous record of volcanic H_2S0_4 in the Antarctic ice sheet. *Nature.* 327:671-676.

Leivistad, H. & Muniz, I.P. 1976. Fish kill at low pH in a Norwegian river. *Nature* 251:391-392.

Lindberg, S.E. & Garten, C.T. 1988. Sources of sulphur in forest canopy throughfall. *Nature.*, 336:146-151.

Lindsay, R.A., Charman, D.J., Everingham, F., O'Reilly, R.M., Palmer, M.A., Rowell, T.A. & Stroud, D.A. 1988. *The Flow Country: The peatlands of Caithness and Sutherland.* Nature Conservancy Council.

Long, D.C. & Morton, A.C. 1987. An ash fall within the Loch Lomond Stadial. *Journal of Quaternary Science* 2:97-101.

Lorius, C. 1990. Environmental records from polar ice cores. *Phil. Trans. R. Soc. Lond.* A:330:459-462.

Lotter, A.F. & Birks, H.J.B. 1993. The impact of the Lacher See tephra on terrestrialand aquatic ecosystems in the Black Forest, Southern Germany. *Journal of Quaternary* Science. 8(3):263-276.

Lough, J.M. 1992. Climate in 1816 and 1811-20 as reconstructed frm western North American Tree-Ring Chronologies. In Harington, C.R. (ed) *The year without a summer.* Ottawa. Canadian Museum of Nature.

Lough, J.M. & Fritts, H.C. 1985. The southern oscillation and tree-rings: 1600-1961. *Journal of Climate and Applied Meteorology.* 24:952-966.

Lee, J.A., Press, M.C., Studholme, C., & Woodin, S.J. 1988. Responses to acid deposition in Ombotrophic mires in the U.K. In Hutchinson, T.C. & Meema, K.M. (eds) *Effects of atmospheric pollutants on forests, wetlands and agricultural ecosystems.* Springer-Verlag, London, Paris, Tokyo.

Lovering, T.S. 1957. Ash, Valley of 10,000 smokes, Alaska. *Bulletin of the Geological Society of America* 68:1585-1604.

Lowe, D.J. 1988. Late Quaternary Volcanism in New Zealand: towards an integrated record using distal airfall tephras in lakes and bogs. *Journal of Quaternary Science* 3(2):111-120.

Luckman, B.H. & Colenutt, M.E. 1992. Early nineteenth century tree-ring series from tree line sites in the middle Canadian Rockies. In Harington, C.R. (ed) *The year without a summer? World climate in 1816.* Ottawa. Canadian Museum of Nature.

Luhr, J.F. 1991. Volcanic shade causes cooling. *Nature.* 354:104-105.

Mackereth, F.J.H. 1965. Chemical investigations of lake sediments and their interpretation. *Proceedings of the Royal Society of London.* B161: 295 - 309.

Mackereth, F.J.H. 1966. Some chemical observations on post-glacial lake sediments. *Philosophical Transacations of the Royal Society of London B250*, 165-214.

Mackinnon, I.D.R., Gooding, J.L., McKay, D.S. & Clanton, U.S. 1984. The El Chichon statospheric cloud: solid particulates and settling rates. *J. Volcanol. Geotherm. Res.* 23:125-146.

MacLean, D.C. & Schneider, R.E. 1981. Effects of gaseous hydrogen fluoride on the yield of field grown wheat. *Environmental Pollution* A 24:39-44.

Maddox, J. 1984. From Santorini to Armageddon. *Nature.* 307:107.

Maguire, D. and Ralph, N. 1983. Early land use on Dartmoor, Palaeobotanial and pedological investigations on Holne Moor. In Jones, M. & Fleming, A. (Eds) *Integrating the Subsistence Economy. B.A.R. S181.*

Maitland, P.S. & Holden, A.V. 1983. Inland waters of the inner Hebrides. *Proc. Roy. Soc. Edinburgh.* 83B:229-244.

Maizels, J.K. & Dugmore, A.J. 1985. Lichonometric dating and tephrochronology of sandur deposits, SólhheimajÖkull, southern Iceland. *Jökull.* 35:69-77.

Maizels, J.K. & Caseldine, C. (eds) 1991. *Environmental change in Iceland: Past and Present.* Kluwer A.P. Netherlands.

Malincolico, L.L. 1987. On the variation of SO_2 emission from volcanoes. *J. Volcanol. Geotherm. Res.*, 33:231-237.

Mandl, R.H., Weinstein, L.H. & Keveny, M. 1975. Effects of hydrogen fluoride and sulphur dioxide alone and in combination on several species of plants. *Environmental Pollution* 9:133-143.

Mangerud, J., Furness, H. & Johansen, J. 1986. A 9000 year old ash bed on the Faroe Islands. *Quaternary Research* 26:262-265.

Manion, P.D. 1988. Decline as a phenomenon in Forests: pathological and ecological considerations. In Hutchinson, T.C. & Meema, K.M. (eds) *Effects of atmospheric pollutants on forests, wetlands and agricultural ecosystems.* London. Springer-Verlag.

Manley, G. 1974. Central England temperatures: monthly means 1659 to 1973. *Quart. J. Royal Meteorological Society.* 100:389-405.

Manley, G. 1979. The climatic environment of the Outer Hebrides. *Proceedings of the Royal Society of Edinburgh* 77B: 47 - 59.

Mann, D.H. 1986. Reliability of a Fjord glaciers fluctuations for palaeoclimatic reconstructions. *Quaternary Research* 25:10-24.

Manning, S.W. 1988. Dating of the Santorini eruption. *Nature.* 332:401.

Marinatos, S.P. 1939. The volcanic destruction of Minoan Crete. *Antiquity.* 13:425-439.

Martin. G.C. 1913. The recent eruption of Katmai Volcano in Alaska. *National Geographic,* 24(2):131-181.

Mason , B.J. 1990. Acid rain - cause and consequence. *Weather.* 45:70-79.

Mass, C. & Scneider, S.H. 1977. Statistical evidence on the influence of sunspots and volcanic dust on long term temperature records. *J. Atmospheric Science.*, 34:1995-2008.

Mass, C.F. & Portman, D.A. 1989. Major volcanic eruptions and Climate: A critical evaluation. *Journal of Climate.* 2:566-593

Mass, C.F. & Portman, D.A. 1990. Reply. *Journal of Climate.* 3:589-590.

Matyazovsky, I. Further results of the Analysis of central England Temperature Data. *Theoretical and applied climatology.* 39:126-139.

McAdam, J.H., Chance, S.M. 1988. Long term changes in output and vegetation on a small Northern Ireland hill farm. In Usher, M.B. & Thompson. D. B. A. *Ecological change in the Uplands.* Blackwell. Oxford.

McClelland, L., Simkin, T., Summers, M., Nielsen, E. & Stein, T.C. 1989. *Global Volcanism 1975-1985.* Prentice Hall, New Jersey.

McCormick, M.P., Swissler, T.J., Fuller, W.H., Hunt, W.H. & Hunt, M.T. 1984. Airborne and ground-based lidar measurements of the El Chichón aerosol cloud from 90°N to 56°S. *Geofis. Int.* 23:187-221.

McGhee, R. 1981 Archaeological evidence for climate change during the last 5000 years. In Wigley, T.M.L., Ingram, M.J. & Farmer, G. (Eds) *Climate and History: Studies in past climates and their impact on man.* C.U.P.

McGlone, M.S. Neall, V.E., & Clarkson, B.D. 1988. The effect of recent volcanic events and climatic changes on the vegetation of Mt Egmont, New Zealand. New Zealand *Journal Of Botany.* 26:123-144.

McGuire, W.J. 1992. Changing sea levels and erupting volcanoes: Cause and effect. *Geology Today* July-August:141-144.

Miles, J. 1988. Vegetation and soil change in the uplands. In Usher, M.B. & Thompson. D. B. A. *Ecological change in the Uplands.* Blackwell. Oxford.

Miles, M.K. & Gildersleeves, P.B. 1978. Volcanic dust and changes in northern hemisphere temperature. *Nature* 271:735-736.

Miller, H.G. 1984. Deposition-plant-soil interactions. *Phil. Trans. R. Soc. Lond.* B 305:339-352.

Mitchell, Sir A. 1757. A letter to The Royal society. *Phil. Trans. Roy. Soc. Volume L.* (1).

Mitchell, J.M. 1971. The effect of atmospheric aerosols on climate with special references to temperatures near the earth's surface. *J. Applied Meteorology.*, 10:703-714.

Mitchell, M.J., David, M.B. & Uurl, A.J. 1985. Sulphur distribution in lake sediment profiles as an index of historical deposition patterns. *Hydrobiologia* 121:121-127.

Moore, P.D. 1973. The influence of prehistoric cultures upon the initiation and spread of Blanket Bog in upland Wales. *Nature.* 241:350-353.

Moore, P.D. 1975. Origin of Blanket Mires. *Nature.* 256:267-269.

Moore, P.D. 1991. Ups and Downs in Peatland. *Nature* 353:299-300.

Morrison, W.R.J., & Battarbee, R.W. 1988. Effects on Freshwater flora and fauna (excluding fish). In Ashmore, M., Bell, N., & Garretty, C. (eds) *Acid rain and Britain's natural ecosystems.* ICCET.

Moseley-Thompson, E. & Thompson, L.G. 1982. Nine centuries of micro-particle deposition at the South Pole. *Quaternary Research* 17:1-13

Mossman, R.C. 1896. The meteorology of Edinburgh. *Transactions of the Royal Society of Edinburgh.* 39:63-207.

Mukherjee, B.K., Indira, K., & Dani, K.K. 1987. Low Latitude Volcanic eruptions and their effects on Sri Lankan Rainfall during the North - East Monsoon. *Journal Of Climatology.* 7:145 -155.

Mulder, J., Van Breemen, N. 1988. Differences in Aluminium mobilization in spodosols in New Hampshire (USA) and in the Netherlands as a result of acid deposition. In Hutchinson, T.C. & Meema, K.M. (eds) *Effects of atmospheric pollutants on forests, wetlands and agricultural ecosystems.* Springer-Verlag, London, Paris, Tokyo.

Mulder, J., Van Breemen, N. & Eijck, H.C. 1989. Depletion of soil Aluminium by acid deposition and implications for acid neutralization. *Nature* 337:247-249.

Murcray, D.G., Murcray, F.J., Barker, B.B. & Mastenbrook, H.J. 1981. Changes in Stratospheric water vapor associated with the Mt. St. Helens eruption. *Science* 211:823-824.

Murray, F. & Wilson, S. 1988. Effects of SO2 and HF on wheat and barley. *Environmental Pollution* A 55:239-249.

Murray, W.H. 1973. *The Islands of Western Scotland.* London. Eyre Methuen.

Nesje, A. and Johannessen, T. 1992. What were the primary forcing mechanisms of high-frequency Holocene climate and glacier variations. *The Holocene* 2,1:79-84.

Neumann, J. 1990. The 1810s in the Baltic region, 1816 in particular: Air temperatures, grain supply and Mortality. In *Climatic Change.* 17(1):97 - 120.

Neumann, J. 1992. The 1810's in the Baltic region, 1816 in particular; Air temperatures, Grain supply and Mortality. In Harington, C.R. (ed) *The year without a summer.* Ottawa. Canadian Museum of Nature.

New Scientist. 1989. Corrosive mist sets puzzle for scientists. *New Scientist* 21 October:28.

Newell, R.E. 1981. Further studies of the atmospheric temperature change produced by the Mt. Agung eruption in 1963. *J. Volcanol. Geotherm. Res.* 11:61-66.

Newell, R.E. 1981. Introduction. *J. Volcanol. Geotherm. Res.* 11:1-2.

Newhall, G.C. and Self, S. 1982. The volcanic explosivity index (VEI): An estimate of explosive magnitude for al volcanism. Journal of Geophysical Research. Vol 87, No C2:1231-1238.

Newnham, R. & Lowe,D.J. 1991. Holocene vegetation and Volcanic Activity, Auckland Isthmus, New Zealand. *Journal of Quaternary Science* 6(3):177-193.

Nicholls, N. 1988. Low latitude volcanic eruptions and the El Niño Southern oscillation. In *Journal of Climatology.* 8:91-95.

Nicholls, N. 1990. Low latitude volcanic eruptions and the El Niño Southern oscillation: A reply. *International Journal of Climatology* 10:425-429.

Nilsson, S.I., Miller, H.G., & Miller, J.D. 1982. Forest Growth as a possible cause of soil and water acidification: an examination of the concepts. *Oikos* 39:40-41.

Ninkovich, D. & Donn, W.L. 1976. Explosive Cenozoic volcanism and climatic implications. *Science.* 194:899-906.

Nordenskiöld, A.E. 1876. Distant transport of volcanic dust. *The Geological Magazine. New Series Decade II*, Vol III:292-297

Norton, S.A. 1988. The stratigraphic record of atmospheric loading of metals at the Ombotrophic Big Heath Bog, Mt. Desert Island, Maine, U.S.A. In Hutchinson, T.C. &

Meema, K.M. (eds) *Effects of atmospheric pollutants on forests, wetlands and agricultural ecosystems*. London. Springer-Verlag..

Nriagu, J.. & Coker, R.D.1983. Sulphur in sediments chronicles past changes in lake acidification. *Nature 303*, 692-694.

Oldield, F. & Richardson, N. 1990. Lake sediment magnetism and atmospheric deposition. In Battarbee, R.W., Mason, Sir John, Renberg, I. & Talling, J.F. (eds). *Palaeolimnology and Lake Acidification*. London. The Royal Society. pp99-104.

Ogilvie, A.E.J. 1986. The climate of Iceland 1701-1784. *Jökull* 36:57-73.

Ogren, J.A., Charlson, R.J., Radke, L.F. & Domonkos, S.K. 1981. Absorption of visible radiation by aerosols in the volcanic plume of Mt. St. Helens. *Science* 211:834-836

Oliver, R.C. 1976. On the response of hemispheric mean temperatures to stratospheric dust: an empirical approach. *Journal of Applied Meteorology* 15:933

Ogilvie, A.E.J. 1986. The climate of Iceland 1701-1784. *Jökull* 36:57-73.

Oskarsson, N. 1980. The interaction between volcanic gases and Tephra: Fluorine adhering to tephra of the 1970 Hekla eruption. *J. Volcanol. Geotherm. Res.* 8:251-266.

Oskarsson, N. 1992. Aluminium Fluoride in a volcanic cloud: Evidence from the 1991 Hekla eruption. *Proceedings of the Nordic Geological Conference 1991.*

Oskarsson, N., Gronvold, K., & Larsen, G. 1984. Modan Fra Skafta Eldran. In Gunnlaugsson, G.A., Gudbergsson, G.M., Thorarinsson, S., Raffnson, S. & Einarsson, T. (eds) 1984. *SKAFTAR ELDAR 1783-1784*. Mal Og Menning. Iceland. (In Icelandic with English summaries.)

Oswalt, W.H. 1957. Volcanic activity and Alaskan Spruce growth in A.D.1783. *Science.* 126:928-929.

Ottaway, J.R & Mattews , M.R. 1988. Trace element analysis of soil samples from a stratified archaeological site. *Environmental Geochemistry and Health* 103:105-112.

Palais, J.M. & Sigurdsson, H. 1989. Petrologic evidence of volatile emissions from major historic and pre-historic volcanic eruptions. In Berger, A., Dickinson, R.E., & Kidson, J.W. (eds). *Understanding Climate Change. Geophysical Monograph 52*. IUGG Volume 7.:31-53.

Pande, P.C & Mansfield, T.A. 1985. Response of spring barley to SO2 and NO2 pollution. *Environmental Pollution* A 38:87-97.

Pang, K.D., Slavin, J.A., & Chou H. 1987. Climatic anomalies of the late third century B.C.; correlation with volcanism, solar activity and planetary alignment. *Eos* 68:1234.

Pang, K.D., Srivastava, S.K. & Chou H. 1988. Climatic impacts of past volcanic eruptions: Inferences from ice-core, tree-ring and historical data. *Eos* 69:1062.

Pang, K.D., Keston, R., Srivastava, S.K. & Chou H 1989. Climatic and hydrologic extremes in early chinese history: possible causes and dates. *Eos* 70:1095. anomalous weather events and volcanic eruptions.

Pankhurst, R.J. and Mullin, J.M. 1991. *The Flora of the Outer Hebrides.* London, Natural History Museum Publications.

Park, C.C. 1987. *Acid Rain Rhetoric and Reality* London. Methuen.

Parker, D.E. 1985. Climatic impact of explosive volcanic eruptions. *The meteorological Magazine* 114:149-161.

Parker, D.E. 1985. Frost rings in trees and volcanic eruptions. *Nature* 313:160-161.

Parker D.E. 1988. Stratospheric aerosols and sea surface temperatures. *Journal of Climatology* 8:87-90.

Parker D.E. & Browscombe, J.L. 1983. Stratospheric warming following the El Chichon volcanic eruption. *Nature* 301:406-408.

Parker, D.E., Legg, T.P., Folland, C.K. 1992. A new central England temperature series. *International Journal of Climatology* 12:317-342.

Parnell, R.A. Jr & Burke, K.J. 1990. Impact of acid emissions from Nevado del Ruiz volcano, Colombia, on selected terrestrial and aquatic ecosystems. *J. Volcanol. Geotherm. Res.*, 42:69-88.

Parry, M.L. 1975. Secular climatic change and marginal agriculture. *Transactions of the Institute of British Geographers* 64:1-13.

Paterne, M., Guichard, F. & Labeyrie, J. 1988. Explosive activity of the south italian volcanoes during the past 80,000 years as determined by marine tephrochronology. *J. Volcanol. Geotherm. Res.* 34:153-172.

Patrick, S.T., Timberlid, J.A. & Boyle, J.F. 1990. The significance of land-use and land-management change in the acidification of lakes in Scotland and Norway: an extended summary. In Battarbee, R.W., Mason, Sir John, Renberg, I. & Talling, J.F. (eds). *Palaeolimnology and Lake Acidification.* London. The Royal Society. pp137-142.

Peacock, J.D. 1984. *Quaternary Geology of the Outer Hebrides.* British Geological Survey Report no. 16(2), H.M.S.O., 26 pp.

Pennington, W. 1943. Lake sediments: the bottom deposits of the North Basin of Windermere with special reference to the diatom succession. *New Phytologist 43*, 1 - 27.

Pennington, W. 1981a. Record's of a lake's life in time: the sediments. *Hydrobiologia* 79:197-219.

Pennington, W. 1981b. Sediment composition in relation to the interpretation of pollen data. *Proc. IV int. palynol. Conf., Lucknow (1976-1977)* 3:188-213

Pennington W. and Lishman, J.P. 1971. Iodine in lake sediments in northern England and Scotland. *Biological Review 46*, 279-313.

Pennington, W., Haworth, E.Y., Bonny, A.P. and Lishman, J.P. 1972. Lake Sediments in Northern Scotland. *Philosophical Transactions of the Royal Society of London* B264, 191-294.

Persson, C. 1971. Tephrochronological investigations of peat deposits in Scandinavia and on the Faroe islands. *Sveriges Geologiska Underskōning.* Ser C 656.

Peterson, D.L., Arbaugh, M.J. & Robinson, L.J. 1991. Regional growth changes in ozone-stressed ponderosa pine *[Pinus ponderosa]* in the Sierra Nevada, California, USA. *The Holocene* 1(1):50-60.

Petit, J.R., Mounier, L., Jouzel, J., Korotkevich, Y.S., Kotlyakov, V.I. and Lorius, C. 1990. Palaeoclimatological and chronological implications of the Vostock ICE core. *Nature.* 343:56-58.

Pétursson, G., Palsson, G.A., & Georgsson, G. 1984. Um Eiturahrif. In Gunnlaugsson, G.A., Gudbergsson, G.M., Thorarinsson, S., Raffnson, S. & Einarsson, T. (eds) *SKAFTAR ELDAR 1783-1784.* Mal Og Menning. Iceland. (In Icelandic with English summaries.)

Phemister, J. 1960. *British Regional Geology. Scotland: the Northern Highlands.* Edinburgh, H.M.S.O. (3rd ed.).

Pilcher, J.R. 1990. Ecology of subfossil oak woods on Peat. in Doyle, R.G. (ed) *Ecology and conservation of Irish Peatlands.* Dublin. Royal Irish Academy:41-47.

Pilcher, J.R., Baillie, M.G.L., Schmidt, B. and Becker, B. 1984. A 7272-year tree ring chronology for western europe. *Nature.* 312: 150-152.

Pilcher, J.R., Hall, V.A. 1992. Towards a tephrochronology for the north of Ireland. *The Holocene* 2(3):255-259.

Pollack,J.B., Toon,O.B., Sagan, C., Summers, A., Baldwin, B., & Van Camp, W. 1976. Volcanic explosions and climatic change: A theoretical assessment. *Journal of Geophysical Research.* Vol 81, No 6:1071-1083.

Pollack,J.B. 1981. Measurements of the volcanic plumes of Mt. St. Helens in the stratosphere and troposphere: Introduction. *Science.* 211:815-816.

Porter, S.C. 1981. Recent glacier variations and volcanic eruptions. *Nature* . 291:139-141.

Post, J.D. 1977. *The Last Great Subsistence Crisis of the Western World.* John Hopkins U.P.

Powers, A.H. & Gilbertson, D.D. 1987. A simple preparation technique for the study of opal phtoliths from archaeological and Quaternary sediments. *Journal of Archaeological Science* 14:529-535.

Powers, A.H., Padmore, J. & Gilbertson, D.D. 1989. Studies of Late Prehistoric and Modern opal phtoliths from coastal sanddunes and Machair in Northwest Britain. *Journal of Archaeological Science* 16:27-45.

Powers, W.R. & Jordan, H.J. Human biogeography and climate change in Siberia and Arctic North America in the fourth and fifth millenium B.P. *Phil. Trans. R. Soc. Lond.* A 330:665-670.

Pratt, K. 1992. *Vegetational History of the Upper Borve Valley, Barra, Outer Hebrides.* Unpublished M.Sc. dissertation, University of Sheffield.

Preining, O. 1991. Aerosols and Climate - An overview. *Atmospheric Environment* 25A(11):2443-2444

Pyatt, F.B. and Lacy, D. 1988. An appraisal of atmospheric pollution by aluminium fumes emanating from smelter works in Western Norway. *Environment International* 14:407-416.

Pyle,D.M. 1989.Ice core acidity peaks, retarded tree growth and putative eruptions. *Archaeometry.* 31:88-91.

Pyle, D.M. 1992. On the "Climatic Effectiveness" of volcanic eruptions. *Quaternary Research.* 37:125-129.

Quinn, W.H., Zopf, D.O., Short, K.S., Short, D.O. & Kuo Yang R.T.W. 1978. Historical trends and statistics of the Southern Oscillation, El Niño,and Indonesian droughts. *Fish. Bull.* 76:663-678.

Quinn, W.H., Neal, V.T. & de Mayolo, S.E.A. 1987. El Niño occurrences over the past four and a half centuries. *Journal of Geophysical Research* 92:14449-14461

Rabek, K., Ledbetter, M.T. & Williams, D.F. Tephrochronology of the western gulf of Mexico for the last 185 000 years. *Quaternary Research* 23:403-416.

Rafnsson, S. Livestock and Settlement in Iceland at the end of the Laki eruption. Gunnlaugsson, G.A., Gudbergsson, G.M., Thorarinsson, S., Raffnson, S. & Einarsson, T. 1984. *SKAFTAR ELDAR 1783-1784.* Rekyavik. Mal Og Menning. (In Icelandic with English summaries.)

Rahn, K.A. & Lowenthal, D.H. 1986. Who's polluting the Arctic. In Stonehouse, B.(ed) *Arctic Air Pollution.* Cambridge. Cambridge University Press.

Ram, M. & Gayley, R.I. 1991. Long range transport of volcanic ash to the Greenland ice sheet. *Nature.* 349:401-404.

Ramage, C.S. 1986. El Niño. *Scientific American* 254(6):55-61.

Ramaswamy, V. 1992. Explosive start to last ice age. *Nature* 359:14.

Rampino, M.R. 1988. Volcanic Winters. *Ann. Rv. Earth Planet Sci.* 16:73-99.

Rampino, M.R., & Self, S. 1982. Historic eruptions of Tambora (1815), Krakatau (1883), and Agung (1963), their stratospheric aerosols and climatic impact. *Quaternary Research.* 18:127-143.

Rampino, M.R. & Self, S. 1984. Sulphur rich volcanic eruptions and stratospheric aerosols. *Nature* 310:677-679.

Rampino, M.R., & Self, S. 1992. Volcanic winter and accelerated glaciation following the Toba super eruption. *Nature* 359:50-52.

Rampino, M.R., Self, S. & Fairbridge, I.W. 1982. Can rapid climate change cause volcanic eruptions? *Science* 206:826-829

Rampino, M.R. Stothers, R.B. 1984. Terrestrial mass extinctions, cometary impacts and the Sun's motion perpendicular to the galactic plane. *Nature.* 308:709-712.

Rampino. M.R., Stothers, R.B. & Self. S. 1985. Climatic effects of volcanic eruptions. *Nature.* 313:272.

Rasmusson, E.M. & Carpenter, T.H. 1982. Variations in tropical sea surface temperaturesand surface wind fields associated with the Southern Oscillation/El Niño. *Monthly Weather Review* 110:326-332

Rasmusson, E.M. & Wallace, J.M. 1983. Meteorological aspects of the El Niño / Southern Oscillation. *Science* 222:1195-1202

RCAHMCS 1928. Royal Commision on Ancient and Historical Monuments and Constructions of Scotland. *Ninth Report with Inventory of monuments and constructions in the Outer Hebrides, Skye and the smaller Isles.* Edinburgh, H.M.S.O.

Reinert, R.A. 1984. Plant responses to air pollutant mixtures. *Ann. Rev. Phytopath.* 22:421-442.

Renberg, I. 1990. A 12600 year perspective of the acidification of Lilla Öresjön, south-west Sweden. In Battarbee, R.W., Mason, Sir John, Renberg, I. & Talling, J.F. (eds). *Palaeolimnology and Lake Acidification.* London. The Royal Society. pp131-136.

Renberg, I & Helberg, T. 1982. The pH history of lakes in south-western Sweden, s calculated from the subfossil diatom flora of the sediments. *Ambio* 11:30-33.

Renberg, I., Korsman, T. & Anderson, N.J. 1990. Spruce and surface-water acidification: an extended summary. In Battarbee, R.W., Mason, Sir John, Renberg, I. & Talling, J.F. (eds). *Palaeolimnology and Lake Acidification.* London. The Royal Society.

Renfrew, C. 1979. The eruption of Thera and Minoan Crete. *Volcanic activity and human ecology.* Academic press.

Renfrew, C. 1990. Climate and Holocene culture change: some practical problems. *Phil. Trans. R. Soc. Lond.* A 330:657-663.

Rietmeijer, F.J.M. 1988. Enhanced residence of submicron Si rich volcanic particles in the lower stratosphere. *J. Volcanol. Geotherm. Res.* 34:173-184.

Rietmeijer, F.J.M. 1990. El Chichon dust, a persistent problem. *Nature* 344:114-115.

Rippey. B, Murphy. R.J, and Kyle, S.W. 1982. Anthropogenically derived changes in the sedimentary fluxes of Mg, Cr, Ni, Cu, Zn, Hg, Pb and P in Lough Neagh, Northern Ireland. *Environmental Science and Technology 16* 23-30.

Rippey, B. 1990.Sediment chemistry and atmospheric contamination. In Battarbee, R.W., Mason, Sir John, Renberg, I. & Talling, J.F. (eds). *Palaeolimnology and Lake Acidification.* London. The Royal Society. pp85-90.

Robock, A. 1979. The Little Ice Age. Northern hemisphere average observations and model calculations. *Science* 206:1402-1404.

Robock, A. 1981. The Mount St. Helens volcanic eruption of 18 May 1980: Minimal climatic effect. *Science* 212:1383-1384.

Robock,A. 1981. A latitudinally dependent volcanic dust veil index, and its effect on climatic simulations. *J. Volcanol. Geotherm. Res.* 11:67-80.

Robock, A. 1984a. Climate simulations of the effects of the El Chichón aerosol. *Geofiscia Internacional* 23:403-414.

Robock, A. 1984b. Snow and ice feedbacks prolong effects of nuclear winter. *Nature.* 310:667-670.

Robock, A. & Matson, M. 1983. Circumglobal transport of the El Chichón volcanic dust cloud. *Science* 221:195-197.

Rogers, C.F., Hudson, J.G. & Kockmond, W.C. 1981. Measurements of cloud condensation nuclei in the Stratosphere around the plume of Mt. St. Helens. *Science* 211:824-825.

Rose, W.I. 1977. Scavenging of volcanic aerosol by ash: atmospheric and volcanological implications. *Geology* 5:621-624.

Rose, W.I. & Chesner, C.A. 1990. Worldwide dispersal of gas and ashes from the Earth's largest known eruption: Toba, Sumatra, 75ka. *Palaeo', Palaeo', Palaeo'.* 89:269-275.

Rosenqvist, I.T. 1977. *Acid Soil - Acid Water.* Oslo. Ingeniørlaget.

Rosenqvist, I.T. 1978. Alternative sources for acidification of river water inNorway. *Science of the Total Environment* 10:39-49.

Rudd, M.J. 1985. The role of sulphate reduction in the long term accumulation of organic and inorganic sulphur. *Limnology and Oceanography 31,* 1281-1291.

Schell, I.I. 1961. The ice off Iceland and the climates during the past 1200 years, approximately. *Geografiska Annaler* 43:354-362.

Schimel, D.S., Parton, W.J., Kittel, T.G.F., Ojima, D.S. and Cole C.V. 1990. Grassland Biogeochemistry: Links to atmospheric processes. *Climatic Change* 17(1): 49 - 68.

Schneider, S.H. 1983. Volcanic dust veils and climate: How clear is the connection? *Climatic Change* 5:111-113.

Schneider, S.H. and Mass, C. 1975. Volcanic dust, sunspots and temperature trends. *Science.* 190:741-746.

Schonweise, C.D. & Mather, J. 1987. The CO2 temperature response. A comparison of results from General circulation Models with Statistical Assesssments. *Journal of Climatology.* 7:215-229.

Schove, D.J. 1950. Tree-rings and summer temperatures. *Scottish Geographical Magazine.* 66(1):37-42.

Schove, D. 1954. Summer temperatures and Tree rings in Northern Scandinavia. In *Geografiska Annaler*. 36:40- 80.

Scorer, R.S. 1968. *Air Pollution*. New York. Pergamon.

Scuderi, L.A. 1990. Tree ring evidence for climatically effective volcanoes. *Quaternary research*. 34:67-85.

Scuderi, L.A. 1992: Climatically effective volcanism. *Quaternary Research*. 37:130-135.

Sear, C.B., Kelley,P.M., Jones, P.D. and Goodess C.M. 1987. Global surface temperature responses to major volcanic eruptions. *Nature*. 330:365-367.

Seaward, M.R.D. 1988. Effects of quantitative and qualitative changes in air pollution on the ecological and geographical performance of lichens. In Hutchinson, T.C. & Meema, K.M. (eds) *Effects of atmospheric pollutants on forests, wetlands and agricultural ecosystems*. Springer-Verlag, London, Paris, Tokyo.

Sedlacek, W.L., Mroz, E.J., Lazruz,A.L., & Gandrud,B.W. 1983. A decade of stratospheric sulfate measurements compared with observations of volcanic eruptions. *J. Geophysical Research*. 88 (C6):3741-3776.

Self, S., & Rampino, M.R. 1981. The 1883 eruption of Krakatau. *Nature* 294:699-704.

Self, S. & Sparks, R.S.J. (eds) *1981. Tephra studies*. Amsterdam. Reidel.

Self, S., Rampino, M.R. & Barbera, J.J. 1981. The possible effects of large 19th and 20th century volcanic eruptions on zonal and hemispheric surface temperatures. *J. Volcanol. Geotherm. Res.*, 11:41-60.

Sigurdsson, H. 1982. Volcanic Pollution and climate: The 1783 Laki eruption. *Eos. Transactions, American Geophysical Union*. 63(32):601-603.

Sigurdsson, H. 1990. Evidence of volcanic loading of the Atmosphere and of climate response. *Palaeo', Palaeo', Palaeo'*. 89:277-289.

Sigurdsson, H., Devine, J.D & Davis, A.N. 1985. The petrologic estimate of volcanic degassing. *Jökull* 35:1-8.

Simkin, T., Siebert, L., McClelland, L., Bridge, D., Newhall, C., & Latter, J.H. 1981. *Volcanoes of the World*. Hutchinson Ross, Strandsburg, Pa.

Sinclair, W.A. 1964. Comparisons of recent declines of White ash, oaks and sugart maple in northeastern woodlands. *Cornell Plantations, Ithaca*. NY 20:62-67.

Sinclair, W.A. 1966. Decline of hardwoods: Possible causes. *Proc. Inter. Shade. Tree Conf.* 42:17-32.

Skiba,U., Cresser, M.S., Derwent, R.G., & Futty, D.W. 1989. Peat acidification in Scotland. *Nature*. 337:68-69.

Smith, C.M.S., Cresser, M.S. & Mitchell, R.D.J. 1993. Sensitivity to acid deposition of Dystrophic peat in Great Brtain. *Ambio* 22(1):22-26

Smith, D.C., Borns, H.W., Baron, W.R. & Bridges, A.E. 1981. Climatic stress and Maine agriculture. In Wigley, T.M.L., Ingram, M.J. & Farmer, G. (Eds) *Climate and History: Studies in past climates and their impact on man.* C.U.P.

Smith, D.I. and Fettes, D.J. 1979. The geological framework of the Outer Hebrides. *Proceedings of the Royal Society of Edinburgh* 77B:75 - 83.

Smith,K. 1981. The Shaugh Moor Project, third report. *Proceedings of the Prehistoric Society* 47.203-278.

Smith, H.W., Okazaki, R. & Knowles, C.R. 1977. Electron Microprobe analysis of glass shards from Tephra assigned to Glacier Peak, Washington. *Quaternary Research* 7:197-206.

Smith, H.W., Okazaki, R. & Knowles, C.R. 1977. Electron Microprobe analysis of glass shards from Tephra assigned to set W, Mt. St. Helens, Washington. *Quaternary Research* 7:207-217.

Spence, D.H.N. 1960. Studies on the vegetation of Shetland. III. Scrub in Shetland and South Uist. *Journal of Ecology 48,* 73 - 95.

Stanley, D.J., Sheng, H. 1986. Volcanic shards from Santorini (Upper Minoan Ash) in the Nile Delta. *Nature.* 320:733-35.

Steinthorsson, S. 1992. Climatic effects of Large volcanic eruptions with special reference to the Skáftar fires of 1783-85. *Nordic Geological Conference.*

Stephenson, F.R. 1990. Historical evidence concerning the Sun: interpretation of sunspot records during thr telescopic and pretelescopic eras. *Phil. Trans. R. Soc. Lond.* A 330:499-512.

Stevens, P.A., Adamson, J.K., Anderson, M.A.. & Hornung, M. 1988. Effects of clearfelling on surface water quality and site nutrient status. In Usher, M.B. & Thompson. D. B. A. *Ecological change in the Uplands.* Blackwell. Oxford.

Stoiber R.E. and Jepsen, A. 1973. Sulphur dioxide contributions to the atmosphere by volcanoes. *Science.* 182:577-578.

Stoiber, R.E., Williams, S.N. & Huebert, B. 1987. Annual contribution of Sulphur dioxide to the atmosphere by volcanoes. *J. Volcanol. Geotherm. Res.*33:1-8.

Stommel, H & Stommel,E. 1979. The year without a summer. *Scientific American* 240(6):134-40.

Stommel, H & Stommel,E. 1983. *Volcano Weather. The story of 1816, the year without a summer.* Seven Seas, Newport.

Stothers, R.B. 1984. Mystery cloud of AD 536. *Nature.* 307:344-345.

Stothers, R.B. 1984b. The great Tambora eruption in 1815 and its aftermath. *Science.* 224:1191-1198.

Stothers, R.B. and Rampino, M.R. 1983. Historic volcanism, european dry fogs and Greenland ice precipitation. 1500 B.C.-A.D. 1500. *Science* 222:411-413.

Stothers, R.B. and Rampino, M.R. 1983. Volcanic eruptions in the mediterranean before A.D.630 from written and archaeologcal sources. *Journal of Geophysical Research.* Vol 88, No B8:6357-6371.

Stothers, R.B., Rampino, M.R., Self, S. & Wolff, J.A. 1989. Volcanic Winter? Climatic effects of the largest volcanic eruptions. In Latter, J.H. (ed) *Volcanic Hazards.* Springer-Verlag. Berlin, London, New York.

Suffling, R. & Fritz, R. 1992. The ecology of a famine: North western Ontario in 1815-17. In Harington, C.R. (ed) *The year without a summer? World climate in 1816.* Ottawa. Canadian Museum of Nature.

Sullivan, D.G. 1988. The discovery of Santorini Minoan tephra in western Turkey. *Nature.* 333:552-554.

Sveinbjarnardóttir, G. 1991. A study of farm abandonment in two regions of Iceland. In Maizels, J.K. & Caseldine, C. (eds) *Environmental change in Iceland: Past and Present.* Kluwer A.P. Netherlands.

Symonds, R.B., Rose, W.I. & Reed, M.H. 1988. Contribution of Cl- and F- bearing gases to the atmosphere by Volcanoes. *Nature* 332:415-418.

Symons, G.J. 1888. *The eruption of Krakatau and subsequent phenomena: Report of the Krakatau Committee of the Royal Society of London.* Trubner. London.

Takamatsu, T., Boratynski, J. & Satake, K. 1992. Effects of volcanic acid deposition on Soil Chemistry: I. Status of exchangeable cations and sulfur. *Soil Science.* 154(6):435-448

Taylor, B.L., Gal-Chen. T. & Schneider, S.H. 1980. Volcanic eruptions and long term temperature records: An empirical search for cause and effect. *Q. J. R. Met. Society.*, 196:175-199.

Taylor,J.A. 1980. Culture and environment in prehistoric Wales. *British Archaeological Reports.* 76.

Thompson, L.G. & Mosley-Thompson, E. 1981. Temporal variabilty of microparticle properties in polar ice sheets. *J. Volcanol. Geotherm. Res.* 11:11-28.

Thompson, S.L., Schneider, S.H. 1986. Nuclear winter reappraised. *Foreign Aff.* (Summer):981-1005.

Thompson, W. & Bradshaw, R.H. 1986. The distribution of ash in icelandic lake sediments and the relative importance of mixing and erosion processes. *Journal of Quaternary Science* 1:3-11.

Thomson, D.V. 1990. Time series analysis of Holocene climatic data. *Phil, Trans. Roy Soc. London.* A. 330:601-616.

Thórarinsson, S. 1967. *The eruption of Hekla 1947-1948. The eruptions of Hekla in historical times.* Reykavik. H.F. Leiftur.

Thorarinsson, S. 1969. The Lakagigar eruption of 1783. *Bulletin Volcanologique.* 33(3):910-929

Thorarinsson, S. 1979. On the damage caused by volcanic eruptions with special reference to tephra and gases. In *Volcanic Activity and Human Ecology*: 125-159. Academic Press.

Thorarinsson, S. 1980. Langleithir, gjósku úr Thremur Kötlugosum. *Jökull.* 30:65-73. (Distant transport of Tephra in three Katla eruptions.)

Thorarinsson, S. 1981. Greetings from Iceland. Ash falls and volcanic aerosols in scandinavia. *Geografiska Annaler.* 63 A. (3-4):109-118.

Thorarinsson, S. 1981. The application of Tephrochronology in Iceland. In Self, S. & Sparks, R.S.J (eds) Tephra Studies. Amsterdam. Reidel.

Thordarson, Th. 1992. Eruption dynamics of the 1783 laki eruption, S. Iceland. *Abstract of the Nordic Geologists conference.* Rekyavik 1992.

Thordarson, Th., Self, S. & Larsen, G. 1987. Eruption sequence of the Skáftar fires 1783-1785, Iceland. *Eos* 68:1550.

Thordarson, Th. & Self, S. & 1988. Old maps help interpret Icelandic eruption. *Eos* 69:86.

Thordarson, Th, Larsen, G. & Steinthorsson, S. 1992. Eruption dynamics of the 1783 Laki eruption, S. Iceland. *Proceedings of the Nordic Geological Conference.*

Thordarson, Th., Self, S. 1993. The Laki [Skaftár Fires] and Grímsvötn eruptions in 1783-85. *Bulletin Volcanologique* 55:233-263.

Thunell, R., Federman, A., Sparks, S. & Williams, D. 1979. The age, origin and significance of the y-5 ash layer in the mediterranean. *Quaternary Research* 12:241-253.

Torrence,R., Specht, J. and Fullagar, R. 1990. Pompeiis in the Pacific. *Australian Natural History.* 23(6):457-463.

Tripoli, G.J. & Thompson, S.L. 1988. A three-dimensional numerical simulation of the atmospheric injection of aerosols by a hypothetical basaltic fissure eruption. In: *Global Catastrophes and Earth History, Abstr vol LPI and NAS conf., Snowbird, Utah, 20-23 Oct 1988*, pp. 200-201.

Turco, R.P., Whitten, R.C. & Toon, O.B. 1982. Stratospheric aerosols observation and theory. *Rev. Geophys. Space Phys.* 20:233-279.

Turco, R.P., Toon, O.B. Ackerman, T.P. Pollack, J.B. & Sagan, C. 1983. Nuclear winter: global consequences of multiple nuclear explosions. *Science.* 222:1283-1292.

Turco, R.P., Toon, O.B. Ackerman, T.P. Pollack, J.B. & Sagan, C. 1984a. "Nuclear Winter" to be taken seriously. *Nature.* 311:307-308.

Turco, R.P., Toon, O.B. Ackerman, T.P. Pollack, J.B. & Sagan, C. 1984b. The climatic effects of Nuclear war. *Sci. American.* 251(8):33-43.

Turco, R.P., Toon, O.B. Ackerman, T.P. Pollack, J.B. & Sagan, C. 1985. Ozone, dust, smoke and humidity in nuclear winter. *Nature.* 242:32-3.

Ugolini,F.C. & Zazoski,R.J. 1979. Soils derived from Tephra. In *Volcanic activity and human ecology*.:83-123.London. Academic Press.

UK Acid Waters Review Group. 1989. *Acidity in United Kingdom Fresh Waters.* Department of The Environment.

Unsworth, M.H. 1984. Evaporation from forests in cloud enhances the effects of cloud deposition. *Nature.* 312:262-264.

Vilhjalmson, V.O. 1991. Radio carbon dating and Icelandic archaeology. *Laborativ Arkeologi 5.* Stockholm University.

Villalba, R. Climatic Fluctuations in Northern Patagonia during the last 1000 years as inferred from tree-ring records. *Quaternary Research* 34:346-360.

Vilmundardóttir, E.G., Kaldal, I. 1982. Holocene sedimentary sequences at Trácidarlækur Basin, Thjórsárdalur. southern Iceland. *Jökull.* 32:49-59.

Vogel, J.S., Cornell, W., Nelson, D.E. and Southon J.R. 1990. Vesuvius/Avellino, one possible source of seventeenth century BC climatic disturbances. *Nature* 344:534-537.

Vogelmann, A.M., Ackermann, T.P. & Turco, R.P. 1992. Enhancements in biologically effective radiation following volcanic eruptions. *Nature* 359:47-49.

Vossler, T., Anderson, D.L., Aras, N.K., Phelan, J.M., Zoller, W.H. 1981. Trace element composition of the Mt. St. Helens plume: Stratospheric samples from the 18 M ay eruption. *Science.* 211:827-830.

Walker, G.P.L. 1980. The Taupo pumice: product of the most powerful known (ultraplinian) eruption. *Journal of Volcanology and Geothermal Research* 8:69-94.

Walker, G.P.L. 1981. Generation and dispersal of fine ash and dust by volcanic eruptions. *J. Volcanol. Geotherm. Res.* 11:81-92.

Walker, G.T. & Bliss, E. 1932. World Weather V. *Mem. R. Met. Society.* 4:53-84.

Walker, M.J.C., Ballantyne, C.K., Lowe, J.J. and Sutherland, D.G. 1988. A re-interpretation of the Late Glacial environemntal history of the Isle of Skye, Inner Hebrides, Scotland. *Journal of Quaternary Science 3*, 135 - 146.

Walker, R. 1988. Diatom and pollen studies of a sediment profile from Melynllyn, a mountain tarn in Snowdonia, North Wales. *New Phytologist 8*:791 - 804.

Walton. C. 1985. Satellite measurement of sea surface temperatures in the presence of volcanic aerosols. *Journal of Climate and Applied Meteorology.* 24:501-507.

Wang Shao - Wu & Zhao Zong - Ci. 1981. Droughts and floods in China, 1470-1979. In Wigley, T.M.L., Ingram, M.J. & Farmer, G. (eds) *Climate and History: Studies in past climates and their impact on man.* C.U.P.

Warner, R. 1990. The "Prehistoric" Irish annals: Fable or History? *Archaeology Ireland* 4(1):30-33.

Waterston, A.R, Holden,A.V., Campbell, R.N. and Maitland, P.S. 1979. The inland waters of the Outer Hebrides. *Proceedings of the Royal Society of Edinburgh* 77B:329-351.

Waterstone, A.R. & Lyster, I.H.J. 1979. The macrofauna of brackish and freshwaters of the Loch Druidibeg National Nature Reserve and its neighbourhood, South Uist. *Proceedings of the Royal Society of Edinburgh* 77B:353-376

Watkins, N.D., Sparks, R.S.J., Sigurdsson, H. & Huang, T.C. 1978. Volume and extent of Minoan tephra from the Santorini volcano: new evidence from deep sea sediment cores. *Nature.* 271:122-126.

Watt Committee On Energy. 1984. *Report number 14. Acid Rain.* The Watt Committee on Energy Limited.

Welsh, W.T. 1987. The Loch Dee Project: runoff and surface water quality in an area subject to acid precipitation and afforestation in SW Scotland. *Trans. Roy. Soc Edinburgh. Earth Sciences.* 78:249-260.

Westgate, J.A. & Gorton, M.P. 1981. Correlation Techniques in tephra studies. In Self, S. & Sparks, R.S.J (eds). *Tephra Studies.*:73-94.

Wexler, H. 1956. *Tellus.* 8:480-494.

Wheeler, R. and Dunning, C. 1976. Trace element geochemistry of piston cores from western Michigan coastal lakes. Can. Min. 14, 23-31

Whelpdale, T.M. 1978. Large-scale sulphur studies in Canada. *Atmos. Environment* 12:661-670.

White, G. 1789. *The natural history of Selbourne.* Reprinted 1977. London. Penguin.

Whitehead, P.G. & Neal, C. 1987. Modelling the effects of acid deposition in upland Scotland. *Trans. Roy. Soc Edinburgh. Earth Sciences.* 78:385-392.

Whittington, G. and Ritchie, W. 1988. Flandrian environmental evolution on north-east Benbecula and southern Grimsay, Outer Hebrides, Scotland. *O'Dell Memorial Monograph no. 21.* University of Aberdeen, Department of Geography.

Wigley, T.M.L., Ingram, M.J. & Farmer, G. (Eds) 1981. *Climate and History: Studies in past climates and their impact on man.* C.U.P.

Wigley, T.M.L. & Kelly, P.M. Holocene climatic change, ^{14}C wiggles and variations in solar irradiance. *Phil. Trans. R. Soc. Lond.* A 330:547-560.

Wik, M. & Natkanski, J. 1990. British and Scandinavian lake sediment records of carbonaceous particles from fossil-fuel combustion. In Battarbee, R.W., Mason, Sir John, Renberg, I. & Talling, J.F. (eds). *Palaeolimnology and Lake Acidification.* London. The Royal Society. pp93-98.

Wilcox, R.E. 1959. Some effects of the recent volcanic ash falls with special reference to Alaska. *US Geological survey Bulletin.* 1028-N, 409-476.

Wilkins, D.A. 1984. The Flandrian woods of Lewis (Scotland). *Journal of Ecology 72*, 251 - 258.

Williams, H. & McBirney, A.R. 1979. *Volcanology*. Freeman. San francisco.

Williams, L.D., Wigley, T.M.L. 1983. A comparison of Evidence for Late Holocene Summer Temperature variation in the Northern hemisphere. *Quaternary Research* 20:286-307.

Wisniewski, J. 1982. The potential acidity associated with dews, frosts and fogs. *Water, Air, and Soil Pollution.* 17(4):361-377.

Wood, A. 1984. The amazing and portentous summer of 1783. *Eos*. 65:410-411.

Wood, J.D. 1965. The complicity of climate in the 1816 depression in Dumfriesshire. *Scottish Geographical Magazine.* 81:5-17.

Woodin, S.J., 1988. Acidic deposition and upland conservation: an overview and the way ahead. In Usher, M.B. & Thompson. D.B.A. *Ecological change in the Uplands.* Blackwell. Oxford.

Wright, P.B. 1986. Precursors of the Southern Oscillation. *Journal of Climatology* 6:17-30.

Xiangding, W. & Xuhzi, Z. 1991: Tree-ring width and climate change in China. *Quaternary Science Reviews*. 10:545-549.

Yadav, R.R. 1992. Dendroindications of recent volcanic eruptions in Kamchatka, Russia. *Quaternary Research* 38:260-264.

Yadav, R.R. 1993. Reply to yamaguchi's letter to the editor on Tree-ring records of volcanic events in Kamchatca and elsewhere. *Quaternary Research* 40:264.

Yadav, R.R. & Kulieshius, P. 1992. Dating of earthquakes: tree-ring responses to the catastrophic earthquake of 1887 in Alma-Ata, Kazakhstan. *The Geographical Journal* 158:295-299.

Yamaguchi, D.K. 1983. New tree-ring dates for recent eruptions of Mt. St. Helens. *Quaternary Research.* 20:246-250.

Yamaguchi, D.K. 1993. On Tree-Ring records of volcanic events in Kamchatka and elsewhere. *Quaternary Research* 40:262-263.

Zubakov, V.A. and Borzenkova, I.I. 1988. Pliocene palaeoclimates: Past palaeoclimates as possible analogues of mid Twenty First century climate. *Palaeogeography, Palaeoclimatology and Palaeoecology*, 65:35-49.