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University Of Alberta

Climate, Environment And Culture Change: Creating A Palaeotemperature Record For Northern Iceland

By

Lisa Yvonne Mutch

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A thesis submitted to the Faculty of Graduate Studies and Research in partial fulfillment of the requirements for the degree of Master of Arts

Department Of Anthropology

Edmonton, Alberta
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The undersigned certify that they have read, and recommend to the Faculty of Graduate Studies and Research for acceptance, a thesis entitled Climate, Environment And Culture Change: Creating A Palaeotemperature Record For Northern Iceland submitted by Lisa Yvonne Mutch in partial fulfillment of the requirements for the degree of Master of Arts.

Dr. Charles Schweger

Dr. David Lubell

Dr. Karlis Muehlenbachs

For my Dad and me

ABSTRACT

This thesis details complex and systemic interrelationships between the Norse population, cultural landscape, and environment of Iceland, and demonstrates the failure of stable isotopy to construct a temperature profile for northern Icelandic peatlands.

Independent data predating instrumental records are needed to assess the duration and magnitude of past climate fluctuations (Medieval Warm Period and Little Ice Age) in Iceland since the time of settlement. Such data would allow researchers to understand more fully how climate variations interact with cultural changes seen in the archaeological and palaeoecological records at the northern Icelandic sites of Gjögur and Svalbarð.

The failure of the stable isotope (H/D) method to construct a temperature profile for northern Iceland is due to failure of the laboratory analysis (most likely caused by incomplete delignification or nitration). Further, it is felt that peat does not fulfill the requirements for an appropriate study material in this type of research.

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CHAPTER 1

INTRODUCTION

Aims of the Study

The Norse colonization of Iceland in the ninth century was attended by extensive cultural and ecological changes. The documentation of variations in resource use and settlement patterns, as well as in the surrounding landscape, has led archaeologists and historians to question the driving forces behind cultural and environmental change in Iceland. One popular hypothesis is that many effects are caused primarily by climate. It is known that relatively minor fluctuations may have anomalously large effects on marginal settlements like those in the North Atlantic, and some cultural changes apparently succeed recorded climatic changes. However, the full effects of the differing magnitudes and duration of climate fluctuations and the role played by human cultures in the system is not well understood.

Increased amounts of high-resolution information are required to assess the duration and magnitude of past climate fluctuations in Iceland, including the Medieval Warm Period and Little Ice Age. This will in turn clarify the interactions between human activity and environmental change during those times, and test assumptions based on climate change theories. In order to provide such data, researchers have attempted to provide climatic reconstructions for the periods following Norse settlement in ca. A.D. 870. However, sparse historical records and problems in the application of proxy methods have necessitated the use of new techniques in archaeological chemistry.

Within this context, the present research has two major aims. First, it will demonstrate the complex and systemic relationships between past climate variations and culture changes apparent in the archaeological, historical and palaeoecological records in Iceland, specifically at the sites of Gjögur and Svalbarð. Having demonstrated the importance of climate in the Icelandic system, this research will test the ability of hydrogen-deuterium stable isotopy to create a high-resolution record of temperature changes which occurred at these two northern Icelandic peatlands over the last millennium.

Palaeoenvironmental Studies, Historical Analogs, and the Present

In recent times, increasing levels of atmospheric carbon dioxide and evidence of global climatic warming have induced urgent scientific interest. In response, studies of *past* climate change endeavor to model and simulate *future* changes, as well as to more fully understand the processes involved and their possible effects on modern human cultures worldwide.

> Growing concern about the influence of human activity on global temperatures and on large ecosystems like rain forests has raised questions about the changes humans may be making to the climate of the Earth. The more dire predictions of climate change, which include catastrophic sea-level rise, desertification, and severe disturbance to existing ecosystems, make it imperative that the causes of climate change be better understood. (Morrison 1993:190)

Some researchers refute the importance of models designed to predict climate change which have been created using historical data. "They argue that 'novel circumstances' - twentieth century chemicals, burgeoning population, scale changes in the human ability to modify the environment, and so on - render any historical analog irrelevant" (Crumley 1994:4). It is true that effects due to the drastically increased production of modern-day pollutants may obscure any long-term perspective of the natural baseline of these systems.

However, data compiled from palaeoenvironmental and historical records of climate in pre-industrial times may provide the solution.

> Evidence from the past, during periods of exceptional warmth or where temperatures were increasing [such as the Medieval Warm Period], could help us to understand the characteristics of a future warm climate and will provide essential hard data needed to test whether computer models can adequately simulate climate during periods of rapid change. (Peel 1989:508)

Historical records can thus be used to estimate the magnitude, range and duration of future fluctuations (Mason 1978). In fact, researchers suspect that the Medieval Warm Period might act as a "pre industrial control against which to measure the present global warming trend", as present levels of solar activity are considered to be much like those from A.D. 1100 to 1250, and might be expected to last for 150 years (Zimmerman 1994:47; Jirikowic and Damon 1994).

To reduce the complications associated with successive cultures' activities in a single area, settlement and colonization of previously unsettled lands has become a focus for research. By eliminating the potentially confounding evidence due to the palimpsest of cultures, "island colonization provides a unique context for understanding the effects of introducing a human presence into a pristine ecosystem" (Smith 1995:319). Within this context, Iceland has earned a special status. This North Atlantic island provides an ideal location to study the interactions between people and environment, including the effects of climate changes on the Norse populations which settled and farmed the land (Zutter 1992). Factors which have led researchers such as Buckland et al. (1986) and Maizels and Caseldine (1991:1) to term Iceland "a crucial laboratory" include (see chapter 2):

1. its location, spanning boundaries between air and ocean circulation patterns which are of major atmospheric and oceanographic significance (Kelly et al. 1987; Maizels and Caseldine 1991);

2. its proximity to the huge Greenlandic continental ice sheet, currently providing detailed information on past climate changes through the GISP2 and GRIP ice core programs;
3. an extensive tephrochronology developed for much of Iceland (Thorarinsson 1970; Larsen 1984; Smith 1995);
4. late settlement by a single archaeologically and historically known literate Norse population pursuing a relatively homogeneous economy (Berthórsson et al. 1988; Zutter 1989; Smith 1995);
5. settlement in a relatively small and agriculturally marginal subsistence zone, where climatic variations might be expected to have had far-reaching effects on populations, their social structures, and subsistence activities (Ogilvie 1981; McGovern et al. 1988),
6. Lengthy records of agricultural productivity and meteorological data for the same periods, and finally;
7. a sustained population: factors which ended Norse settlements on Greenland may have affected Icelanders less severely, and this success in comparison to the apparently catastrophic problems of their neighboring island has increased research interest.

However, confusion stemming from the combined effects of climate change and human impacts on previously pristine areas has not been resolved. Even in relatively culturally isolated and sensitive zones, interpreting palaeoenvironmental data can be complicated: which effects are of natural, and which of anthropogenic, origin? How do human and natural systems interact to affect the landscape (Morrison and Mayewski 1990; Maizels and Caseldine 1991; Crumley 1994)? Thus, understanding which effects are brought about by natural changes and which by human agency is an important goal in palaeoenvironmental reconstructions (Morrison and Mayewski 1990). As more is understood, the full extent of the effects of the Icelandic culture and economy on the natural landscape has been realized. At the same time, some researchers have cautioned against overuse of restrictive and exclusive "culture" and "nature" categories, which hinder efforts to create a holistic and organic model in investigations, and instead propose that man can be envisioned as a natural organism interacting with, changing, and responding to his environment through time (Ingerson 1994).

With increasing understanding about how past peoples have interacted with their changing cultural and ecological surroundings has come recognition of how people use culture to mediate and adapt to changes. It has also demonstrated cases where spectacular human migrations, abandonments and mortality have been caused (or exacerbated) by the inability of culture to be flexible in changing circumstances.

These lessons of the past have great import for the future. In a time of increasing knowledge about how human agency has impacted global ecosystems comes concern about how these changes might affect them in the future. Assessing the effects of past changes such as the Medieval Warm Period or Little Ice Age and projecting these into the future should allow the cultures and policy-makers of the 20th century to deal more adequately with the changes in store for the 21st century. While climatic changes may have affected Norse settlers with their relatively primitive technology and settlements in marginal zones, the potential for large-scale global changes to affect modern society requires serious consideration.

Stable Isotopy and Archaeological Chemistry

Interest in isotopes followed the detonation of the nuclear bomb (or A-Bomb) near the end of the second World War, and research has continued since that time. The applicability of the methods of stable isotopy to climatic phenomena has been demonstrated since the mid-1950s and 1960s, when pioneering work by I. Friedman, H. Craig, and W. Dansgaard showed that isotopic ratios could be measured in common materials, and that these varied with altitude, latitude and amounts of precipitation. The work of such researchers as M. DeNiro, S. Epstein, B. Marino and others has greatly enhanced the understanding of the relationship of isotopic ratios to environmental and post-depositional changes. Further work by these and other researchers introduced the possibility that palaeoclimatological data could be retrieved from sediments incorporating plant materials, such as peat. While it is not yet feasible to create an absolute temperature profile for these materials, such methods produce a relative scale for temperature variations through time, which can be examined for the relative magnitude, duration and frequency of changes relating to climate change.

Related Studies

This thesis is set within a context of past and present studies of the climate of the North Atlantic region. The North Atlantic Biocultural Organization (NABO), a multidisciplinary, non-governmental research co-operative, was created in 1992 to research the human impact on environment, the environmental impact on humans, and intercultural interactions, all within the sphere of the North Atlantic region (NABO 1994:1). The Icelandic Paleoeconomy Project (IPP) was developed in 1985 to address questions about past economic activities, and test highly conservative models of Norse responses to subsistence crises (focussing on the northwest Arneshreuppur and northeast Thistilfjörd/Bogarfjörd-eystri districts) (Amorosi 1991:273).

Climatological information for the Icelandic and European/North Atlantic regions can be retrieved from a number of historical and proxy sources, including: historical records (Lamb 1979, 1982a, 1988; Ogilvie 1980, 1984a, 1986, 1991, 1992); ice core studies (Dansgaard et al. 1975; Morrison and Mayewski 1990; Mayewski and O'Brien 1993; Mayewski et al. 1993; O'Brien et al. 1995); glaciology (Caseldine 1991; Häberle 1991; Martin et al. 1991; Grove and Switsur 1994); distributional studies, crop production and phenology (Le Roy Ladurie and Baulant 1981; Pfister 1981b; Bell 1982, Osbourne 1982; Buckland et al. 1986, 1991a); dendroclimatology (LaMarche 1978, 1974); sedimentology (Barber 1982; Buckland et al. 1992; Bond et al. 1993); and stable isotopy

(Schiegl 1972; Chatwin 1981; Brenninkmeijer et al. 1982; Molloy 1993; White et al. 1994a).

Work in the immediate study area in northern Iceland includes archaeological and archaeofaunal research at Svalbarð and Gjögur (Amorosi 1991, 1992; Amorosi and McGovern 1992), stable isotopy of marine carbonate shells at Svalbarð (Molloy 1993), and palynology and macroremains at the Svalbarð and Gjögur sites (Zutter 1989, 1996). The work by Zutter is the most closely associated with this study, as sediment cores taken in 1993 provided materials for this and Zutter's investigations, and it is hoped that the two studies can incorporate the results from stable isotopy and palynology in order to reveal yet more information (Barber 1982; de Beaulieu et al. 1994).

Chapter Contents

In the next chapter (Chapter 2), a brief discussion of the geography and history of Iceland provides background to the archaeological questions concerning the nature of human settlements and land use in Iceland. Chapter 3 discusses how present-day researchers record and reconstruct climate variations, the past climate of Iceland and surrounding environs (including the Medieval Warm Epoch and Little Ice Age), and a discussion of views on the degree to which such climate changes affect human activities and the environments in which these occur. This chapter also presents a model demonstrating the relationships between environmental and climatic factors which interact with human activities in Iceland. Chapter 4 presents methodology, including site description, core collection and palaeobotanical procedures, stable isotopy, and laboratory procedures. Results from stable isotopy are presented and discussed in the context of the study in chapter 5. Chapter 6 presents conclusions. Summaries are given at the end of each chapter.

CHAPTER 2

ICELANDIC GEOGRAPHY AND HISTORY

Location and Topography

Iceland is a volcanic island situated between 63°23' to 66°32' N, and 13°30' to 24°32' W, a total land mass of 103 000 km^2 estimated to be fifteen million years old (Einarsson 1970; Blöndal 1987; Buckland and Dugmore 1991). Iceland is nearest to Greenland, 290 km to the northwest, while Scotland is 800 km to the southeast, and Norway 970 km to the east (Preusser 1976). The average altitude is 500 m a.s.l. Only 33 100 km^2 of the land lies below 400 m altitude; most of the land mass (60 000 km^2) is high plateau, a terrain dominated by glaciated mountains, central upland plateau characterized by rocky deserts, glaciers and lava fields (Einarsson 1970; Ogilvie 1991).

Iceland is commonly known as the land of fire and ice. Since settlement times, an estimated two hundred eruptions from forty or fifty volcanoes have rocked the island, such as: Eldgja, dated to A.D. 934 ± 2 years; the explosive Hekla I eruption at A.D. 1104; Katla at A.D. 1173 ± 10 and at A.D. 1357; Oræfajökull at A.D. 1362; and destructive Laki on June 8th, 1783 (Thórarinsson 1970; Einarsson 1973; Hammer et al. 1980; Hammer 1984; Buckland et al. 1986). Such high volcanic activity is evidenced by a great number of geothermal springs and geysers, which provide hot water and household heating; as well, soils in 'hot spot' areas may have been used to plant gardens, as is presently done. Both dryland soils and peatlands are rich in loessial and volcanic materials (Blöndal 1987).

Iceland's many glaciers retreat and advance with climatic changes, and claim 11 800 km^2 of Iceland's surface. The largest of these is Vatnajökull (8 400 km^2) (Einarsson 1970). Glacial activity has created deep and irregular fjords along the north, northwest and east coasts of Iceland, while the flat south and southeast coasts are *sandur* (glacial outwash plains) (Einarsson 1970).

Arable land and settlements mostly occur in lowland areas in the southwest, below limits on agricultural production at 400 m (below 300 m in northern Iceland) (Stone 1967; Preusser 1976; Arnalds et al. 1987; Sveinbjarnardóttir 1992). Presently, approximately one-quarter of Iceland is suitable for agriculture, but only about 1 500 km^2 (1.5%) is actually cultivated (Gelsinger 1981; Blöndal 1987). Highland areas are used for communal grazing, but these areas have suffered from extensive devegetation and erosion since settlement times, particularly in active volcanic regions where soils are sensitive to disruption (Arnalds et al. 1987).

Climate

The first Icelandic instrumental observations date from 1749-1751. The meteorological station at Stykkishólmur established in 1845 at the mouth of Hvammsfjörður on the west coast, has regularly recorded data since that time. In 1873 another station on the east coast at Berufjörður was established. By 1971 the number of stations in Iceland totalled 127 (Einarsson 1970).

Iceland is marked by distinct regional variation between the northern and southern coasts, which are separated by only 300 km (Preusser 1976; Ogilvie 1984b). The transition between cool temperate oceanic and sub-polar oceanic climate zones lies across Iceland's landmass, running east-southeast from the west peninsula of Snaefellsnes to Vatnajokull (Preusser 1976; Maizels and Caseldine 1991). Regional differentiation is caused by various factors, including: drift ice occurrence, proximity to glaciers, distance inland from the sea, altitude, and topography (Preusser 1976; Parry 1978). Mountains, valleys and fjords also affect the intensity of winds or create rain shadows which lessen precipitation (Einarsson 1970).

The harshest and most variable climate occurs in the north, which is often affected by the proximity of cold ocean currents and air masses passing over the sea from Greenland, and temperatures can change drastically when cold northerly and northwesterly winds blow (Eythorsson 1949; Einarsson 1970; Lamb 1982a; Bergthórsson et al. 1988). The mildest climate occurs in the south, and is partly due to the mediating effects of warm ocean currents (Eythórsson 1949; Ogilvie 1984b).

Temperature and Precipitation

Seasonal temperatures in Iceland are mediated by its maritime location, and its climate is much like that of Northern Scotland (Jónsson 1946b). Summers are cool and winters mild, and both the annual and diurnal temperature ranges are small (Einarsson 1970; Preusser 1976; Ogilvie 1992). Mean annual temperatures in the lowland areas of Iceland range from 2.0°C to 5.7°C; in the highlands, temperatures are lower. In the winter, daily temperatures range only about 1°C, where summer days might see ranges of 3-6°C (Einarsson 1970). Summers are cool with mean monthly temperature values averaging 11.2°C in July (1931-1960), and winters are mild with monthly means at 0.4°C in January (1931-1960), but strong winds out of the north can make temperatures seem colder (Ogilvie 1991).

Winter runs from December to March, spring from April to May, summer from June to September, and autumn falls in October and November (Eythórsson 1949). January and February are the coldest months of the year. Winter frosts are common, but are mediated by frequent thaws. The number of frost-free days is fewer in the interior and in the north of the country, but these areas are also drier during the summer, which is essential for the hay-curing process (Einarsson 1970).

Precipitation values vary extensively both annually and with local conditions - southwest and western coastal values are the highest, ranging from 1000 to 1600 mm (700-1000 mm inland). North and northeast values are much lower (400-600 mm), and while these areas enjoy longer periods of clear weather, much more of their precipitation falls as snow. The mean annual rainfall in Iceland is 704 mm: May and June are the driest months, while autumn and early winter (particularly October) show highest precipitation values, with the exception of the interior north-northeast, where maximum precipitation falls in July or August (Einarsson 1970; Bergthórsson et al. 1988; Ogilvie 1991).

Air and Ocean Currents

Warm tropical air and the cold polar front, which is always over the North Atlantic, converge near Iceland, causing changeable weather conditions. "The opposition of these two air-masses are responsible for the disturbances which move from west to east and bring abundant rain" (Magny 1982:39). The track of cyclones (winds rotating around a minimum pressure zone) in the area affect Iceland's weather:

> Cyclones which form as disturbances on [the polar] front often intensify and pass close to Iceland and irregular and large pressure variations are therefore common. . . . Maps of annual mean pressure over the North Atlantic confirm that cyclones must be frequent near Iceland, as a mean low pressure centre - the *Icelandic Low* - is found a short distance southwest of the country. The travelling cyclones bring precipitation and strong winds, and rapid changes in weather may occur in their path. (Einarsson 1970:675-6)

Additionally, the high over Greenland can have considerable effect on Iceland's weather, strengthening the northeasterly air flow. Wind speeds are highest along the coasts, whereas calms are relatively frequent in the lowland interior (Einarsson 1970).

Iceland also lies at the convergence of two oceanic currents, which create temperature fronts at the northwest and southeast coasts (Einarsson 1970; see Grove 1988:17). The warm Irminger Current branches off from the North Atlantic Drift and flows clockwise along the south and west coasts, travelling to the north of Iceland. These warm waters allow harbours in those areas to remain ice free (Eythórsson 1949; Thórarinsson 1956). In the northeast, the East Iceland Current (branching off the East Greenland polar current) moves southward and down the coast, meeting the North Atlantic Drift off the southeast shore (Eythórsson 1949; Einarsson 1970; Ogilvie 1984b, 1991).

Sea Ice

Winds and the East Iceland Current bring sea ice to the shores of Iceland. While ice does not normally reach the coast, its arrival at certain times reflects a conjunction of conditions in the Greenland Sea and Polar Basin, the movement and character of ocean currents, and local weather near Iceland (Einarsson 1972; Ogilvie 1984b). Drift ice movement is dependent on the south-flowing East Greenland Current, in which changes in temperature and salinity of sea waters are closely related to the incidence of ice (Einarsson 1970; Bergthórsson 1972). In turn, such ocean currents depend to a large degree on wind-driven ocean circulation (Aagaard 1972). Kelly et al. (1987:10842)

> demonstrated that the advance of ice onto the Icelandic coast is dependent on atmospheric conditions during the winter and spring months. The main atmospheric factors appear to be enhanced northerlies over the northern Greenland Sea during winter coupled with enhanced westerlies just north of Iceland in both winter and spring.

The Icelanders distinguish between two different types of ice - one type is considered productive because it brings driftwood and other materials to the shore, while the other does not (Einarsson 1972). Drift ice occurs most often from the late winter to early spring (April - May). In severe seasons it can remain into summer and autumn (September and December usually see the least ice), and may extend along the northwest, north, east and possibly even the southern coastlines (travelling westwards) (Einarsson 1970; Ogilvie 1984b). From the end of February until May, the ice margin is close to Iceland's shores, about 120 km north-northwest of Grímsey (off the north coast of Iceland); at this time the ice is sensitive to fluctuations in wind speed and direction and can move 100 to 250 km in a day. Thus, weather conditions are a major influence on sea ice incidence (Einarsson 1972).

The complex relationship between sea ice and temperature has been demonstrated (see figure 1). Sea ice is associated with decreased precipitation, and a fall in land and sea temperatures, particularly in coastal areas (Bergthórsson 1969; Fridriksson 1969; Thórarinsson 1969; Einarsson 1970).

> Should the ice become land-fast and completely cover the surface of the surrounding sea, the country has then really become part of the polar regions. In such cases it is reasonable also to expect a prevailing north or northeast wind, which will bring polar air to Iceland that warms up very little on its way entirely over ice. (Fridriksson 1969:150)

Sea ice has a feedback effect on temperatures: cooling extends the ice sheets, which in turn cool northerly winds moving across Iceland. Since sea ice is highly persistent with regards to atmospheric temperatures, the chances of two bad years in succession increases (Bergthórsson 1985). It can be assumed that lengthy periods of high sea ice incidence indicate colder climatic periods in Iceland (Kelly et al. 1987) and possibly the whole North Atlantic region (Thórarinsson 1956). Lamb (1979) proposed that the most severe climatic years in Iceland may be linked to times when the warm currents may not have reached the south Iceland coast. Researchers have attempted to reconstruct pre-instrumental climatic conditions based on this relationship (Bergthórsson 1969; Ogilvie 1980, 1984b, 1986).

Icelandic Fauna and Flora

As is the case with many of the North Atlantic islands, Iceland's geographical isolation and glacial history has led to a "depauperate"

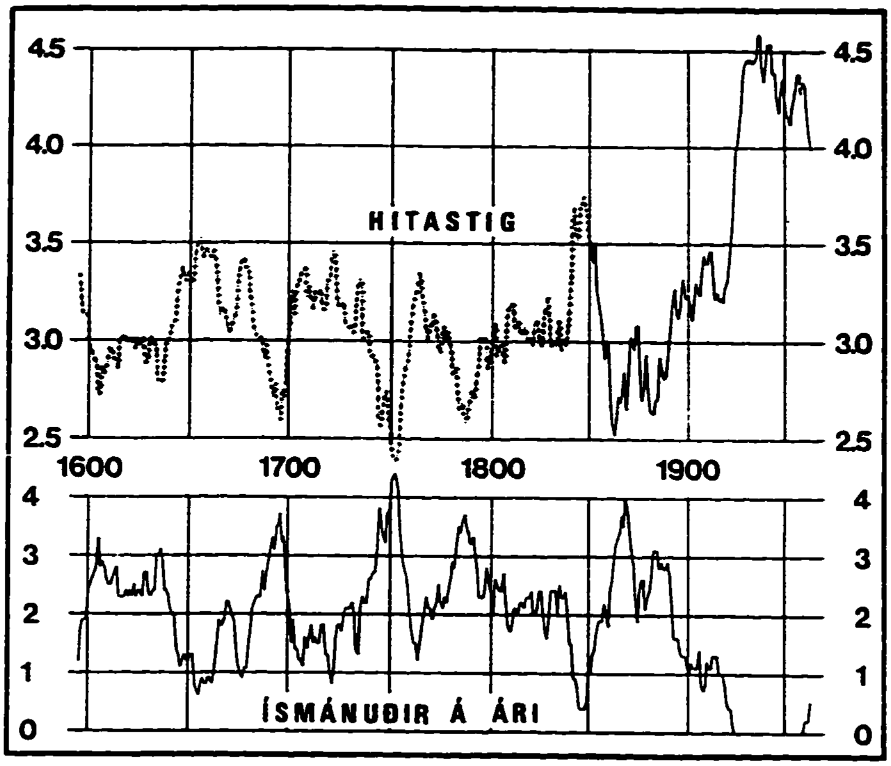


Figure 1. Correlation between temperatures "Hitastig" (in decadal running temperature means, top) and number of ice months "Ismánuðir á ári" (below). Estimated values are represented by the dotted line. Reproduced by permission from *Jökull* from Bergthórsson 1969:98.

flora and fauna (Amorosi 1991:274), though the climate could support a much richer biota (Blöndal 1987). Buckland and Dugmore argue that it is unlikely that all of the biota survived glacial times *in situ*, but some species also do not seem to be recent arrivals:

> It therefore seems most probable that colonization occured during the earliest Holocene on ice rafts and in flood debris from a rapidly decaying Fennoscandinavian ice sheet. Whilst not excluding other mechanisms of dispersal, this model appears to offer the most complete explanation for the origins of the biota,

> and is supported by the fossil evidence. (Buckland and Dugmore 1991:107)

Land mammals are meagre, represented only by the arctic fox and the imported reindeer: occasionally, a polar bear will come to Iceland on the drift ice from Greenland (Jónsson 1946a; Smith 1995). In contrast, Iceland's bird species are varied and numerous (240 species), including the ptarmigan, eider-duck, swan, eagle, and falcon. The rivers and sea produce many exploitable species to be fished or hunted, including Atlantic salmon, trout, cod, haddock and herring, shellfish (clams, blue mussels and some gastropods), as well as seal, walrus and whale (Jónsson 1946a; Preusser 1976; Amorosi 1989; Smith 1995).

About 440 species of vascular plants presently occur on Iceland, about 20% of which have been imported by human agency; a very small number of native plants such as *Carex* may have survived the last ice age in refugia (Einarsson 1963; Steindorsson 1963; Blöndal 1987). Woodlands are populated by the native dwarf birch *(Betula pubescens)*, willow *(Salix)* and rowan (*Sorbus aucuparia*), while other areas support hardy grasses, sedges, fen- and heathland species (Einarsson 1963; Blöndal 1987; Smith 1995).

Peat Formation and Use

Peat is primarily the waterlogged and "partially decayed remains of the bog plants" (Barber 1982:103). Peat formation depends on high amounts of rainfall, as well as the maintenance of a near-surface water table; often this is accomplished by *Sphagnum* species which keep water near the surface and acidify water flowing through or falling on the mosses (Barber 1982).

> Waterlogging, as in peat bogs, owes its preservative effect to the fact that in a waterlogged deposit air is excluded, so that the oxygen-rich atmosphere, essential for the well-being of animals and aerobic fungi and bacteria, is lacking. Under such conditions

> plant material may be preserved for thousands of years (though biochemical changes may take place over long periods of time). . . . In fact, the formation of peat itself is direct proof of such preservation. (Dimbleby 1967:97)

Icelandic *myrar* (= mires) are generally of two types: "Flói" (level mires), and "Hallamyri" (mires on sloping mountain- and hillsides) (Einarsson 1963; Steindórsson 1975). The cool and rainy climate of Iceland lends itself to the formation of mires, which are fed by rain and/or runoff. Icelandic mires which receive *adfluvial* water (= to the river, runoff) are *minerogenic*; when the water is in motion (the majority of cases), they are classified as *soligenic*; if it is still, the mire is *topogenic* (Steindórsson 1975:13-14). "The term [mire] comprises all land inundated by water, which either floods the grass roots or reaches their level during the better part of the year. The term mire also embraces the vegetation found on such land" (Steindórsson 1975:10).

> For the most part [the vegetation] consists of Cyperacéa, moss remnants are slight and particularly Sphagnum is much more conspicuous in the lower layers of the peat than in those closer to the surface. . . . Knots from Salix and Betula nana are widely found in the peat, and in most mires there are two log layers of Betula pubescens which testify to warm and dry climatic periods. (Steindórsson 1975:15)

Carex (sedge), *Empetrum* (Crowberry), *Eriophorum* (floss-grass) and *Salix* (willow) occur in great numbers in northern Icelandic peatland sites. These woody and grassy species are more likely to be preserved during the creation of peats. The depth of Icelandic mires varies considerably, and is usually 0.5 to 3 metres, but some of limited area have been found to go as deep as 6 to 8 metres (Steindórsson 1975).

The use of peat turf is documented in many north Atlantic areas. Turf cutting does not extend as deep as peat cutting (<1 m versus up to 3 m in the latter case) (Guðmundur Olafsson, personal communication 1995). It provided fires for cooking, smithing, and warmth, shelters (both roofing and walls, and insulation), bedding and litter, and saddle pads for horses (Jónsson 1946a; Amorosi et al. 1992; Sveinbjarnardóttir 1992; Buckland et al. 1995; Smith 1995; Guðmundur Olafsson, personal communication 1995). In the Orkney Islands, peat was

> an invaluable fuel, releasing what little native timber could be found for structural purposes; the supply of larger timber depended upon ample driftwwod and imported stocks from mainland Scotland and Norway. (Ritchie 1993:35)

In Iceland's law books Grágás (Grey Goose) and Jónsbók, the right and obligation of dependent farmers to cut turf for fuel is stressed, to preserve stocks of brushwood whenever possible (Sveinbjarnardóttir 1992:12)

Man's activities have had drastic effects on the Icelandic peatlands. Efforts at draining peatlands for use as pasturage (reclamation) and turf cutting both shrink and dry surface layers (Barber et al. 1994), allowing aerobic decomposition: "once that has happened subsequent waterlogging, of course, cannot restore what has been destroyed, even though new peat growth may develop" (Dimbleby 1967:97). Such events also affect species distribution of flora and fauna inhabiting the peatlands, and sediment inputs, and these changes can be documented in later studies of post-settlement ecological impacts (Buckland et al. 1986; Barber et al. 1994).

Viking Age Expansions

The eighth and ninth centuries A.D. saw an outbreak of Norse settlers from Scandinavian countries into Europe and the North Atlantic islands. Norwegian settlers were often accompanied by those of Irish descent, and their slaves (Eylands 1946; Hollander 1967). The Shetlands, Orkneys and Faeroe Islands, Iceland and Western Greenland were all settled before the end of the first millennium A.D., with varying degrees of success (Jones 1984; McGovern 1990; Morris 1985) (see figure 2). This great movement westward was the result of a complex of political and economic

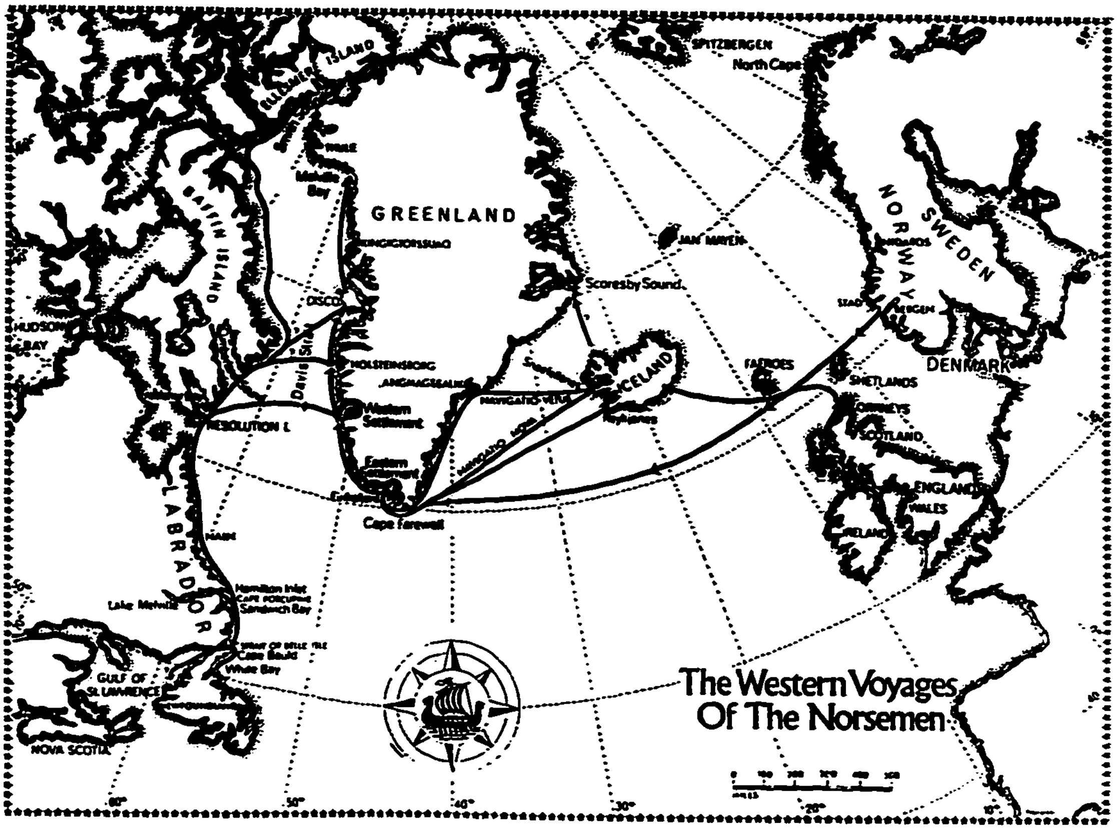


Figure 2. The western voyages of the Norsemen. Ca. 700 to 1000 A.D. Reprinted by permission of Oxford University Press from *A History of the Vikings* (Jones 1984:271).

pressures, technology (including ships and navigational techniques), and beneficial climatic conditions such as a reduction in sea ice and storminess of North Atlantic waters.

The ninth and tenth centuries were a time of increasing political suppression in Norway. King Harald "the Fairhaired" (ca. A.D. 870 to 945) began to exert control over the chieftains, and those who were not willing to swear allegiance found it expedient to leave Norway (Jones 1984), as chronicled in Laxdaela Saga:

> When Ketil learned that King Harald was intending to subject him to the same treatment as other chieftains, who had been forced to become the king's vassals and had been denied

compensation for fallen kinsmen, he summoned his own kinsmen to a meeting and addressed them thus:

'You are all aware of our past dealings with King Harald, and there is no need to recount them here; our more urgent task is to try to solve the problems that face us now. I have reliable reports of King Harald's hostility towards us, and I am sure we need look for no mercy from that quarter. It seems to me that there are only two courses open to us: either to flee the country, or else be killed off each in his own place.' (Magnusson and Pálsson 1969:48)

The desire for riches and fame that would make them powerful at home drove some Vikings west to seek their fortunes in precious metals and slaves, while others simply wanted safe havens and farmlands (Jones 1984; Ritchie 1993). "By the second half of the eighth century all three Scandinavian people were in search of betterment by means of trade and piracy, the seizure of goods and territory in wealthier lands, and the discovery of new and undefended pastures, hunting grounds and fisheries" (Jones 1991:8). In many cases, such requirements were met at the expense of people already settled in Scotland, England, Ireland, and Northern Europe.

During this period, overpopulation occurred throughout Scandinavia, but Norway particularly felt the scarcity of productive, available farmlands (Gelsinger 1981). Cleared and cultivated lands extended 100 to 200 m further up the valleys and hillsides in Central Norway from A.D. 800 to 1000, which may indicate increasing population pressures as well as a warmer climate (Lamb 1965). Newly-discovered islands offered new areas to support a growing population (particularly land-hungry younger sons), and despite its name, Iceland had fertile grasslands which often stretched considerable distances inland (Gelsinger 1981; Ritchie 1993).

During the ninth and tenth centuries, innovations in shipbuilding allowed the Vikings to sail longer distances in greater safety, and take the necessary settlement goods with them. Sailing ships such as that found at Oseberg (ca. A.D. 800), were coastal longships incapable of sailing in unprotected waters; the more solid Gokstad ship (ca. A.D. 850) was an ocean-going warship, but was not suitable as a merchant ship for trading or exploration. An ancestor of the Skuldelev I-type ship (ca. A.D. 1050-1100), the ocean-worthy *hafskip* or *knörr*, was more likely the working ship of Viking exploration (Gelsinger 1981; Jones 1984). These clinker-built ships were strong and elastic, and made to stand rough ocean waters, but were not well suited to weather a severe storm. The mast of the *hafskip* could not be lowered while the ship was in use and therefore was liable to be broken, and the sail, usually made of *vaðmal* (wool), could be torn if unfurled in high winds. A ship attempting to avoid a storm or run before it could find itself well off course, or near unknown lands (Jónsson 1946a; Ingstad 1969; Gelsinger 1981). Two of the three saga stories about the discovery of Iceland attribute this event to an "accident of weather" (Jones 1984:273). By the time ocean-worthy craft had been developed, the Vikings could put all their experience of local seamanship and navigation into ever-increasingly long distance summer voyages (Jones 1984). The Norse probably knew and used ocean currents, sightings of birds, the sun, moon and stars to aid their voyages through the North Atlantic, travelling to Iceland, along the east, south and west coasts of Greenland, and then along the Labrador Current southward to *Vinland* (Jónsson 1946a; Ingstad 1969).

There are indications that a considerably warmer period late in the ninth century caused mild, dry, and storm-free conditions in the Atlantic and North Sea during this period of Viking expansion (Bergthorsson 1969; Lamb 1982a; Ogilvie 1991), so that voyages such as those made by Eirik the Red were made in relatively ideal sailing conditions (Dansgaard et al. 1975). However, fall and winter were still seasons of violent storms, and even during summer the weather could suddenly change, bringing cloudy weather, a shift in the winds, or ice to block a harbour (Gelsinger 1981). Sea ice could both hinder voyages and act as a navigational aid: during cold years when sea ice persisted well into the spring or summer months, the start of a voyage could be delayed into late July or August; along the Greenland and Labrador coasts, ice masses could completely block any navigation far into the summer (Pohl 1966; Ingstad 1969). However, familiarity with a variety of such natural phenomena may have actually provided 'signposts': "Icefloes, the temperature of the water when close to Greenland, and areas known to be usually engulfed by fog, as well as the sense of smell . . . must have been other natural indications useful to the skilled navigator" (Gelsinger 1981:54).

Landnám

In Iceland, the Settlement Period, or *Landnám* (= Old Norse, land-taking) occurred between A.D. 874 and 930. Traditionally, at this point all available land had been occupied, although land-taking may have continued for a somewhat longer period in the more climatically marginal or remote areas, particularly in the north (Smith 1995). Like Norse settlement elsewhere in the North Atlantic, the

> usual compulsions, land shortage, pressure of population, restlessness, ambition or emulation, prospects of trade and hope of easy pickings, played a part in the colonization of Iceland, in addition to the special factors of the viking setbacks around 900 and the 'tyrrany' of Harald Fairhair after Hafrsfjord. (Jones 1984:279-281)

Islendingabók (Book of Icelanders) and *Landnámabók* (Book of Settlements) record that Irish *papar* (= religious fathers, hermits) dwelt in south-eastern Iceland before the Norse arrived, but that they 'went away' (Pálsson and Edwards 1972; Jones 1991:11). The settlers therefore "came to an empty land, only about one-sixth of which was suitable for human habitation. They at once set about exploring it and taking it into private ownership" (Jones 1991:11).

Between the end of the initial settlement period and the loss of political independence to Norway's King Hakon Hakonarson in 1262-1264, the Commonwealth period of Icelandic history is regarded as a prosperous "golden age" when many of the sagas were written, and Iceland enjoyed political independence (McGovern et al. 1988:227). The Later Medieval Period followed the loss of Icelandic independence (A.D. 1264-1500), and was succeeded by the Early Modern Period (A.D. 1500-1800), during which time the Little Ice Age was probably at its height in the North Atlantic (Amorosi 1991).

From Iceland, Greenland was settled in ca. A.D. 984, by the outlaw Eirik the Red.

> With Norway and Iceland barred to him he decided to sail west and fill in his time by finding and exploring a new land sighted some fifty years earlier by a Norwegian sailor named Gunnbjorn, when he had been storm-driven south then west of Iceland (Jones 1984:290).

Having successfully fufilled his three year term of banishment and returned home, Eirik sailed again to Greenland, accompanied by Icelanders who established farms at the southern tip of Greenland (Eastern Settlement), and east of present-day Nuuk (Western Settlement) about a decade later. At its height, the population of Greenland was about 3000 persons, who could boast of sixteen parish churches, a cathedral at Garðar (modern Igaliko), a monastery and nunnery (Jones 1984). However, Greenland's settlements did not last; from around the time that Greenland surrendered her independence to Norway in the thirteenth century (A.D. 1261), to the fifteenth century, these outposts of the Norse world began to decline. The reasons are still debated. However, it seems that a complex of factors were at work, including: its geographical location far from Europe; dependence for communication with Europe on a sea-route which became increasingly untenable, due to increasing sea-ice and political conditions in Norway; worsening cold in a marginal environment perched between the northern sea and glaciers; competition with the Eskimo, or *Skrælingar*, with little attempt to borrow technology from them that would allow hunting on sea ice; decreasing interest in their luxury exports; and the Greenlandic Norse populations' mismanagement of available resources (Jones 1984; McGovern et al. 1988; McGovern 1991, 1994; Buckland et al. 1996) In any case, the "detailed knowledge of Greenland in the thirteenth century is remarkable, and is a striking contrast to the darkness which shrouded it at the opening of the fifteenth century"

(Carus Wilson 1933:156). By ca. 1350, the Eastern Settlement alone survived in Greenland, and by ca. 1500, this too was deserted.

At the end of the first millennium, the Norse briefly travelled to the eastern shores of North America from Greenland, in search of timber and wine in *Vinland* (Old Norse = Wine Land). Eirik's son Leif is credited with the first Norse landing in the New World, following Bjarni Herjolfsson's reports of this land after his ship had been blown off course en route to Greenland (Jones 1984). Later, Thorfinn Karlsefni (Leif's sister-in-law's husband) overwintered in Vinland at Leifsbuðir - probably the three complexes totalling eight buildings which were intended for year-round use, excavated at L'Anse aux Meadows in Newfoundland. These may have been intended as a base for exploration of the surrounding lands; investigation revealed the absence of burial grounds, and almost nonexistent middens, implying a very short occupation (Wallace 1991). By A.D. 1020, voyages of exploration to Vinland were rare, and were intended only to bring back timber or furs (Jones 1984). By the time of Columbus' exploratory voyages to the New World, the Norse settlements which had first contacted those shores were probably dying out, and all such voyages were over (McGovern 1994).

The Cultural Landscape

'Landscape' expresses the relationship between humans and their environment (Crumley 1994). The cultural landscape is a 'natural' landscape modified by a cultural group; resulting changes to the ecosystem can be studied, and often reflect changing cultural practices through time (Zutter 1996). Cultural landscape acts as a mental template, which is peculiar to individual cultural systems (Jones 1988; Zutter 1996). Therefore, when Norse settlers emigrated from their homelands, they took with them goods and livestock, plants, northern farming expertise, Iron Age technology, and perhaps most importantly, a predetermined ideal of the lifestyle they would pursue in the new lands (Zutter 1989; Amorosi 1991). The landscape which the Norse settlers created when they imprinted their mental template onto the pristine island can be seen as a cultural artifact. Zutter (1996:25-6) proposes that such an artifact can be compared to more traditional conceptions of the attributes of artifacts: that the material (the terrain) is intentionally modified; that the modifications have distinctive cultural forms and features; that it is maintained; that it contributes to the economy; that it represents social wealth and/or political power, and is transportable.

The Norse Cultural Landscape and Economy

Historically, the Icelandic economy was dependent mainly on farming and animal husbandry, supplemented by fishing: until the 1800s, up to 90% of the population subsisted on these activities, and lived almost exclusively on individual farmsteads (Preusser 1976). Settlement of scattered farms occurred in the lowland portions of Iceland which were suitable for cultivation, but which also had access to fishing grounds (Jónsson 1946b; Gelsinger 1981; Sveinbjarnardóttir 1992).

> The low-lying, vegetated regions, mostly below 100 m in altitude, including the narrow, often discontinuous coastal strips alongside the steep mountain slopes, and the low-lying parts of the valleys, particularly in the north, were the areas in which people settled. In contrast with the situation today, the limit of colonisation extended further inland at that time, especially along the valleys, though it also encroached upon the highlands, particularly where the transition from lowland to highland was broad and gradual. (Preusser 1976:58)

In early times, the use of lower coastal areas may indicate settlers' need of maritime and riverine resources to act as buffers in case of agricultural failure in untried lands (Smith 1995). Icelandic settlers seemed to have been adapting to a new environment by utilizing a wide network of exploitable local species as survival foods, while the primary focus was on traditional and culturally favoured imported resources (Amorosi 1991; Smith 1995).

Animal husbandry dependent on grazing was the most optimum land-use. Sheep, cattle and horses were the main focus of animal husbandry, providing manure for the fields, wool, dairy products, meat, and transportation (Preusser 1976; Zutter 1989). The Norse also brought with them goats, pigs, and probably geese and hens (Adasteinsson 1991). Special consideration was paid to meadows and pastures available in the immediate vicinity of the farm and in the nearby uplands when homesteads were chosen (Jónsson 1946b; Fridriksson 1972; Preusser 1976). Essential hayfields and meadows in the immediate vicinity of the farm produced hay for the winter (Zutter 1989; Adalsteinsson 1991), and were manured to enhance their productivity. These infields converted the richness of summer to storable resources (Fridriksson 1972), and during times when the hay crop failed, excess animals were slaughtered in the autumn so that the remaining stock would survive (Adalsteinsson 1991).

While use of upland pastures or *shielings* was not documented until the 14th century (Sveinbjarnardóttir 1991, 1992), the traditional land-use models show rich grassland pasturage reserved for milk-producing stock (cows and ewes), while highlands were used for summer grazing of young animals and fattening older ones for slaughter.

Cereal agriculture has been of secondary importance for the Icelandic economy, since short summers and low temperatures severely limit the areas which can support cereal grains (Preusser 1976). During the early settlement times and while Medieval warmth lasted, cereal grain cultivation was more feasible and widespread than at any other period in Iceland's history. Historical evidence for the past cultivation of barley and possibly wheat and rye is based on place names incorporating words such as *bygg* (= barley), *korn* (= cereal crop), and *akur* (= field) in many parts of Iceland, as well as remnants of fields (Thórarinsson 1956; Ogilvie 1981). As well, naturally occurring *Elymus* grass may have been collected and harvested as bread-cereal (Preusser 1976). After cooling began in the 14th century, traditional cereals were grown only in few places in South Iceland, and then only barley (Bergthórsson 1969).

Harvesting of wild resources supplemented agricultural activities, especially fishing of the abundant cod in Icelandic waters. This was an important resource for people living directly on the coast, and was later exploited for an immense commercial export trade to urban Europe (Ogilvie 1981; Buckland et al. 1996). Occasional beached whales and seals, birds, eggs, wild berries, herbs and grasses were exploited (Jóhannesson 1974; Preusser 1976). Amorosi indicates that "the current archaeofauna suggest a colonizing population emphasizing cattle breeding and exploitation of native wild species in a previously unhunted landscape" (1991:280). Generally, the Icelandic Norse settlers showed a willingness to exploit a variety of resources, which may have sustained them during times of stress (McGovern et al. 1988; Zutter 1989).

Chapter Summary

Iceland's few settlement areas are found mostly along the coastlines and in the lowlands, away from inland volcanic uplands and glaciers. Distinct regional variations in temperature, precipitation, and incidence of sea ice are due to air and ocean currents, as well as topography. The fauna and flora are relatively sparse; in lowland wet areas, peat bogs form, which provide materials for a wide range of human use.

Norse settlers came to this island in the late 9th century primarily from Norway. Their movements to the west were due to a complex of factors, including political pressure, land hunger, and technological innovations which made sea travel possible in a time of lessened storms and ice in the North Atlantic. From Iceland, Greenland was settled in the late 10th century, and from there Vinland (North America) was discovered ca. A.D. 1000.

The Norse carried with them a predetermined ideal of the economy and lifestyle they would pursue in the newly settled lands. They imported European animals and plants and pursued an agricultural economy based on individual farmsteads, cattle, sheep and grain/hay production; their own produce was sometimes supplemented with wild resources.

CHAPTER 3

CLIMATE CHANGE

Climate and Sources of Climate Change

Climate can be described as "an average of the various day-to-day weather conditions in a region, usually over a 30-year period. Climate is the weather we might expect in a given area at a particular time based on past experience; weather is the atmospheric conditions we actually find" (Miller 1988:94). Changes in weather occur over days; changes in climate occur on longer time scales (Gunn 1994). Abrupt changes in climate can be defined as those on a "time-scale of the order between 50 and 200 years, while the temperature difference is of the order of about half the difference between glacial and interstadial" (2-3°C) (Ghazi 1983:2). In the North Atlantic, "climatic deterioration corresponds to a descent in latitude of the cold polar air masses and thus also to a parallel descent of the polar front" which results in decreased mean annual temperatures and increased dampness in maritime locations north of the front (Magny 1982:39-40). Amelioration displaces the polar air to the north, so that tropical air masses moving north increase mean annual temperatures (Magny 1982).

Naturally occurring climate changes are due to: changes in the energy output of the sun; secular changes in the earth's orbit (Milankovitch cycles); changes in the amounts of greenhouse gases in the atmosphere (e.g. natural changes in SO_2 and dust from volcanic sources); changes in salinity, currents, or surface temperature of the oceans; topographic changes such as mountain building, and vegetation growth or decay; and changes in albedo, the percentage of solar radiation reflected back from the surface of the earth (Shutts and Green 1978; Stanley 1986; Zimmerman 1994). Increased amounts of volcanic dust in the atmosphere, increased area of ice cap cover, and desertification all increase albedo (causing a reduction in mean atmospheric temperatures), which may be exacerbated by feedback effects (Shutts and Green 1978; Stanley 1986).

Human activities capable of causing climate change are essentially of two main types: those actions decreasing vegetative cover (particularly through overgrazing or clearing/overcutting), therefore increasing albedo; and those which produce increased amounts of greenhouse gases, particularly CO_2. Between 1860 and 1986, carbon dioxide levels in the atmosphere increased by 26%, primarily due to deforestation, combustion of fossil fuels, and other sources of atmospheric pollution (Stanley 1986).

Concerns about Climate Reconstructions

Climate reconstructions are based on three suppositions: 1) that the source of information is accurate and data can be directly extrapolated into the past; 2) that reconstructions can be applied to times and places which extend beyond that of the study; and 3) that timing can be accurately measured to provide comparable data sets. Recently, many researchers have begun to re-examine these assumptions and the ways in which their data are applied.

While direct instrumental measurements of climate changes are valuable in providing independent records, they are not always available. Studies to correlate proxy indicators of climate with actual meteorological data are essential to understanding the relationship between indicator data and climate, so that these might be extrapolated into the past with greater confidence (de Vries 1981). Information for climatic reconstruction is found in a variety of sources (see figure 3). Oftentimes, such data is used to approximate climatic changes across a wide area, and explain an array of physical and cultural phenomena. Concern over assumptions being made about the interactions between climatological variations and historical evidence for changing human behaviours has led to a call for independent comparative records (see Le Roy Ladurie 1971;

Halstead and O'Shea 1989). Sources of information must always be established separately before they are combined, and then reinforced through cross-checks to other independent sources in the same area, at the same time (Herlihy 1981; Crumley 1994). Paradoxically, historical climatologists have sometimes drawn on archaeological reconstructions of changes in human activities as support for climatic change, while archaeologists in their turn have relied on those 'independently proven' climatic records for their own reconstructions (Harding 1982). In order to avoid such circularity, "in the absence of independent climatic evidence, such "events" cannot be made to serve as both meteorological evidence and evidence of the human impact of climate" (de Vries 1981:21).

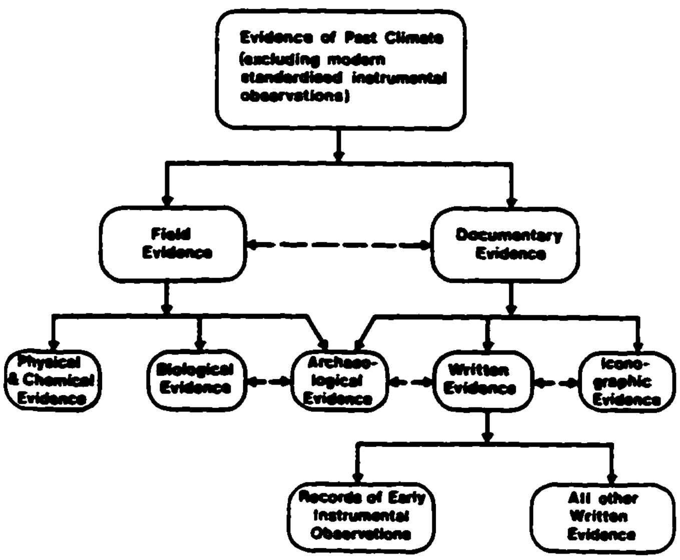


Figure 3. Data useful for reconstructing palaeoclimate. Note that categories overlap and interact. Reprinted by permission from Nature (Ingram et al. 1978:329). Copyright (1978) Macmillan Magazines Ltd.

The last millennium has been a time of relatively large fluctuations in climate, affecting many areas. However, often climatic data cannot be extrapolated far temporally nor areally: any data found in one region must not be considered representative of global or hemispheric conditions (de Vries 1981; Landsberg 1981; Kelly et al. 1987; Stuiver et al. 1995). Variations in climate have not necessarily occurred synchronously over the northern hemisphere or even across the North Atlantic region, although broad similarities in the records from Greenland, Iceland and England can be found back to ca. A.D. 1000 (Dansgaard et al. 1975) (see figure 4). Other researchers have found that variations are almost simultaneous, even those which occur in Greenland and other territories:

> The main climatic events in the last 500 years were synchronous for all the Arctic (to within 10 years) but their amplitudes were different; individual warm or cool periods could be more or less pronounced in different areas. We suppose that reports about time lags in some regions were due to incorrect dating of proxy data. (Tarussov 1992:515)

However, this does not address the concerns of an apparent time lag of 10 to 15 years in some instances, and 200 or 300 years in others (Bergthórsson 1972; Dansgaard et al. 1975; Porter 1981; Mayewski et al. 1993).

Such inconsistencies between studies are compounded by the complexity of the nature of the changes. For example, climatic variations in the North Atlantic/Scandinavia and Central/Western Europe may be broadly similar but asynchronous, or changes in one area may not be reflected in another (Porter 1981; Magny 1982). Grove (1985) showed that variations in glacial advancements can conflict even within Norway. "The significant differences found between regions are interesting in themselves, but also offer a powerful argument for caution in interpreting records from any one district" (Ogilvie 1984b:149). Studies based on documentary sources suffer from the specific nature of regional climatic records (Bryson and Padoch 1981).

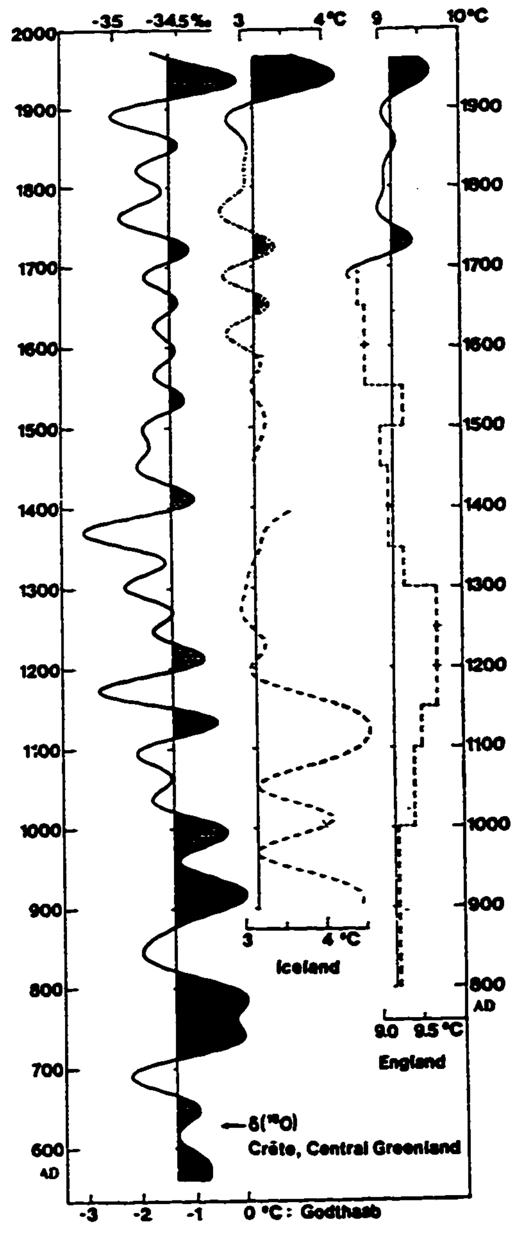


Figure 4. Comparison of $\delta^{18}O$ values for Crête (Greenland) and temperatures for Iceland and England. Dash-dot lines (Bergthórsson 1969), dashed lines (Lamb 1966 and Bergthórsson 1969). Reprinted with permission from Nature (Dansgaard et al. 1975:25). Copyright (1978) Macmillan Magazines Ltd.

Finally, proxy data used to measure time limits and effects of the cooling can be inaccurate, radiocarbon dates can be ambiguous for very recent dates, and the materials used for dating can be inappropriate. As well, techniques such as lichenometry which seem to be promising for more recent times cannot be applied to more distant climatic events (Grove 1985; Grove and Switsur 1994).

Recorded Indicators of Past Climate Change

Instrumental Records

Systematic instrumental records of climate date from the mid-19th century, and in some cases provide very detailed records of past changes (Thórarinsson 1956). However, data from early years of collection can be problematic with regards to instrumental accuracy and sensitivity, methodology (including the time and location of measurements), and the nature of conversion scales (Sigfusdóttir 1969; Brooks 1970; Einarsson 1970; Ingram et al. 1981a). A more serious problem is that records often do not extend sufficiently into the past to show long-term climate trends; as well, the geographical area within which such records are applicable can be very limited (Brooks 1970; Ingram et al. 1981a).

Written or Pictorial Records

Throughout the world, sources of written data are numerous, and include: myths and legends; plays and fictive works; ancient inscriptions (stele, papyri, carved oracle bones); annals, chronicles and histories; personal papers (letters, diaries, journals); public administration/government records (tax yields, crop yields/failures, tithe records, military campaign records); church records of polling bells and prayers; private estate records and farm accounts; early journalism recording weather at home and abroad; maritime commercial and exploration records (ships' logs, naval officers' diaries, commercial day journals of wind direction, barometric pressure and ocean conditions, catches and distribution of marine resources), and finally, works of early natural historians such as Tycho Brahe (Bell and Ogilvie 1978; Herlihy 1981; Ingram et al. 1981a; Landsberg 1981; Ogilvie 1991, 1992). Pictorial documents such as pictographs and petroglyphs, tomb reliefs, pottery drawings, paintings, pictures and photos can also act as source of climatic information, but tend to be less precise (Ingram et al. 1981a).

Many written sources (e.g. sagas, government records, farming, fishing and shipping records) have largely been drawn upon in Icelandic studies (see Vilmundarson 1972; Ogilvie 1991). Unfortunately, such sources must be used with caution, as they can be riddled with inaccurate or uncertain dates, amplified or distorted reproductions of observations, willful misrepresentation of observations and reports, omissions, and multiplication of events through mis-dating, which can be introduced as accounts are copied second-hand or as fragments are pieced together (Vilmundarson 1972; Bell and Ogilvie 1978; Ingram et al. 1978; Pfister 1992). For example, the original *Landnámabók* does not survive. A 17th century transcript of a second generation copy, probably made in ca. 1275-80 by Sturla Thórðarson, remains, though he added material from other sources (Page 1995). It is difficult to determine how much of the surviving material was in the original.

> It seems certain that, at the beginning of the twelfth century, there was an effort to collect together the traditions of the settlement of the country, and the existing versions of Landnámabók represent that collection in greater or lesser degree. (Page 1995:60)

The need to verify reliability of sources based on spatial and temporal proximity to events, access to such first-hand reports, identification of the authors' independent sources, and cross-checking with other sources has been stressed by many authors (Vilmundarson 1972; Bell and Ogilvie 1978; Ingram et al. 1978; Herlihy 1981).

As well, climatic reconstructions for areas where references are rare or sporadic can introduce the possibility that other researchers, unaware of the nature of such reconstructions, inappropriately use them as they would instrumental records, resulting in misleading conclusions (Molloy 1993). Finally, the errors introduced through the subjectivity of human authors is always problematic. "As a crude meteorological instrument, man tends to act as a high pass filter and his subjective observations show only short-term fluctuations about an ever-changing norm" (Ingram et al. 1978:333). While there have been attempts to quantify essentially qualitative reports on climate, such reconstructions are tentative and should be seen as such (de Vries 1981).

Proxy Indicators of Climate Change

Records of weather-related phenomena provide proxy data which are generally more abundant than meteorological records (Herlihy 1981; Ingram et al. 1981). Proxy data focus on a variety of natural phenomena, including: the relationship between temperature fluctuations and ice/glacial conditions or distribution of temperature-dependent species; the relationship between seasonal warmth, vegetative growth and ripening; sedimentary structures; or the relationship between naturally occurring isotopes and environmental phenomena.

However, applying climatic values to measured economic or social data is problematic in proxy indicator studies (de Vries 1981). "While the nature of climate at a given time may in some instances be inferred from its effects, the converse does not hold; the historical effect cannot be inferred from the climate" (Anderson 1981:340). In such cases, it cannot be determined whether the study reflects climate conditions or cultural changes which have been correlated with them, so it is essential that such studies focus simply on the physical phenomena of climate change.

Ice Core Data

Both the geographical location and high resolution of ice cores have made the geochemical information produced from the GISP2 and GRIP Greenlandic ice cores an important source of data for this study. These ice cores provide direct and proxy information over tens of thousands of years, with up to seasonal resolution (Mayewski 1988). Comparison with other lower resolution records, including deep-sea cores, glacial records, sediment cores, and other ice cores is also possible (Mayewski 1988; Morrison and Mayewski 1990).

However, this technique has not been fully exploited in many areas of the world, including low and middle latitude, high elevation sites in Asia, the Americas, and Europe (Mayewski 1988). A more serious problem is that of dating the seasonal and yearly fluctuations found in the ice cores. Hammer (1984) used high acidity peaks to trace historically recorded Icelandic eruptions to give the Dye 3 and Crête cores (Southern Greenland) a precise chronology. However, the accuracy of such methods have been questioned by Vilhjalmsson (1991), who asserts that acidity peaks do not serve as chemical signatures as tephras do, and that any identified peak could actually be due to any volcanic episode in the Northern Hemisphere. Therefore,

> to extract meaningful paleodata from polar ice cores it is first necessary to construct a reasonably accurate timescale based on reliable net accumulation measurements. By itself a simple count of annual layers from the surface downward is not a flawless dating scheme. Difficulties exist with this method if sections of the core record are missing due to drilling mishaps or a hiatus in the sequential layering. The reliability of a timescale based on numerical modeling is greatly enhanced if well-defined isotope or chemical indicator signals are present which represent historically recorded natural or artificial atmospheric events. In practice, it is necessary to use all the above approaches in combination and to make constant depth level cross checks of the various time series data sets to establish an acceptable time scale. (Langway et al 1995:16241)

Unfortunately, the Icelandic glaciers are subject to melting from summer temperatures and volcanic eruptions below the ice. This makes tham inappropriate for coring.

Snow and Ice Conditions

Reports of drift ice and icing of water bodies can indicate the number of days with daily mean temperatures below freezing, and wind speed and direction: frequently such sources will also specify how thick the ice was (i.e. thick enough to carry men and cargo), and its duration (Thórarinsson 1956; Messerli et al. 1978; Ogilvie 1980, 1984b; Pfister 1992). Recorded amounts of snowfall and days of snow cover can also indicate the severity of winters (Le Roy Ladurie 1971; Pfister 1981a, 1992), and an increase in drift ice years correlates with increasing thickness of glaciers (Bergthórsson 1969; Thorarinsson 1969). Sea ice incidence also correlates with cooler temperatures on adjacent land masses (Fridricksson 1969); however, "the Iceland data cannot be considered representative of conditions over the Northern hemisphere as a whole or even over a substantial portion of the hemisphere" (Kelly et al. 1987:10842).

Glacial fluctuations can indicate the presence of weather situations favouring accumulation or ablation, average temperatures and amounts of precipitation (Pfister 1992). Both temperature and precipitation control the budget of glaciers: periods of advance coincide with higher snowfall during summer and/or cooler seasonal mean temperatures in spring, autumn and winter (Thórarinsson 1969; Messerli et al. 1978). Oscillations of the glacier terminus can be precisely recorded when they directly affect the livelihoods of people in the region, but oftentimes reconstructing their advances and retreats is a more complicated process (Bradley and Jones 1993).

Dating glacial movement is problematic, as Holocene dating techniques are not always applicable. Many of the lichens which have been studied can only provide calibrated dates 150 to 200 years into the past - no time calibration surfaces predate 1870 in Iceland (Grove 1985; Caseldine 1991; Grove and Switsur 1994).

Radiocarbon dating depends on finding suitable materials directly over-ridden or disturbed by the ice (Bradley and Jones 1993; Grove and Switsur 1994). Later advances by an ice mass can destroy evidence for earlier ones (Caseldine 1991; Grove and Switsur 1994).

> Whereas considerable progress has been made in unravelling the pattern of the last two centuries, information about earlier periods, and even the earlier part of the 'Little Ice Age', is at best piecemeal. (Caseldine 1991:231)

As well, different types of glaciers respond less to temperature fluctuations than to the amount of precipitation in a given year (Martin et al. 1991).

Distributional Studies

Distributional studies are based on present-day knowledge about temperature, light, and other environmental constraints on the distribution of species. In some cases the destruction of habitat by man is enough to affect a whole species' ecology; in others where the species is presently found in more ameliorated climates (e.g. warmer, wetter, access to more sunlight), the change may be due to a deterioration in climate or regional conditions (Osborne 1982; Stine 1994).

Studies conducted on insect remains can correlate certain species with human activity areas, and have wider implications for climatic conditions (Buckland et al. 1986, 1991a, 1996). Marine species such as cod and molluscs are susceptible to changes in ocean water temperature, and their movements can be traced through fishing records (Lamb 1982a, 1982b; Molloy 1993). Archaeofaunal evidence of seal exploitation often gives clues to the distribution of species associated with colder times: in areas where common seals are exploited, the sudden appearance of quantities of bones of the harp and bearded seal, walrus, and polar bear is associated with cooling and the southward movement of sea ice (Amorosi 1992).

Former plant communities, tree line fluctuations and successional changes can be reconstructed through the study of pollen frequencies, palaeoethnobotany, and surviving communities outside their present ranges (Crumley 1994a). These techniques apply not only to naturally occurring species and weeds, but also to cultigens such as grains or garden-produced potatoes (introduced in the 18th century, during the Little Ice Age) which are also climatically sensitive - the choices that people made at planting time in the past can give clues to the climate (Bergthórsson 1985; Birks 1988; Grove 1988; Hicks 1988; Zutter 1989, 1992; Crumley 1994a).

However, lag in response time, variations in tolerance to climate changes, and the difficulty in discerning climatic from ecological (i.e. wildfires) and anthropogenic effects (i.e. controlled fires for clearing) are all problematic in short-term studies of climatic fluctuations (Parry 1978; Osborne 1982; Crumley 1994a). Multidisciplinary efforts have attempted to correct this situation through the use of combinations of such sources (see Sveinbjarnardóttir et al. 1981; Birks 1988; Buckland et al. 1991a; McGovern 1991).

Phenology

Phenology is the study of the historical distribution of plants and vineyards, and the recorded ripening, blossoming, fruiting or harvest dates for various species (Pfister 1992). Early fruit harvests depended on warm temperatures and sunny conditions between fruiting and budding: "other factors being equal, late harvest dates are indicative of a vine-growth period . . . during which average temperatures were mostly cold" (Le Roy Ladurie and Baulant 1981:259). Studies have shown that good grape harvests coincide with good cereal harvests in years with warm midsummer temperatures and mild glacial conditions (Le Roy Ladurie 1971; Pfister 1981b).

However, such studies must account for variations based on individual farmers' decisions (e.g. delays in the harvest for sweeter grapes), so for reliable climatic information, events must occur in many locations at once (Le Roy Ladurie 1971). As well, the effects of modern agricultural technology must be accounted for: plants probably reacted more to climate variations in the past before hybrids and fertilizers were readily available to mediate such changes (de Vries 1981).

Dendroclimatology

Dendroclimatological information can be extremely valuable and precise. Tree rings record "favourable" growing conditions in the density and condition of the rings they produce during the year, which can be measured through X-ray densitometry (Pfister 1981a). This method is increasingly popular, as time definition is very good and can easily compared with temperature records to produce very detailed records which can be extrapolated into the past (LaMarche 1974, 1978; Pearman et al. 1976; Fritts et al. 1981; Libby 1983).

In moderate zones growth is dependent on both heat and moisture and is difficult to interpret: the signal is clearer in marginal areas (where it is mainly the temperature of the short vegetative period which controls growth) (Le Roy Ladurie 1971; Pfister 1992). However, this is offset by very poor tree growth in extreme locations like Iceland, where dendroclimatology would be possible for very limited time periods (Vilhjalmsson 1991).

Sedimentology

The development of sediments of evaporative origin can indicate warmer and/or drier conditions, as lake beds and springs dry out and river and sea levels drop (Brooks 1970; Livingstone 1971; Ghazi 1983; Pfister 1992). Information can also be gleaned from flooding and flood levels permanently marked on buildings or other structures, low water levels marked on emerging rocks, increased landslide activity and river sedimentation, and even discussions about how far a person could walk on a dried up river bed (Bell 1982; Buckland et al. 1991b; Pfister 1992). Geochemical information can be attained from ocean floor cores containing weathered clays, carbonates or silica (Ghazi 1983). Finally, studies of relatively wet and dry periods in peats, and times and effects of tephra falls can be very effective (Barber 1982; Buckland et al. 1986; Barber et al. 1994).

However, many of these sources of proxy data suffer from a lack of datable surfaces or matrixes, sediment mixing and cryoturbation, and discontinuous stratification (Einarsson 1963; Bell 1982; Ghazi 1983; Hammer 1984; Smith 1995).

Stable isotopy

In an effort to overcome problems associated with the proxy and instrumental records discussed above, several studies have been undertaken using stable isotope methodology to provide an independent record of climate (see Duplessy 1978; Gray 1981; Wilson 1981; Herz 1990; Bowen 1991). Oxygen isotopes have been used on ice cores (Fisher and Koerner 1981; Dansgaard and Oeschger 1989), lake cores (Edwards and McAndrews 1989), marine and fresh waters (Epstein and Mayeda 1953), deep sea cores (Emiliani et al. 1978; Bond et al. 1993), and tree rings (Gray and Thompson 1976; Burk and Stuiver 1981). Carbon and oxygen isotopes have been used on marine shells and molluscs (Longinelli 1966; Mook 1971; Molloy 1993), lake sediments (Stuiver 1975), and peat deposits (White et al. 1994a). Hydrogen isotope ratios of trapped fluids in speleothems (calcite deposits) (Harmon et al. 1979), tree rings (Schiegl 1974; Wilson and Grinstead 1975; Epstein and Yapp 1976; Libby et al. 1976; Yapp and Epstein 1977; Ramesh et al. 1985, 1986; White et al. 1985, 1994b; Feng and Epstein 1994), plant fossils (Long et al. 1990) and peat deposits (Schiegl 1972; Chatwin 1981) have also been examined.

Studies have also focussed on quantification of the specific relationship between isotopes and environmental parameters such as growing season rainfall temperatures, effects of plant transpiration and post depositional changes. These include: Schiegl and Vogel 1970; Ziegler et al. 1976; DeNiro and Epstein 1979; Yapp and Epstein 1982b; Lawrence and White 1984; Francey and Tans 1987; Marino and DeNiro 1987; DeNiro et al. 1988; DeNiro and Cooper 1989; and Long et al. 1990. Such studies build on basic research already completed on the nature of isotopes in the environment (see Friedman 1953; Craig 1961; Dansgaard 1964).

Climate Reconstructions of the Last 1000 Years

Although climatic reconstructions vary in their applicability due to regional effects and the reliability of their sources, a discussion of reconstructed climate of the last millennium in the North Atlantic and Icelandic regions is still valuable. Particularly, it demonstrates the need for high resolution climate and temperature data to resolve issues of timing and magnitude of changes.

Many researchers studying climatic fluctuations of the last thousand years agree that the names Medieval Warm Period (or Little Climatic Optimum) and the Little Ice Age should be used with caution, partially because they give the impression that variations are better understood than they actually are (see Grove and Switsur 1994; Buckland et al. 1996). As well, use of the term "Ice Age" to describe relatively minor and sporadic regional cooling could be perceived as a misnomer (Grove 1988).

"The available evidence suggests that the MWP was global in extent and not uniform climatically" (Grove and Switsur 1994:166). Additionally, "although low-temperature events in the latter half of the present millennium are well documented, it is clear that these are neither temporally nor spatially synchronous in all localities of the North Atlantic region" (Buckland et al. 1996:88). In particular, uncertainty in the timing and character of the Little Ice Age is due to: a) the complication of the cool period lasting from ca. A.D. 1200 to 1400, before the mid-16th century cooling which signalled the extreme phase of the Little Ice Age; b) some geographical variations in timing; and c) the presence of warm periods occurring within this period of time which are not represented by the name 'Little Ice Age' (Pfister 1981b; Grove 1988; Bradley and Jones 1992; Grove and Switsur 1994).

The Medieval Warm Period (MWP)

During the High Middle Ages/middle of the last millennium, a warmer climatic period dominated the North Atlantic regions and northern Europe. The onset of this warm period has generally been set from A.D. 700 - 750 in the far north (Dansgaard et al. 1975; Bryson and Padoch 1981), and A.D. 900 - 1000 in the European Alps (Lamb 1965; Grove and Switsur 1994), with GISP2 showing the height of warmth at ca. A.D. 975 (Stuiver et al. 1995). Ogilvie (1984b, 1991) has tentatively dated this period to A.D. 870 - 1170 in Iceland, but has indicated that evidence is sparse.

> There is no contemporary documentary evidence on the climate of Iceland in early settlement times, and the few weather descriptions for this time which occur in later accounts are insufficient to give a reliable description of the climate of the early period. Most of the evidence for a mild climate at the time of settlement, and shortly thereafter, is circumstantial. (Ogilvie 1984b:140)

Despite uncertainties in the timing, there are indications that at settlement (ca. A.D. 870) and for the next two to three centuries, Iceland was characterized by a mild climate. According to reconstructions, temperatures were 1-2°C above 1950 normals (Lamb 1966; Bergthórsson 1969; Dansgaard et al. 1975). Evidence is scanty, but drift ice reports from Iceland seem to be rare in the 800s and 900s, and the ice was apparently completely absent from A.D. 1020 to 1200 (Lamb 1965, 1966). Place names and fossil pollen studies indicate cereal grains were grown in locales which are now unsuitable (Thórarinsson 1956; Bergthórsson 1969) and some early settlements were placed in areas subsequently engulfed by glacial advances (Thórarinsson 1956; Ogilvie 1984b). During this period, conditions have been characterized as generally mild, dry, and storm-free in the Atlantic Ocean and North Sea (Lamb 1982a; Ogilvie 1991) (see figure 5).

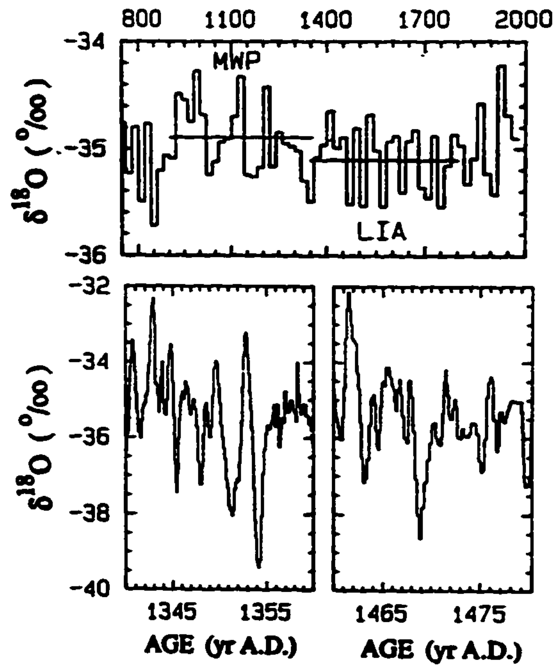


Figure 5. Mean bidecadal GISP2 $\delta^{18}O$ for the A.D. 820-1985 interval (upper curve). Horizontal lines show higher average annual $\delta^{18}O$ for the Medieval Warm Period (MWP) and lower average annual $\delta^{18}O$ for the Little Ice Age (LIA). Lower curves provide intra-annual detail for the A.D. 1340-1360 and A.D. 1460-1480 intervals (tickmark denotes the summer of that year). Reproduced by permission from Academic Press Inc., copyright 1995 (Stuiver et al. 1995:344).

Twelfth Century cooling

Around the twelfth or thirteenth century, this climatic optimum began to deteriorate. Colder conditions were first felt in Greenland around A.D. 1000 and ca. A.D. 1150-1200 in Iceland

(Lamb 1965, 1982b; Dansgaard et al. 1975; Bryson and Padoch 1981; Ogilvie 1984b). From ca. A.D. 1150-1200, Arctic sea ice and storminess around Greenland and Iceland expanded, making seafaring and communications more difficult (Lamb 1966, 1982b; Bryson and Padoch 1981). Cooling which began at A.D. 1200 in Iceland is recognized as a period of erratic climatic fluctuations and extremely variable conditions, which lasted two centuries in the North Atlantic, preceding the Little Ice Age (Lamb 1966, 1982a; Ogilvie 1984b). This cold period lasted until A.D. 1400, culminating around A.D. 1300, during which time mean annual temperatures may have fallen 1 to 2°C (Lamb 1982a; Ogilvie 1984b, 1991). GISP2 records very cold winters and minimal summer warmth in the years 1351 to 1355 (Stuiver et al. 1995) (see figure 5 above).

The Little Ice Age (LIA)

Generally, the onset of the Little Ice Age dates from A.D. 1550 to 1570 (Lamb 1965, 1966; Bryson and Padoch 1981; Flohn 1981; Ogilvie 1992). Studies of the Greenlandic ice cores indicate that cooling started there at the end of the 14th century, with the coldest intervals of the LIA at about A.D. 1450 and 1690-1700, and that cool temperatures lasted until 1850 (Fisher and Koerner 1981; Dansgaard and Oeschger 1989; Mayewski et al. 1993; Stuiver et al. 1995). In Iceland, it is "primarily during the period ~1750 to ~1900 that the 'Little Ice Age' must be sought" (Ogilvie 1992:114).

This was a period of advancing mountain glaciers all over the world, especially around the middle of the 18th century and for the next 150 years (Lamb 1966, 1982b; Flohn 1981; Ogilvie 1992). The extent of glacier growth reached the largest proportions since the last ice age ten thousand years ago (Bradley and Jones 1992).

While the 16th century was a little colder than other centuries of the millennium, it does not show dramatic cooling as might be expected (Bergthórsson 1969; Dansgaard et al. 1975). Studies of the nature of the Little Ice Age in Europe reinforce the complexity of this period. Phenological data provided by Le Roy Ladurie and Baulant

(1981) for western Europe show clusters of warm years interspersed with cool ones throughout the 17th, 18th and 19th centuries. As well, Briffa and Schweingruber (1992) detected four synchronous alternately cool and warm phases during the same time, but no other periods from 1750-1875 showed synchronous conditions in all their study areas. It was also noted that the Scandinavian curve showed remarkable interannual variability from 1790 to 1810.

As well as temporal and regional variability, clusters of anomalously cold and warm seasons and years occurred in which fluctuations of the same type were repeated (Flohn 1981; Pfister 1992). Extremes were often more frequent and more marked than those registered in the instrumental period (Flohn 1981; Pfister 1992). Even annual fluctuations could be large; the very hot summers in 1665 and '66 which resulted in the Great Fire of London occurred during the coldest century of the last millennium (Lamb 1982a).

The Little Ice Age was characterized by an increase in cold winters and very wet and variable summers in Europe and the North Atlantic (Lamb 1982b; Pfister 1981b). Lamb estimates there was a general European decline in temperature of about 1.5°C from the 13th to 17th centuries (1977, 1982b). In Iceland, cooling of 1.5-3°C below modern values ended the sixteenth century and began the seventeenth, but was interrupted by a mild period in the 1610s (Bergthórsson 1969; Dansgaard et al. 1975; Ogilvie 1992). Prolonged periods of cold occurred from the mid-17th century to the 1840s, with the last decade of the 17th century being notably extreme (Ogilvie 1986, 1991, 1992).

From A.D. 1600 to 1900, sea ice was more frequent in Iceland than it had been for the first 300 or 400 years of settlement (Thórarinsson 1956). The period from 1675 to 1704, and particularly the decade following 1690 was noted for the severity of sea ice, which seasonally blocked the coast of Iceland, reached the Faeroe Islands, and possibly also western Norway (Lamb 1977; Flohn 1981). In 1695, Iceland was completely surrounded by ice which cut off contact with ships; ice reached all the way to Norway and the ocean surface temperature may have been 5°C colder than present

(Lamb 1977). That winter, annals recorded extremely harsh and frosty conditions, that "the sea ice had passed west of Reykjanes", and there was "such a girth of ice in the sea around this country that ships could hardly reach the shore, except in a small area in the south" (Vilmundarson 1972:162-164). The same type of conditions occurred from A.D. 1756 to 1800, when sea ice affected the coast of Iceland for up to 30 weeks of the year and sea temperatures may have been 1-3°C cooler than present (Lamb 1966, 1982a, 1982b).

Along with the sea ice, increased storminess plagued ocean travel during the Little Ice Age as it had in the 13th century. From 1580 to 1700, the 1690s, and the late 18th and 19th centuries (Lamb 1982a), sea ice increasingly separated the Norse colonies in Greenland and Iceland from the rest of Europe (Lamb 1982b).

Warming to recent levels (increases of approximately 2°C) has occurred only in the last 100 to 150 years (Caseldine and Stotter 1993). Various researchers place the end of Little Ice Age cooling from the mid-19th century to ca. 1915 (Bergthórsson 1969; Bryson and Padoch 1981; Flohn 1981; Lamb 1982b).

Climate and Human History

If history is defined as "unique sequences of contingent events that shape entire social and ecological systems" (Ingerson 1994:44), to what degree did climatic changes affect the history of Norse settlers and the areas they inhabited? Traditional views on the role of climate in human history generally range between 'environmental determinism', in which nature and climate cause economic and social change, to the opinion that societies use culture and technology to mediate or nullify effects of the environment. Research has shown environmental determinism to be overly simplistic and deterministic; correlation takes on the shape of causation. For instance, decreased storminess and milder conditions may have aided in settlement of Greenland and Iceland, and the subsequent worsening of climate may have contributed to abandonment, but it does not follow that climatic conditions were the only variable at work in these movements, nor even the most important one (see for example McGhee 1977 for a discussion of the failures of climatic determinism; McGovern 1977, 1991; Schneider and Temkin 1978; Parry 1981). Study of the role climate plays in interaction with societies should be a recognition of ecological principles which seek to place human society in a wider environmental and social context (Bryson and Padoch 1981). Perhaps it might be more appropriate to view "nature and culture as quantitative variations along a single spectrum rather than as an either/or dichotomy" (Ingerson 1994:44).

The relationship is not a simple nor deterministic one; sometimes the question of the intrinsic adaptability of cultures to different *rates* of change is not addressed at all (Parry 1985). Often the physical environment only gives bias to a range of possible reactions, which in turn depend on the individual or culture (Bryson and Padoch 1981; Parry 1985; Hooey 1988; Amorosi 1991). Temporal and spatial distributions, and the intensity, rate and degree of variability (unpredictability) determine the severity of impact on human societies, and the buffering options they can exercise to cope with change and scarcity (i.e. mobility, diversification, physical storage and exchange systems) (Parry 1981; Lamb 1982a, 1982b; Halstead and O'Shea 1989).

> The reason that the harm done, over longer time periods, is often (but not always) so slight is that in the long run societies adjust. Even primitive technologies have some capacity for adaptation. In measuring the human consequences of climate change our attention should be focused on those processes of adaptation. (de Vries 1981:50)

Such processes can be embedded in practices which transmit other cultural information as well, such as seasonal rituals or the telling of traditional folktales, in which

> captured, packaged knowledge can be passed across times when it is not useful or adaptive and saved for times when it will again be adaptive . . . it transgresses multiple generations nurturing unseen progeny at unknown future time depths. (Gunn 1994:88-9)

Settlers who are not fully aware of the range of climatic variations their new lands can produce are at a disadvantage, "more susceptible to surprise climatic dislocations because of their limited repertoire" (Gunn 1994:91). In Iceland, the population largely managed to successfully negotiate climatic variations, evidenced by the existence of farms and settlements in many areas which date from the earliest times. These people responded to and interacted with an environment which was constantly changing through time, adapting to local conditions when possible (Amorosi 1991). However, archaeological evidence showing farm abandonment (in some cases during very early periods), would seem to indicate that some settlers were unable to deal with the magnitude of deleterious climate changes or other unexpected setbacks. This may be due to harsher conditions in Iceland, and exacerbated by an absence of that "repertoire" of options developed through familiarity with the land.

Icelandic Farm Abandonment

It is probable that "a considerable and rapid climatic warming late in the ninth century" helped the process of discovery and colonization of Iceland (Dansgaard et al. 1975). Subsequent cooling marked the beginning of famine and farm abandonment in Iceland (Dansgaard et al. 1975). *Landnámabók* records 430 major settlements and many smaller ones (about 540 total), of which many can still be located. Some farms were inland and abandoned by the 12th century, while others not mentioned in the *Landnámabók* were settled and abandoned even earlier (Sveinbjarnardóttir 1992). Abandonment of settlements occurred mostly in the north, east and southeast, but included those at high altitudes in the south (Lamb 1982a). Icelandic farm abandonment may have been due to a complex of interrelated factors, including famine and epidemics, natural disasters, erosion, and the effects of a worsening climate on subsistence activities (Sveinbjarnardóttir 1992).

Famine and Disease

Historians have often assumed a direct relationship between bad weather and harvest failures, shortages and famine. This is at least partially true - unfavorable weather could cause harvest failure, and subsistence crises occurred whenever many subsistence crops failed repeatedly, and at the same time (Appleby 1981; Pfister 1981a). "This was always the result of the cumulative impact of a number of unfavourable weather conditions (wet autumns, long winters, cold springs, cool wet summers), stretching over several years and involving large areas" (Pfister 1981a:237). Societies which had access to storage facilities, markets and trade with less severely affected areas, or the option of reliance on diversified crops, were probably less seriously affected by shortages (Pfister 1981a; Halstead and O'Shea 1989). This is shown by European populations' ability to largely overcome lethal harvest failures resulting in famine by the early 18th century, during the Little Ice Age (Appleby 1981:63-64). Therefore, an ability to adapt to changing weather was crucial, but "a successful adaptation was more difficult in areas of marginal cultivation - such as Scandinavia, Scotland . . . - where the climate played a larger role in fluctuating crop yields", and where there was a more direct relationship between bad harvests and famine (Appleby 1981:83).

Regardless, the effects of famines are always dire when a population is living at or near the subsistence level: if Icelanders had occupied marginal lands during a favorable climatic period, those populations might have been unsupportable when subsequent cooling reduced the land's productivity.

> The danger of fatal famine - brought by bad weather - was particularly intense in these economies after a long, sustained increase in population had reduced the per capita agricultural output to the subsistence level, even in good years. (Appleby 1981:77)

Famine and epidemics were closely associated. When harvests failed and food prices soared, people often flocked to urban centres for charity and relief, and non-epidemic diseases ran rampant through many localities (Appleby 1981).

It is popularly believed that climate is one of the main factors in disease incidence and transmission. Appleby found that while fluctuations in European "mortality crises" of the 16th and 17th centuries coincided with the Little Ice Age and warming around 1700, it was not possible to absolutely correlate the two. Furthermore, he reinforced that weather did not control the severity or incidence of smallpox, fatal childhood ailments, or the plague (which actually should have been somewhat slowed by climatic cooling). However, many diseases seem to follow seasonal cycles, so climate may still be an important factor in some disease transmission (e.g. leprosy might be transmitted as people with relatively little clothing huddled together for warmth, and skin came into contact) (Appleby 1981:65-72). In Iceland, Sveinbjarnardóttir (1992) speculates that reports of the fatal nature of the 'Black Death' (1402-4) may have been overexaggerated. Many farms were reinhabited relatively soon after abandonment, implying that populations in the area had not been permanently reduced by large numbers.

Natural Disasters

Jökulhlaups (catastrophic floods from beneath glaciers) are common, and can last one or more days, flooding all downstream *sandur* (= gravel outwash plain) areas with sediment, ice bergs and water. The flow rate has been estimated at up to 200 000 m^3/s, and water reached depths of tens of metres. *Jökulhlaups* are due to volcanic eruptions beneath or near the glacier, marginal ice-dammed lakes suddenly draining from beneath the glacier, or when the pressure of water bodies within the ice mass grows, and water erupts from fissures or crevasses (Preusser 1976; Grove 1988). Farms that lie in the way of the flooding water are destroyed.

> Earlier jökulhlaups had carried great loads of sediments from beneath the ice and deposited them to form a gently sloping apron, a sandur, running down into the sea. It was upon these

sandur that the first settlements were established. Most of the early settlements were destroyed by hlaups from Kötlujökull between the ninth and eleventh centuries . . . The Kötluhlaup of November 1660 carried away all the houses and the church of Höfdabrekka, so that hardly a stone was left on the original site and so much material was carried down to the shore that a dry beach appeared where previously fishing boats had operated in water 20 fathoms deep . . . But the principal damage, so far as the survivors were concerned, was the destruction of pasture. (Grove 1988:27-29)

Volcanic eruptions, tephras and gases can also be deadly. The 1783-4 eruption of Laki killed many people, both during the eruption, and during the following months. An estimated 70% of livestock animals died from fluorine poisoned grasslands and vegetation failure due to tephra falls (Pétursson et al. 1984 and Rafnsson 1984 in Sveinbjarnardóttir 1992:10). In Thistilfjorður district, the numbers of farms was almost halved (Thórmódsson in Sveinbjarnardóttir 1992).

Birch Lands, Erosion and Reclamation

The oft-quoted 12th century Íslendingabók refers to forests which stretched from mountain to sea-shore at the time of settlement. Vegetation including birch and willow woodlands and wetland vegetation occupied up to 65% of Iceland's land mass (present values are about 25%); areas barren of trees still hold names which incorporate *skógur* (= forest) today (Arnalds 1987; Sveinbjarnardóttir 1992) (see figure 6). It is estimated that the area of birch woodland has decreased tenfold since the 18th century (Arnalds 1987). Most researchers agree that a combination of factors have contributed to the catastrophic reduction in birch lands; including overuse of wood in the past (i.e. for fuel, construction, and charcoal to whet scythes and produce bog iron), natural disasters, slow growth rates, climatic change, and overgrazing by sheep (Arnalds 1987; Arnalds et al. 1987; Sveinbjarnardóttir 1992). Generally, anthropogenic factors seem to the greatest factor in

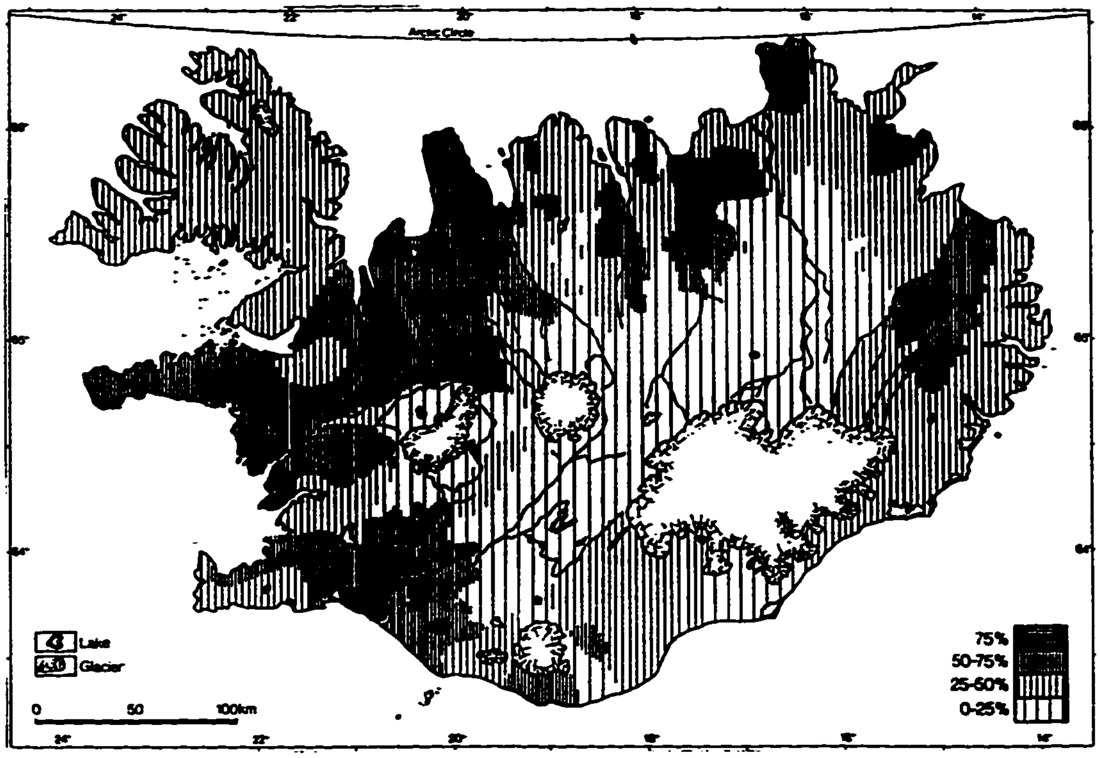


Figure 6. Average vegetative cover in Iceland. Reproduced by permission of the Regents of the University of Colorado from *Arctic and Alpine Research* (Volume 19,1987:510).

woodland loss, but climate plays a part as well (Bell 1982; Gerrard 1991). Pollen studies for some areas show that climate change may have caused a pre-settlement decline in birch (Einarsson 1963; Smith 1995; Zutter 1996). It is probable that massive devegetation and subsequent erosion in Iceland has been caused mainly by settlement and livestock overgrazing in vulnerable areas, coupled with a cold climate. A reduction in vegetation, whether due directly to overgrazing or to cooling climate (including glacial scouring), would have a large impact on soil loss (Zutter 1989).

Although it is clear that changes of climate and land use pressures have both been involved in creating slope instability it is not easy to state, categorically, that one factor has been more influential than another. But, in general, the major influence over the last thousand years appears to be human pressure. (Gerrard 1991:254)

Icelandic vegetation grows very slowly, on soils which are well-drained and silty sediments of volcanic origin, highly susceptible to disturbance and erosion (Arnalds et al. 1987; Thórsteinsson 1972 in Sveinbjarnardóttir 1992) Drying by cold winds from the north accompanying sea ice may contribute to the problem (Fridricksson 1969), and erosion due to winds "is particularly severe on flat lands where soil has a sandy texture and on grassland in windy areas cleared to grow crops or overgrazed by livestock" (Miller 1988:196-7). "In sandy soil landscapes, field erosion by wind is often reported, especially in spring, when tilled fields lie bare and dust particles can be transported over considerable distances" (Aaby 1986:160). Local conditions of stability cause variability in the amount of erosion which occurs (Gerrard 1991), but erosion can be expected on steep and even moderate slopes when they have been cleared of vegetation and the soils are bared (Miller 1988).

Settlement activities cleared the land intended for farmsteads and hayfields; the fire used for clearing often burned out of control and into other areas (Arnalds 1987). Settlement areas were used as bases for extraction of local resources (e.g. birch for lumber and fuel), leading to ecological damage in those areas, which were subsequently settled (Jóhannesson 1974; Smith 1995). This may have been particularly the case once coastal lands had been settled, and people moved further inland - these areas may have been abandoned early when the vegetation failed under increased trampling and grazing by man and domestic animals (Thórarinsson 1961; Miller and Cummins 1987).

This tends to be a complicated problem, as cooling climate and reduced hay crops might force farmers to graze livestock more extensively and intensively. This process reduces stabilization and increases erosion, particularly in the uplands (Zutter 1989, Sveinbjarnardóttir 1992). Re-establishment of plant species in these areas is affected by climate. The North Atlantic region is considered a marginal environment, where the growing season is short with relatively cool temperatures. Many populations of plants are not fully self-sustaining, having been subjected to short-term climatic variations, and unfavorable summer weather which results in meager growth and lower survival rates. For example, in Scotland, heather *(Calluna vulgaris)* mortality in the low alpine zone is 80%, four times that of the forest zone. Winds dessicate the young plants, while the action of frost heave and needle ice kills young seedlings, and exposes the buried seeds which are essential to colonization in the high zones (Miller and Cummins 1987). The short northern growing season and slow rate of growth decrease seed production, and slow soil production, due to slow decomposition and decreased biological activity in the soil (Arnalds et al. 1987:524). These factors inhibit colonization of disturbed areas: the process is so slow that it cannot meet the requirements of bared soils, and destabilization and erosion can be substantial (Miller and Cummins 1987:396-7).

> Instead of a progressive succession we often find evidence of slow advancement, holding position, retardation, retrogression, and reinvasion. In marginal habitats, the progress of succession can be defined as a function of the biological *driving forces* which are intrinsic to the invading and establishing species, and the environmental *resistances* which represent a sum of the adverse factors hindering the success of species establishment. (Svoboda 1987:373)

"In some areas affected by the . . . Little Ice Age . . . the vegetation may have [only] started to recover as recently as a few decades ago" (Svoboda 1987:374). Cooling associated with the Little Ice Age may have functioned to retard the majority of regrowth of the plants upon which the Icelandic Norse were relying for fodder and fuel.

This problem continues into the twentieth century, as erosion rates continue to climb (Runolfsson 1987). Farms in many districts are still abandoned as a result of erosion and moving sand dunes, especially in the south and northeast where soils have high volcanic ash content. *Elymus* grass has been seeded to stabilize sand dunes in these areas, but needs protection from livestock (Sigurjónsson 1958; Runolfsson 1987). A total of 2100 km^2 in 113 areas, or 2% of Iceland, has been enclosed by reclamation fences since 1907, as livestock grazing is now the greatest disturbance factor (Arnalds 1987; Runolfsson 1987) "Some of the highlands have not recovered, even though they are not grazed. This leads to the possibility that vegetation establishment has occurred in the past under more favorable conditions than now exist." (Arnalds et al. 1987:524)

Climate and Resources in Marginal Areas

The Medieval Warm Epoch may have provided the backdrop of mild climate against which large movements of people to the North Atlantic islands occurred. What happened when Little Ice Age cooling descended on settlements? When cooling occurs in an agriculturally marginal environment, impacts on farming are anomalously large for relatively small climatic changes (Dansgaard et al. 1975). Marginal environments and undiversified economies are at risk, since they are first and most severely affected by climatic change and variability (Harding 1982; Carter and Parry 1984). Thus, in Iceland, variations probably played a significant role in people's lives due to the marginality of the environment for cereal and hay production, and the significant role of these crops in farming (Ogilvie 1992). Extensive lands were required to support an economy based on farming with simple technology (Martens 1992).

> Iceland is located at the northernmost limits of technologically developed agriculture and on the edge of the boreal forest zone . . . Therefore, several margins can be delineated that pass through the country. Two of these [mark] the northern limits of viable grassland production and of cereal cultivation, respectively. Relatively small changes in temperature, however, can alter the position of these lines a great deal, i.e. shifting them to the south in cold years and to the north in warm years. (Bergthórsson et al. 1988:412)

Increased access to resources with higher social rank becomes more than simply academic at this point, and makes the discussion of resources extremely complex (the mechanics of status are more fully discussed elsewhere - see for example Jones 1984 and Grove 1988). Those with higher social standing gained access to larger tracts of land, more slaves to work the land (therefore more produce) and a greater number of both domestic and imported resources (in particular, grain) (Amorosi et al. 1992). In some cases, the advantages of high social rank may have effectively offset any hardship due to climatically-induced shortages of grain, hay or livestock.

In the Icelandic case where coastline and altitude severely restricted the amount of territory available, agriculture might have become impossible where relatively small scale variations in temperature, rainfall and growing season length combined unfavourably (Parry 1978; Martens 1992). The marginality of some areas meant that in some cases "people sometimes pushed too far inland at the Landtaking, and also later, and subsequently had to retreat from these areas again" (Preusser 1976:2). The Norse system in Iceland was dependent upon the harvesting of sufficient hay; a concentration of cool/wet summers followed by cold winters or springs could have reduced the ability of crops to mature (Buckland et al. 1996:95).

Fodder and Livestock

The Icelandic agricultural system fed the cattle and sheep which provided the basis of subsistence for the majority of Icelanders until the twentieth century (Thórarinsson 1956; Bergthórsson 1985). "Most scholars agree that year-to-year fluctuations in agricultural output are mainly controlled by the weather" (Pfister 1981a:235). Any variations in temperature could have grave implications for production, by directly influencing the hay crop yield, and by increasing the incidence of sea ice.

Cool temperatures reduce grass yield. A reduction of 1°C in mean temperature reduces growing degree days by 27% and the number of frost-free days by 25 (Bryson 1966; Bergthórsson et al. 1988), which corresponds to a decreased yield of about 10 hayloads of 100 kg each, or one tonne, per hectare (Fridricksson 1969). It is estimated that temperature reductions of 0.8 to 1.8°C would have reduced potential livestock numbers supported by cultivated grassland, and would have resulted in 30% lower production in sheep and 20% less in cattle (Bergthórsson 1985). The effects of variations in precipitation are less well known. Bergthórsson et al. (1988) acknowledged that rain falling on partially frozen ground would negatively affect yield, an excess of rain (which seldom occurs) might damage the hay crop and make drained fields wetter, and a dearth of rain might limit grass growth through water stress in well-drained fields. However, the amount of rainfall seems to affect only a small portion of crop yields, and in one study no relationship was found between precipitation and herbage yields during the growing season (Bergthórsson et al. 1988:461).

Temperature, incidence of sea ice, and livestock numbers are correlated. Poor grass years are correlated with sea ice coming to the shores of Iceland; a shortage of grass is greatest in years when there has been land-fast ice in many areas along the coast (Fridricksson 1969). "It is recognized that the livestock numbers in a particular year depend considerably on the temperature of the preceding years" (Bergthórsson et al. 1988:432), since cattle had to be fed from last year's hay. When hay ran low, animals were slaughtered. The situation was at its worst when cold winters followed cool summers, and animals had to be fed and byred longer on reduced stocks of essential hay (Thórarinsson 1956; Fridriksson 1969; Bergthórsson 1985). Even those sheep and horses which could be turned out during relatively clement periods suffered; spring grazing was affected by snow and late winter killing frosts, and sea ice destroyed seaweed on the shore, which could be used as graze for sheep in hard times (Thórarinsson 1956; Fridriksson 1969). When sea ice moved right onto the shore, vegetation was destroyed and did not grow back for years (Fridriksson 1969). In 1695, the frost and severe conditions meant that "sheep and horses perished in large numbers, and most people had to slaughter half their stock of cattle and sheep, both in order to save hay and for food, since fishing could not be conducted because of the extensive ice cover" (Vilmundarson 1972:164).

Northern farms would probably have suffered more since yields are generally lower than in the milder southern regions even today (see figure 7) (Fridricksson 1969; Ogilvie 1984a), and higher altitude farms are also more at risk than those in the lowlands (Parry and Carter 1985). However, small farmholders would have found a drop in production difficult to survive; in cases where several severe ice years occurred together, these times are correlated with adversity and famine (Thórarinsson 1956; Bergthórsson 1985; Parry and Carter 1988; Sveinbjarnardóttir 1992). Finally, long winters and snowy springs decreased dairy production - cattle which survived the winter often went dry from the stressful conditions (Pfister 1981a).

Cereal Grains

Iceland encompasses the growing limits for cereal grains; like hay, slight variations will affect the production of these crops significantly. Historically, very poor crops are correlated with extreme meteorological conditions, which occasionally were far beyond present-day maxima (Pfister 1981a).

> From the agricultural sciences it is well known that the yield of a crop is vulnerable to large-scale deviations from the long-term means during critical phases of the vegetative period. It is probable, therefore, that the more variable climate of the Little Ice Age was worse for agricultural production than the climate of the late nineteenth and twentieth centuries. (Pfister 1981a:236)

Barley is a light-loving species, naturally adapted to high latitude long solar days, so it can tolerate the slightly lower temperatures at northern locations (Bergthórsson 1985). Despite this

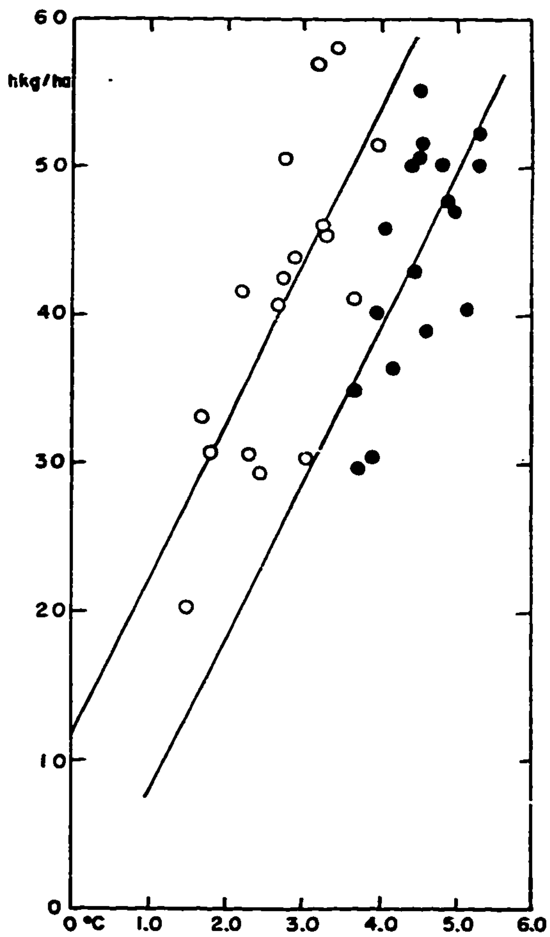


Figure 7. Average hay yields (in 100 kg per hectare) and mean annual temperatures (°C) of two northern (shown by •) and two southern (shown by o) Icelandic districts (1950-1968). Reproduced by permission from *Jökull* (modified from Fridriksson 1969:153)

hardiness, modern estimates show that barley would have ripened in only 60% of the years during the cold period from 1873 to 1922, and only in Reykjavík (Bergthórsson 1985). Despite this, records of grain cultivation exist in Iceland in place names, sales contracts, pollens, and references in sagas (Thórarinsson 1956), so the climate must have been more favourable when cereals were grown. Historical records indicate that cereal grain crops were most extensively raised in the warm south and southwest of Iceland (Thórarinsson 1956; Jóhannesson 1974), and least extensively in the north and Austfirthir, where it ceased entirely as the climate cooled in the 12th century. In the south and southwest, cereal agriculture declined in the 13th to 14th century, while some cereal cultivation persisted to the end of the 16th century along the southern shores of Faxafloi. Modern grain cultivation experiments show that from 1920 to 1940, barley ripened 80-90% of the time in the south, 60-70% of the time in the north, and 30-60% of the time in the west; this reflects the same distributions in which grains were grown historically (Thórarinsson 1956).

Other Resources

One of the ways in which human communities may have dealt with changing or scarce produce is through greater reliance on foodstuffs which were not normally exploited. In Iceland, decreasing numbers of domestic animals (possibly resulting from high neonatal mortality and reduced hay yields), cod stocks and imported goods meant an increasing reliance on hunting sea mammals and birds, and collecting wild plants (Zutter 1989; Amorosi 1992).

Cod (*Gadus morhua*) are abundant in waters between 4-13°C, and prefer cool water between 4-7°C, but their kidneys fail when the temperature falls below 2°C (Lamb 1982a; Grove 1988). This makes them a valuable indicator for water temperatures. As cold Arctic water spread southwest from 1685 to 1704, cod fisheries failed even in the southwest regions of Iceland. At this time, ocean temperatures may have been up to 5°C colder than present. In 1695, when ice surrounded Iceland, cod was scarce all the way to the Shetland Islands, and disappeared almost entirely from Norway's coast (Lamb 1982a, 1982b). When the cod stocks declined, people relied more on other resources which became both increasingly attractive, and increasingly available, from the waters around Iceland. These included shellfish and gastropods, sea mammals and birds (Amorosi 1992).

Evidence for change at Gjögur and Svalbarð

The archaeological and palaeoecological records have provided specific data on the changes which have occured in resource use at Gjögur and Svalbarð, the two sites which yielded peat cores for this study (for site descriptions see Chapter 4). These data are summarized below, and provide evidence which can be compared against that of climate change. Unfortunately, there is no independent record of climate change for the Gjögur site, but the work of Molloy (1993) at Svalbarð allows some limited comparison with her data.

Gjögur

Information for diachronic change at the Gjögur farmsite midden is sparse. However, Amorosi and McGovern (1992) note that in Early Medieval layers, the remains of numerous birds, large cod, seal and domestic livestock were recovered. The Late Norse materials record approximately equivalent numbers of codfish (though smaller in size), and some domestic livestock, but the absence of seals and birds. The most recent Early Modern deposits show the remains of numerous large cod and the appearance of seal, but few domestic livestock or bird remains.

Svalbarð

Amorosi (1992) found evidence of intensive sheep-raising during most of Svalbarð's occupation. However, diachronic patterns show dramatic changes in the relative numbers of major mammal taxa recovered from the OLD unit midden. From A.D. 1636-1800, the numbers of sheep rise markedly compared with those from the same unit from A.D. 1050-1400 (see figure 8). This increase in numbers of sheep relative to cattle is believed to result from "increased emphasis on wool production, and it may also reflect declining prime

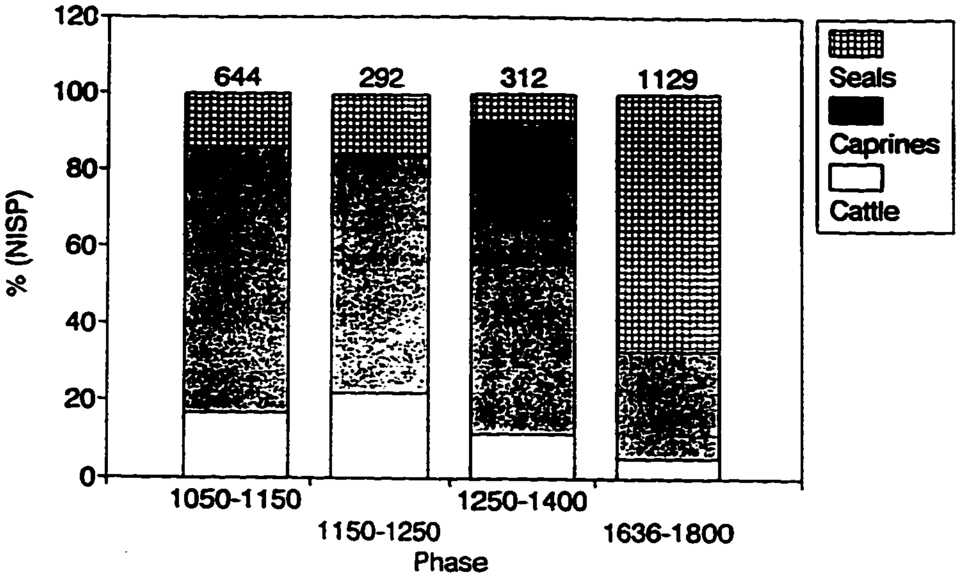


Figure 8. Histogram of the major mammal taxa recovered from Svalbarð (OLD unit midden). Reproduced with permission from Amorosi 1992:125.

pasture areas and a move toward less fodder dependent animals" during cooling (Amorosi 1992:123). The archaeofaunal record also tracks the changing exploitation of fish, harp seals (particularly pups from pupping grounds) and shellfish (Amorosi 1992) (see figure 9). This has been interpreted as a population forced to rely on secondary resources and famine foods such as fish and seals during times of stress starting in the seventeenth century, possibly brought on by climatic cooling (Amorosi 1989, 1992).

> Increased lamb mortality, changing seal bone frequencies, and shellfish concentrations indicate the impact of unfavourable farming conditions, but also the human response to these impacts. Secondary 'buffering' resources (Halstead and O'Shea 1989) were increasingly employed, marine hunting and fishing was expanded, and every possible use was made of the newly available resources of the drift ice . . . The farmers at Svalbarð were thus not passive victims of the Little Ice Age, but actively re-ordered their subsistence system to survive hard times. (Amorosi 1992:130)

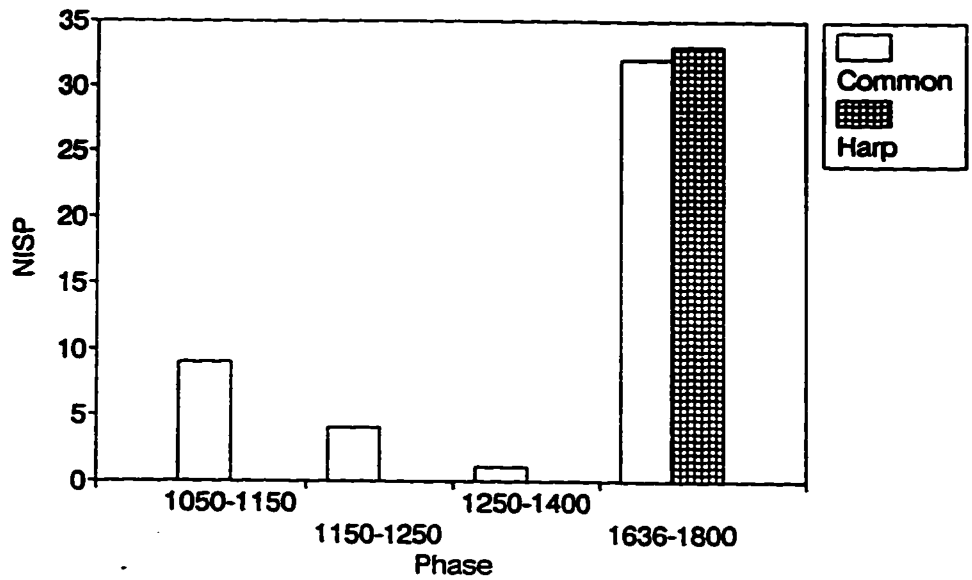


Figure 9. Changing pattern of seal exploitation at Svalbarð (OLD unit). Harp seals associated with drift ice. Reproduced with permission from Amorosi 1992:127.

Zutter (1989, 1992) recovered and studied palaeobotanical macrofossil remains from the midden on the Svalbarð farmsite. The majority of the remains were recovered from the strata spanning A.D. 1050-1150, correlating with the Medieval Warm Period and probable land-clearing activities following settlement. A drastic decrease in macrofossil remains from A.D. 1400-1800 may reflect possible changes in agrarian practices (i.e. deposition of refuse in the fields instead of the midden, possibly to enhance plant productivity during Little Ice Age cooling) (Zutter 1992). While many of the recovered plant taxa are similar to those found at other Norse middens, an absence of grain pollens may reflect unfavourable or unpredictable growing conditions, a lack of preservation, or the focus on animal husbandry at this northern site (Zutter 1992).

Molloy (1993) compared $\delta^{13}C$ and $\delta^{18}O$ data from marine mollusc (*Mytilus edulis*) shells at Svalbarð and Stóraborg, to trace changes in freshwater influx from summer melt into near shore environments. The technique was intended to fill the same gap in climatic records for Iceland that motivates this study. Molluscs are of stationary habit, record climatic information *in situ* in the calcium carbonate secreted during summer months; and can provide dates both in archaeological contexts and directly. A modern baseline is extrapolated back to archaeological examples. Though there are many complicating factors, it may be generalized that enriched (higher) $\delta^{18}O$ values should correlate with a drop in fresh meltwater influx during shorter, cooler summers (associated with cooler climate). The data revealed trends toward enriched $\delta^{18}O$ and $\delta^{13}C$ values during the Little Ice Age and a great deal of interannual variability from A.D. 1400-1717 which "may have been of greater consequence for the inhabitants of the Svalbarð and Stórabog farms than were the long term effects of the Little Ice Age" (Molloy 1993:124). It may be increases in numbers of sheep and reliance on famine foods occurred during this period of variability.

Climate change and culture change in Iceland

The extremely complex systemic relationships discussed above are summarized in figure 10, showing the interactions between human cultures and climate that may have occurred in Iceland over the past millennium. While these were simplified to create the diagram, the relationships remain distinctly complex, and emphasize three points about climate studies:

- While present-day ecological studies are complex, those which attempt to extrapolate into the past are complicated by the fact that most data from the past are proxy, and imperfect (see above discussions of the flaws in various proxy data sources).
- While "hard" data are available on the direct effects of temperature change and other climatic parameters on resources such as hay (see for example exhaustive work by Bergthórsson et al. (1988) detailing this relationship), cultural factors such as access to "status imports" (which can offset food shortages for

some, see above) are nearly impossible to quantify. Hypotheses formed to explain past acts and responses reduce uncertainty, but it is nearly impossible to state categorically causes-and-effects beyond the *likelihood* of it being so.

- One chain of events is not necessarily more effective than any other. For example, while temperature affects land resources directly, we are unable to determine whether this affects those resources *more* than the sequence of: increases in population causing colonization of new areas -> disturbance in those areas -> erosion -> change in land resources. In fact, most of the time we are woefully unable to quantify the comparative effects of variables.

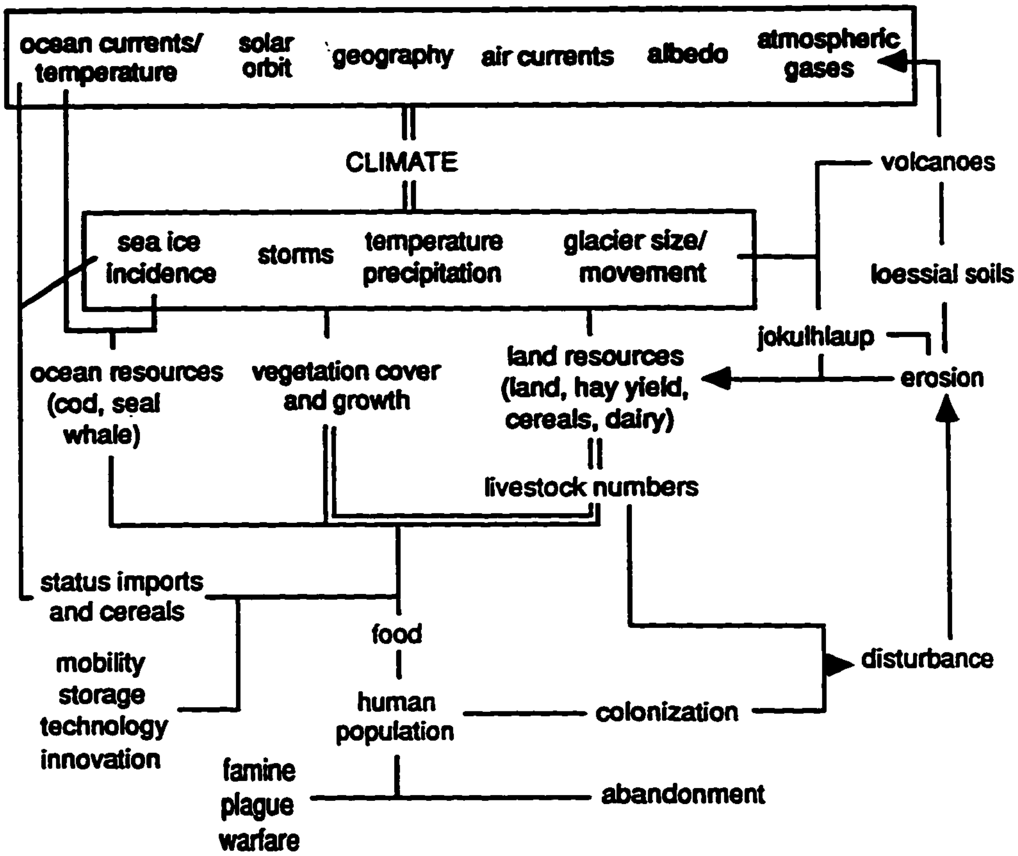


Figure 10. Climate-human interactions in Iceland. Double lines indicate feedback effects. All lines move downward, with the exception of those noted by arrows.

Chapter Summary

Climate changes are due to a number of natural and anthropogenic factors; tracking these through historic records and proxy indicators can be difficult due to regionality, complexity of the changes and dating problems. Sources of information for climate reconstruction can be attained from instrumental records, other written or pictorial records, ice core data, snow and glacier fluctuations, distribution of plants and animals, phenology, dendroclimatology, sedimentology, and stable isotopy.

Although changes are very complex, in Iceland the Medieval Warm Period occurred ca. A.D. 900-1200, followed by an unstable cooling period and the Little Ice Age from ca. A.D. 1600-1900.

Views on the effects of climate on human societies range from determinism to the belief that cultures can nullify the effects of the environment; it is best to view humans as a part of the landscape. Icelandic farm abandonment has been explained primarily in terms of famine and disease, natural disasters, erosion and climate change, but seems to have been a combination of these. Climate plays a large role in Iceland due to agricultural marginality, where hay and livestock, cereals and other resources are affected by relatively small changes. These relationships are summarized and further discussed.

CHAPTER 4

SITE DESCRIPTION AND METHODOLOGY

Site Selection

Initially, five areas of Iceland were chosen for this study: Gjögur farm, Reykjarfjörður (Northwest Iceland); Svalbarð/ Sæverland farms, Thistilfjörður (Northeast Iceland); Fossárdalur, Berufjörður (Eastern Iceland); the area adjacent to Heimaland/ Stóraborg, west of Eyjafjallajökull (Southern Iceland); and Bessastaðir, near Reykjavík (Southwestern Iceland) (see figure 11, #1-5). This encompasses the main areas of settlement as well as taking into account regional variations in climate and topography.

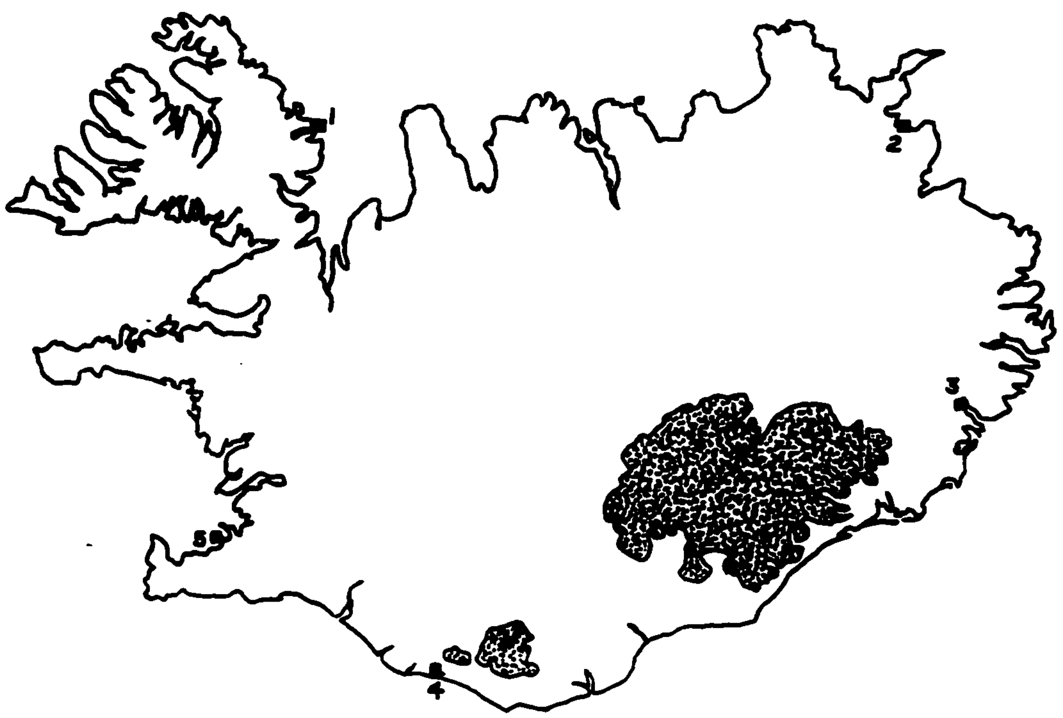


Figure 11. Location of intended sites for coring. 1= Gjögur, 2=Svalbarð/Sæverland, 3=Fossárdalur/Berufjorður, 4=Heimaland/ Stóraborg, 5=Bessastaðir.

We assumed all areas would contain peat deposits. Peat bogs should satisfy conditions for study of past climate in which systems must have isotopes determined by climatic factors or in which other factors can be filtered out, where isotopes have not been subsequently altered (the record is permanent), the record is normally continuous, the strata are datable, and the relatively high accumulation rates provide a time resolution that is appropriate to chosen study parameters (Gray 1981; Jacobson and Bradshaw 1981; Dupont and Mook 1987). As well, peats offer the added advantage that they are often found near lakes and estuaries, which provide alternate coring sites for comparison and correlation (PALE 1993).

Coring sites were chosen based on tested depths of peat deposits (greater than 1 m) and proximity to known archaeological sites. Archaeological work had been done at or near all of the chosen sites: Gjögur farm (4901-7) and nearby Akurvík (4901-1) (Amorosi and McGovern 1992); Svalbarð farm (6706-60) (Zutter 1989, 1992, 1996; Amorosi 1992); abandoned farms in Berufjördur/Fossárdalur and at the island of Papey (Sveinbjarnardóttir 1991; Buckland et al. 1995); Stóraborg (Sveinbjarnardóttir et al. 1981; Sveinbjarnardóttir 1991); and Bessastaðir (Amorosi et al. 1992). The cores and their climatic information must be related to human activities in the area, while being far enough removed from settlements to reduce the effects of human use such as turf-cutting.

Gjögur

Gjögur is situated in *Arneshreuppur* (= Arnes county), on a peninsula between Nordurfjörður and Trékyllisvík to the north, and Reykjarfjörður to the south (see figure 11, #1). "This region offers extensive meadowlands and small landing places (Djúpavík, Gjögur, Nordurfjörður) and was joined to the national road system a short time ago" (Preusser 1976:173). The tip of the peninsula is poorly drained, containing a number of mires and small lakes, including *Gjögurvatn* (= Gjögur's lake). To the north-northwest of the coring site lies a coastal hill and cliff (Reykjarneshyrna, 315 m a.s.l.), with the mountain Orkin (634 m a.s.l.) to the west. In the early 18th century, three major farms were located on the peninsula, including Gjögur. Gjögur was a fishing station from an early date, and in the late 19th century, it became the central station for shark fishing in the Húnaflói; it still provides a sheltered boat landing area. The farm now consists of two houses, several barns and sheds; structures east of the farm near Gjögursvatn probably once belonged to Gjögur. Excavations at the farm mound in 1988 and 1990 showed it to date from late Viking or early Medieval times (possibly as early as ca. A.D. 1000) to ca. 1860 (personal communication, T. Amorosi; Amorosi and McGovern 1992).

Precipitation in this area averages 800 mm (mostly snowfall), the January mean temperature is 0 to -1°C (lower when the coast is affected by sea ice), and the July mean temperature is 6-8°C. At the station near Gjögur (Kjörvogur), cool northerly winds prevail, with calms 21% of the year (Einarsson 1970).

The Gjögur coring site (indicated by • on figure 12, 1:100 000 map, and plate 1) is located on peatland at 65°59'N and 21°21'W, at 42 m a.s.l., on the northwest shore of Gjögurvatn (Gjögur's Lake), and 1.5 km from the farm mound excavated in 1990 (see Amorosi and McGovern 1992). The mire at Gjögur is classified as Flói (level mire):

> Water floods the surface or reaches its uppermost portions for at least a part of the year, and a sheet of ice covers it in winter time. The surface is generally level and the land so flat or so slightly sloping that the ground water is almost stagnant. (Steindórsson 1975:20)

Svalbarð/Sæverland

The Svalbarð farm is situated on the southwest coast of the *Svalbarðshreuppur* (= Svalbarð county) in the Thistilfjörður region (see figure 11, #2). Despite long winters, cool summers and the presence of sea ice, settlements are located in each of the three northeastern bays; "mainly because of the favourable positions with respect to the fishing grounds" (Preusser 1976:210). However, the

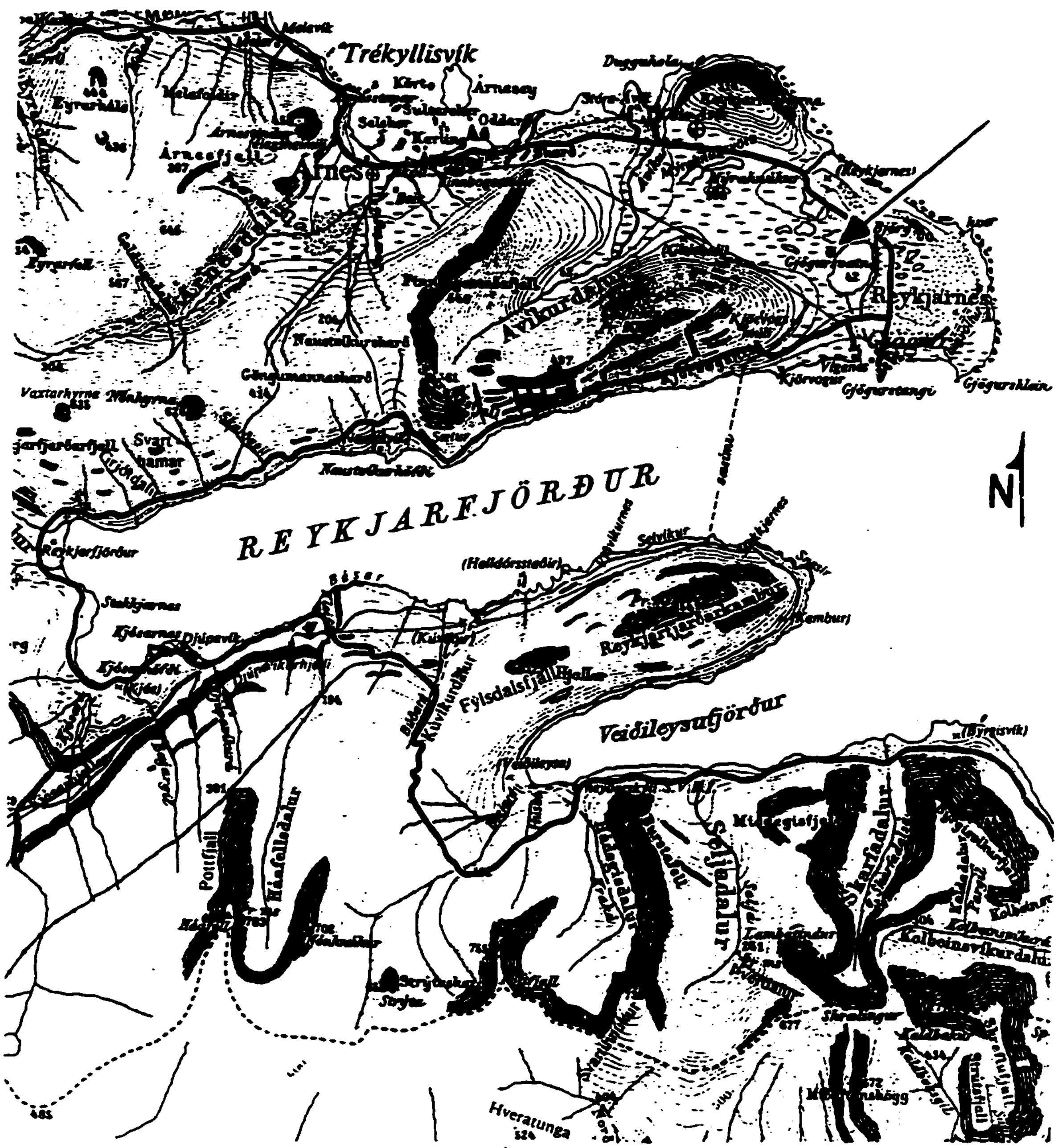


Figure 12. 1:100 000 map location of Gjögurvatn coring site (4901-7).

areas are sparsely inhabited and about 50 inland farms are abandoned (Preusser 1976). The Svalbarð church farm was probably well-established by the early 11th century, with claims to many of the surrounding areas as well as beach rights, and control of one of the relatively few safe boat landings in the area (Amorosi 1992).

Precipitation in this area averages a very low 400-600 mm (again, mostly snowfall), the January mean temperature is -1 to -2°C (lower when the coast is affected by sea ice), and the July mean temperature is 8°C. The nearby station at Raufarhöfn (to the northwest) records that winds from the northeast and northwest dominate, with calms only 9% of the year (Einarsson 1970).

The Svalbarð coring site (indicated by • on figure 13, 1:100 000 map, and plate 2) was located on neighboring farmland (Sævarland), across the *Svalbarðsà* (= Svalbarð's River) and about 1 km north from the farm midden excavated 1987-88 (see Amorosi 1992) and drainage ditch (see Zutter 1996). The mire is located 66°13'24" N and 15°42'24" W, at 12 m a.s.l., bounded by the Svalbarðsà on the east, and terraces to the west which rise to approximately 50 m a.s.l. The terrain rises to Hemundarfell in the west (315 m a.s.l.), and Flautafell (522 m a.s.l.) to the southwest.

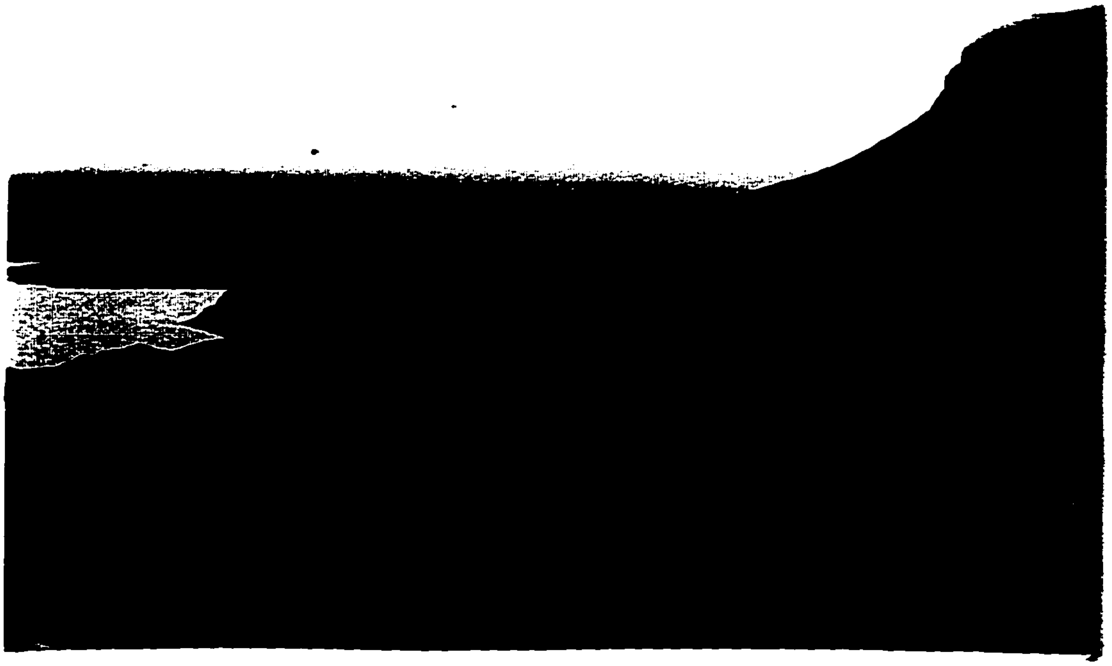
Svalbarð's mire is classified as Flæðimyri (alluvial mire): "Approximately the same degree of moisture as the flói but the water is in constant motion. Only forms along rivers and lakes. The surface is level" (Steindórsson 1975:20) [see description of Gjögur flói-type mire above].

Berufjörður/Fossárdalur

Recent studies have been carried out in the Berufjörður district of eastern Iceland, particularly at the island of Papey and the abandoned farms in Fossárdalur, upvalley from Eyjólfsstaðir (Sveinbjarnardóttir 1991; Buckland et al. 1995) (see figure 11 above, #3).

Papey (64°36' N, 14°11' W) lies about 5-6 km from Djúpivögur fishing port; a 2 km^2 island of basalt. Despite its reputation as the

Figure 13. 1:100 000 map location of Svalbarð/Sæverland coring site (6706-60).



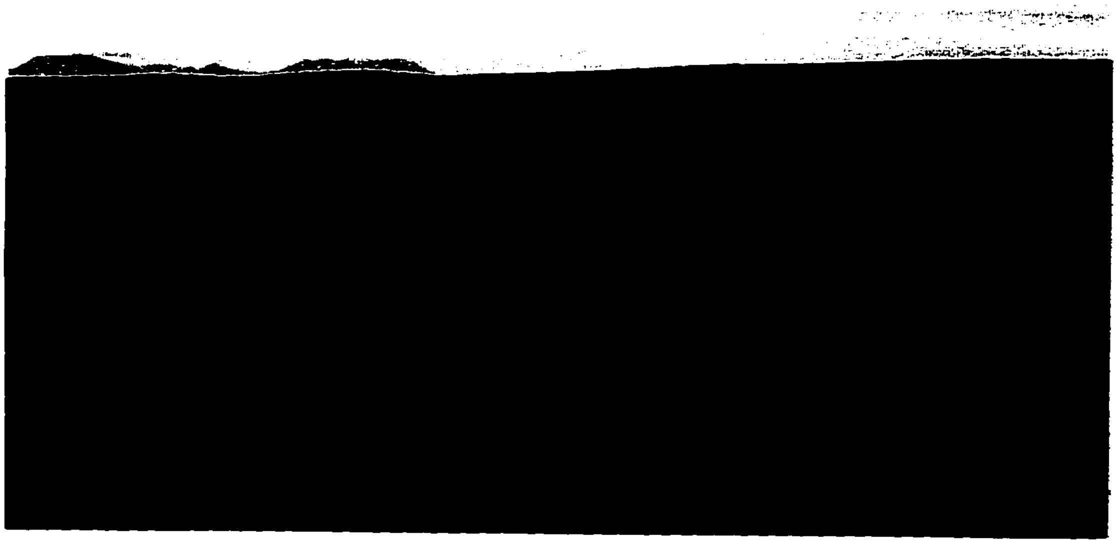


Plate 1 (above). Gjögur coring site, looking southwest. Gjögurvatn to the left, Orkin to the right.
Plate 2 (below). Svalbarð coring site, looking south. Svalbarðsá visible.

island occupied by pre-Norse Irish hermits, no convincing evidence has been found for this. Norse occupation may have been as early as the late 9th or 10th century, but the island is no longer permanently occupied (Preusser 1976; Buckland et al. 1995).

> Until abandonment some forty years ago, the farmer at Papeyjarbær maintained some seventy ewes with their lambs, three cows and a horse on the island and it has since continued to be used as summer grazing for a declining number of sheep. (Buckland et al. 1995:3)

In the Fossárdalur, five definite farm sites have been identified (another possible two have also been found). The farm abandonment process in this region began as early as the mid-14th century and continued into the 20th century, due to changes in the course of the river, increased erosion, and isolation (causing abandonment as people left for the towns and cities) (Sveinbjarnardóttir 1991).

Physical examination of the area yielded no areas to core, particularly near the mouth of the Fossárdalur valley and along the southern edge of Berufjörður.

Heimaland/Stóraborg

The old farm and midden at Stóraborg lies on the southern coast, west of Eyjafjallajökull, between the Kaldaklifsá and Bakkakotsá Rivers, about 6 km west of Skógar (see figure 11 above, #4). The farm was most recently moved inland 0.5 km in 1834: it was "not abandoned as such but rather relocated to sites further inland, away from the encroachment of the sea" (Sveinbjarnardóttir 1991:167). Stóraborg previously occupied the site since ca. 1300, and possibly earlier. Most of the 18th and 19th century remains have been destroyed through erosion by the sea and rivers, but excavation has continued on the remnants since 1978 (Sveinbjarnardóttir et al. 1981; Sveinbjarnardóttir 1991).

On examination this area yielded no obvious coring sites.

Bessastaðir

Occupied at least since the 13th century (and possibly since *Landnám*), the site of Bessastaðir continues to be a high status site in Iceland, functioning as the official residence of the Icelandic president. "The site lies on a narrow isthmus on the Áltanes peninsula some 16 km southwest of Reykjavík" (Amorosi et al. 1992:169), and has been has been under excavation from 1986 (see figure 11 above, #5).

A mire dominated by *Eriophorum* (floss-grass) lies to the north of the official residence; however, investigation of the area showed that sediments were largely silty, and that deposits were shallow (ca. 50 cm).

Core Collection

Cores were collected in 4-inch (10 cm) diameter plastic barrels, the edges of which were filed sharp, pounded into the peat with a sledgehammer and machined metal core cap, then dug free (see plates 3 and 4). Measurements were taken from the surface within and outside the core to note any compaction, which was generally less where the peat was less waterlogged. Cores were then dug free with peat shovels and a post hole digger, and lifted out with the aid of cable vise grips. Ends were capped and sealed for shipping. Five cores in all were taken; two from the Gjögurvatn peatlands, and three from the Svalbarð/Sævarland peatlands.

Core Descriptions and Sampling

Cores were X-rayed, in order to identify the presence of sedimentary structures, tephras, and macrofossils (Dugmore and Newton 1992; PALE 1993). As well as showing the location of possible tephras, the X-rays showed the length of each core, and whether damage had occurred during shipping. This procedure helped to decide which cores would be sampled - only one core from

Plate 3 (above). Digging the cores out of the peat (Svalbarð)
Plate 4 (below). Core barrels in peat, ready to be dug out (Gjögur)

each site would be opened, and the others stored for future study. Core C from Svalbarð (SV-C) and Core 1 from Gjögur (GJ-1) were chosen for initial sampling. Core A from Svalbarð (SV-A) was later chosen for additional sampling.

Once the core had been split longitudinally and cleaned (following Aaby 1986 and Wasylikowa 1986), all three cores were immediately photographed in colour and black-and-white. They were further described by Munsell colour chart and humification values.

Humification occurs mainly in the upper part of the peat, and "the degree of humification essentially depends on how long it takes before the peat becomes anaerobic as determined by the water level" (Aaby 1986:155). This can have implications for peat accumulation rates, but Aaby cautions that "because the compressibility varies in different peat types a clear correlation between measured growth rates and degree of humification cannot always be expected" (1986:160). Humification values presented in Aaby (1986) were modified, and were presented only on a scale ranging from weakly to moderately, strongly and highly humified.

Dr. Andrew Dugmore (University of Edinburgh) sampled the GJ-1 and SV-C cores to observe and identify volcanic tephras deposited in the cores. In this study, tephras were recognized in the cores using a combination of visual and microscopic examination, and by low loss-on-ignition (LOI) values. Loss on ignition samples were taken from the cores at five centimeter intervals, starting from the surface of the core for Svalbarð C (SV-C) and Gjögur Core 1 (GJ-1). Sampling for Svalbarð Core A (SV-A) began at 5 cm below the disturbed surface of the core, and was sampled every 5 cm, with the exception of the area from 35 cm to 45 cm, which was sampled every centimeter.

Loss on ignition procedures followed Aaby (1986:150). Samples were dried for 24 hours at 105°C, weighed and transferred to crucibles, then ignited for 4 hours at 550°C. Samples were then re-weighed and plotted. Distinctly low organic values mark tephras and influxes of sediment due to erosion and ecological disturbance. These in turn can be modified by the rate and amount of initial deposition, the rate of peat decay, and degree of peat compaction (Aaby 1986). Tables 1, 3 and 5 present the numerical results of loss on ignition, figures 16, 18 and 20 present the same data in graph format. Distinctly low organic values mark observed tephras and influxes of inorganic sediments.

Samples were taken every five centimeters from cores GJ-1 and SV-C, where about one-half of a one centimeter thick slice of peat (approximately one-quarter of the split core slice) was removed. In most cases this provided sufficient raw plant material for the initial macrofossil separation, although for some, the resulting samples were too small and further materials had to be removed from the core. Initially, enough was left of the core that if circumstances warranted, additional sampling could be done.

Samples for dating were taken at this time, and also as it became necessary. Samples were dated by both conventional and accelerator mass spectrometer (AMS) radiocarbon methods, and were mainly macrofossils (i.e. pieces of wood), but in some cases, bulk peat was also used. The use of radiocarbon dates in conjunction with examination of the cores made it possible to establish absolute dates for the stratigraphy. Radiocarbon dates for Gjögur Core 1 (GJ-1) were submitted to the Alberta Environmental Centre facility at Vegreville. A total of three samples were taken from GJ-1. Two samples for dating were taken from immediately beneath the tephras (2036-C and 2037-C), and one (2038-C) from the base of the core: all were bulk peat samples. Samples for Svalbarð Core C were submitted to the IsoTrace Lab facility at the University of Toronto. A total of five samples were taken from SV-C; one from the base of the core (TO-4431), one from the base of each tephra (TO-4670 and 4671), and two at what was initially believed to the Landnàm horizon (TO-5786 and 5242). All dates are uncalibrated (see tables 2 and 4).

Samples were wet-screened through 20 and 40 mesh and stored in distilled water in petri dishes. Initially, only the 20 mesh samples were chosen for this examination (40 mesh samples were set aside, but were later re-incorporated into bulk samples for the chemical treatments).

Microscopic Separation

Live specimens of four frequently occurring vascular peat plants (*Carex, Empetrum, Eriophorum* and *Salix*) were collected on-site to aid in identification of these plant remains in the cores during microscopic separation (see appendix A), and to act as modern baselines for the H/D isotopic values of the cellulose extracted from the plant remains in the peat cores.

In any isotopic study of plant cellulose, microscopic separation and identification of plant species must be done, in order to minimize species-specific effects (Ziegler et al. 1976; DeNiro and Epstein 1981; Brenninkmeijer et al. 1982; Sternberg and DeNiro 1983; Dupont and Mook 1987). This effect can be summarized: "Under equal climatic conditions the deuterium content of plants varies with species" (Dupont and Mook 1987:323).

Chatwin (1981) elected to nitrate both separately and in bulk the major peat-forming plants in his study. His results indicated that all the major peat-forming species he analyzed (*Sphagnum*, *Drepanocladus*, *Carex*, and Duckweed vs. "mixture") had "very similar oxygen isotope values, reflecting the constant isotopic composition of the water in which they grew" (Chatwin 1981:69). However, such bulk samples are problematic. "Although the vascular plants of bogs - *Calluna* (heather), *Eriophorum* (cotton-grasses) and a few others can exert some control over their evapotranspiration by closing their stomata (leaf-pores), the *Sphagna* are more or less at the mercy of the climate" (Barber 1982:104). Studies have shown that *Sphagnum* mosses consistently show different values from vascular plant species under the same conditions (see Brenninkmeijer et al. 1982).

Stable isotopy

Selection of isotopes

The initial selection of hydrogen (H/D) and oxygen ($^{16}O/^{18}O$) isotopes for this study was based on the specific goals of this research, which was to determine whether a palaeotemperature profile for northern Iceland could be produced from peatland materials. These two isotopes have been extensively studied and their links with climatic phenomena are relatively well understood.

The naturally occurring stable isotopes of hydrogen and oxygen are: ^{1}H (99.985%), ^{2}H or Deuterium D (0.015%); ^{16}O (99.756%), ^{17}O (0.039%; not commonly measured) and ^{18}O (0.205%) (Faure 1977:324). Water has nine possible isotopic configurations, of which the three most commonly measured are: $H_2{}^{16}O$ (99.768%), $HD^{16}O$ (0.032%) and $H_2{}^{18}O$ (0.2%) (Dansgaard 1964:437). Isotope data are reported as deviation from standards in δ (delta) notation, where:

$$\delta = \left[\frac{R_{sample} - R_{standard}}{R_{standard}} \right] 1000$$

and 'R' is the ratio between concentrations of heavy to light isotopes ($^{18}O/^{16}O$ or D/H) in the sample and is reported in per mil ($^{o}/_{oo}$) (Craig 1961; Dansgaard 1964, 1973). The National Bureau of Standards' manufactured water standard for hydrogen and oxygen isotopes is SMOW (Standard Mean Ocean Water) :

$$R_{SMOW} = 1.008\ R_{NBS\text{-}1} \text{ for } ^{18}O/^{16}O$$
$$R_{SMOW} = 1.050\ R_{NBS\text{-}1} \text{ for D/H}$$

(Craig 1961). In meteoric water, hydrogen and oxygen occur together in a linear relationship demonstrated by Craig (1961):

$$\delta D = 8\ \delta^{18}O + 10$$

Measurement of two sets of isotopes (e.g. H and O) increases the reliability of the correlation with climatic phenomena: "if ratios are measured for two, three, or more independent isotopes in the same organic material, it is possible that the relation to temperature can be firmly established and quantified" (Libby 1972:4310). This is necessary since it is not yet possible to positively establish an absolute temperature scale for dD values alone (Long et al. 1990). Epstein et al. (1976) report a δD of $25^{o}/_{oo}$ for $11^{o}C$ ($2.27^{o}/_{oo}$ per $1^{o}C$)

change in temperature, while White et al. (1994b) propose a 0.5‰ difference per 1°C.

On further analysis of the relationship of these isotopes to the target data (temperature), it was decided that only δD ratios would be measured. Hydrogen ratios can be related to temperature during which source water falls. "The δD of cellulose by itself most closely reflects the isotopic composition of meteoric waters and thus climatic temperature" (Epstein et al. 1977:1215). The utility of oxygen isotopes in palaeoclimatic studies based on plant materials has been contested. Dansgaard found that $\delta^{18}O$ values of precipitation plotted against temperature resulted in a linear relationship at coastal stations (1964). However, researchers note that this relationship is complex and that annual mean $\delta^{18}O$ is not determined by temperature alone (Siegenthaler and Oeschger 1980; Gray 1981). Epstein et al. (1976, 1977) found that oxygen isotopic ratios in land plants are poorly correlated with associated water values, and are dominated by kinetic effects of evapotranspiration. Some researchers have determined that for oxygen isotopes, "organic matter is rather a 'paleo-evaporation' marker than a 'paleo-thermometric' one" (Ferhi and Letolle 1977:369). Others add that oxygen isotope ratios are determined by isotopic exchange during cellulose synthesis or that they may not even accurately reflect atmospheric humidity (Sternberg et al. 1986; DeNiro and Cooper 1989).

Carbon ($^{13}C/^{12}C$) plant ratios are poorly correlated with associated waters and are not necessarily related to atmospheric CO_2 or concurrent local environmental conditions, so these are not generally considered to be useful for this type of work (Craig 1954; Yapp and Epstein 1977; Northfelt et al. 1981).

Fractionation of Isotopes

Fractionation is the process of partial separation of isotopes which occurs during physical or chemical processes (Gray 1981; Bowen 1991). The main cause of fractionation is differences in the physical and chemical properties of the isotopic components of water molecules, and is proportional to differences in masses between them. It occurs mainly in the elements where this proportion is highest, including hydrogen and oxygen (Faure 1977; Gray 1981). The extent of the fractionation process depends on temperature and rate of reaction (Dansgaard 1964; Faure 1977).

Chemically, different isotopes in equivalent positions have different energies. "In a chemical reaction, the various isotopes of the elements present in the system tend to redistribute themselves to different extents in different compounds so as to minimize the free energy of the system" (Gray 1981:55). Any molecule with lighter isotopes has a higher vibrational frequency, higher volatility, and lighter bonds which are more easily broken, making the molecule more reactive (Dansgaard 1964; Faure 1977; Herz 1990). This reactivity is expressed as rate of reaction 'c' (as per Craig 1956):

$$c\,(H_2{}^{16}O) > c\,(HD^{16}O) > c\,(H_2{}^{18}O)$$

and leads to separation (Rankama 1954; Dansgaard 1964; Faure 1977; Herz 1990).

Physical processes leading to fractionation are evaporation and condensation. For example, the vapour pressure of $H_2{}^{16}O$ is about 1% greater than that of $H_2{}^{18}O$, which leads to the selective depletion of ^{18}O in the vapour phase and enrichment of ^{18}O in the source water as evaporation proceeds. During cooling and subsequent condensation, the heavier isotope preferentially condenses and the vapour is increasingly depleted in ^{18}O. Water condensed immediately after evaporation will have essentially the same isotopic composition as the source water, but as condensation proceeds, the precipitation will show falling $\delta^{18}O$ values (Gray 1981).

Climate Implications

Dansgaard identified an "amount effect" associated with stable isotopes. The relationship is an inverse one, resulting in "low δ's in rainy months and high δ's in months with sparse rain" (1964:445). This effect dominates in the tropical latitudes and decreases toward the polar regions, where temperature effects dominate and may be studied. As well, with increases in latitude, altitude and distance inland, lower δ values are seen (Dansgaard et al. 1973).

For studies such as this one, conducted at one location and moving back through time, the amount effects and temperature effects should dominate. Precipitation in summer or during warmer climatic periods should have higher δ values than that from winters or cold climatic periods (Dansgaard et al. 1973). Therefore, plant macroremains contained in peat deposits act as a repository of isotopes which reflect temperatures during the time of plant growth. However, a complicating factor affecting isotopic values at time of plant growth is aspect, or location: "topography can play an important role in determining the average δD values of the soil moisture" (Feng and Epstein 1994:1079). Hillsides are more likely to lose summer precipitation (higher δD) through runoff to flat areas. Plants from flat areas are thus deuterium enriched compared to those on the hillside (Feng and Epstein 1994). This has obvious implications for the δD values of source water feeding peat bogs, and any study using peatlands should be aware of the potential for error. At ground level, differences in height between ground-level plants and those on raised hummocks should be minimal, but have not been studied.

Evapo-transpiration and Photosynthetic Pathway

At the time of plant growth, evapo-transpiration affects palaeobotanical isotope ratios (Epstein and Yapp 1977; Gray 1981). Significant increases in δD values can occur, and are fundamentally dependent on the environmental temperatures experienced by the plant. Warm, windy and dry conditions correlate with increased δD values as lighter isotopes are lost through evapo-transpiration of water to the atmosphere through leaves (Wershaw et al. 1966; Schiegl and Vogel 1970; Dongman and Nurnberg 1974; Epstein and

Yapp 1977; Epstein et al. 1977; DeNiro and Epstein 1979; Sternberg and DeNiro 1983; Allison et al. 1985; Leaney et al. 1985; Dupont and Mook 1987; Long et al. 1990). Evapo-transpiration effects are strongest from 1200 to 1400 hours and weakest around 600 hours, in the early morning (Zundel et al. 1978:207). These effects are most pronounced in tropical and semi-arid regions, but it is not certain whether they occur in all areas. In Iceland, where diurnal variations are minimal, this effect should be correspondingly minimized. As well, recent studies by White et al. (1994b) seem to indicate that carbon-bound cellulose hydrogen isotope ratios in trees are primarily dependent only on source water values; "changes in air vapor δD values and changes in relative humidity are mutually canceling in [the study] area. Thus, changes in these variables are unimportant to the cellulose nitrate δD record in these trees" (White et al. 1994b:861). In any case, plant samples should be collected during mornings and/or under cloud cover whenever possible.

Another factor complicating the relationship between plant materials and resulting isotopic ratios is plant photosynthetic pathway. Incorporated meteoric water can be altered by biological processes and biochemical reactions which convert water to organic materials (Yapp and Epstein 1982a). The fixation of sugars and the subsequent metabolic cycle (known as the Calvin cycle) determines the photosynthetic pathway for any species of plant. C3 plants (woody perennials and grassy species) fix sugars into three-carbon sugar compounds, while in C4 plants (herbaceous annual and perennial species) sugars form four-carbon compounds (Sternberg and DeNiro 1983:949). Photosynthetic pathway affects δD values through the discrimination against deuterium by C3 plants, a process almost absent in C4 plants (Ziegler et al. 1976). The quantifiable effect of such discrimination is still under study. Ziegler et al. (1976) report differences in values from 40 to 50$^{o}/_{oo}$ but Sternberg and DeNiro (1983) reported them to be less pronounced. It is important to note that these effects can be significant and that biological factors could be as important as climatic ones for understanding isotope ratios (DeNiro and Epstein 1981; Sternberg and DeNiro 1983; Dupont and Mook 1987). However, the plants included in this study fall within the the C3 category, as do most plants in North America and Europe (Herz 1990), so this effect is absent.

Cellulose

Anselme Payen first proposed that all cell walls were constructed of the same substance, an extremely decay-resistant material which he called cellulose (Nevell and Zeronian 1985). 'Cellulose' usually refers to α-cellulose, chemically known as poly-1,4-β-D-anhydroglucopyranose, a material never found in its pure form in nature (the most pure (95%) source is cotton fibres) (Nevel and Zeronian 1985).

Cellulose is the end product of complex photosynthetic processes which convert environmental waters into the multiple alcohol $(H\text{-}C\text{-}O\text{-}H)_n$, following:

$$CO_2 + H_2O \dashrightarrow (H\text{-}C\text{-}O\text{-}H)_n + O_2$$

Woods are composed primarily of cellulose (about 75%), and lignins (25%) which provide strength to cells (Libby 1983).

> Plant materials vary a great deal in their resistance to decay; and different environments can promote different types of decomposition. Clearly the soluble parts of the living cell go first, quickly followed by those materials which can be transformed into solubles, e.g. starch, protein. The cell walls are more resistant. All walls are basically of cellulose, but other substances may be laid down on top of the cellulose in tissues having special functions . . . wood cells become lignified, lignin being deposited to give strength. (Dimbleby 1967:95)

Depending on the species, dry wood contains 40 to 55% cellulose, 15 to 35% *lignins*, and 25 to 40% *hemicelluloses*. *Lignins* are very inert complex hydrocarbon polymers found in certain cell walls of true vascular plants (but not in mosses). They are deposited in water-conducting or support cells at the end of the cell expansion stage (developing tissues contain 0-2.5% lignin, mature ones contain

15-36%). They create cell walls that are strong, stress resistant, less permeable to water, and less prone to pathogenic degradation (Haigler 1985). *Hemicelluloses* are polysaccharides (excluding pectin) which remain hydrogen-bonded to cellulose after lignins are removed (Haigler 1985; Nevel and Zeronian 1985).

While it is "to be expected that the deuterium content of the organically bound hydrogen in plants be in some way related to the deuterium content of the moisture absorbed from the soil during growth" (Schiegl and Vogel 1970:309), the relationship between temperature, precipitation and hydrogen values in plant cellulose is complicated. Cellulose has two classes of bound hydrogen: oxygen-bound (hydroxyl, about 30 atom-percent) and carbon-bound (carbonyl, about 70 atom-percent) (Epstein et al. 1976). Hydroxyl hydrogen in cellulose exchanges readily with surrounding environmental waters, confusing the signal and causing elevated δ values. As well, during laboratory separation of lignin from cellulose, hydroxyl hydrogen exchanges readily with oxygen-containing solvents (Libby 1983). Carbon-bound hydrogen remains non-exchangeable and is thus more reliable for palaeoenvironmental studies (Epstein et al. 1976; Yapp and Epstein 1982a).

Cellulose Nitration

Nitration procedures are esterification of cellulose, which takes place uniformly throughout the mass, as the small nitronium ion (NO_2^+) penetrates quickly into the cellulose structure (Nevel and Zeronian 1985; Wadsworth 1985). Although raw plant values show a relationship to nitrated values (all raw cellulose has some percentage of non-exchangeable hydrogen), overoptimistic use of these materials in some studies can show results with large scatter from individual plants (Epstein et al. 1976).

In order to reduce the scatter evident with whole cellulose samples, Epstein et al. (1976), DeNiro (1981), and Yapp and Epstein (1982a) developed a nitration procedure which effectively eliminated the hydroxyl hydrogen from samples. They were able to show very good correlation between δD values of nitrated cellulose, associated waters and mean annual temperatures (see for example Yapp and Epstein 1982a:960; Gray and Jong Song 1984) (see figure 14). Subsequently, Yakir et al. (1989) studied isotopic heterogeneity within plant leaves. They found that the isotopic composition of water within cells can be considerably different from total leaf water, but that bound cellular waters could not be mechanically expressed from the leaf during analysis. Since bound cellular water is used in biosynthesis of organic matter (including cellulose used in isotopic studies), its isotopic signal should remain unchanged and be preserved in palaeobotanicals (Epstein et al. 1976, 1977; DeNiro and Epstein 1979; Yakir et al. 1989).

Additional benefits conferred by the nitration procedures make it possible to store cellulose without significant chemical alteration; short term fermenting or molding and rotting seem to have little effect on δD values; and various food preparation activities which may have been carried out on plant materials do not affect nitrated values. As well, incomplete nitration does not seem to affect values significantly (see Yapp and Epstein 1977; DeNiro 1981; Yapp and Epstein 1982a; Marino and DeNiro 1987). However, cellulose nitrate was first used as a military explosive: samples with high nitrogen contents are inflammable when dry and may explode if exposed to heat or shock, so extreme caution is required in their handling (Green 1963a; Wadsworth and Daponte 1985).

Nitration procedures are time-consuming and rigorous, and involve the use of dangerous chemicals (such as 90% nitric acid). Feng et al. (1993) developed a method of sample preparation based on work previously done by Grinstead and Wilson (1979) which is slightly poorer in terms of resolution ($1\sigma = 2.5^{o}/_{oo}$ vs $1\sigma = 2.0^{o}/_{oo}$), but renders the complex nitration procedures unnecessary. However, as that procedure was relatively new and untested, extraction and nitration procedures were carried out on the samples from the cores, using procedures detailed by Gray and Jong Song (1984) which follow standard protocols developed by Green (1963b), Epstein et al. (1976) and DeNiro (1981) (see appendix B).

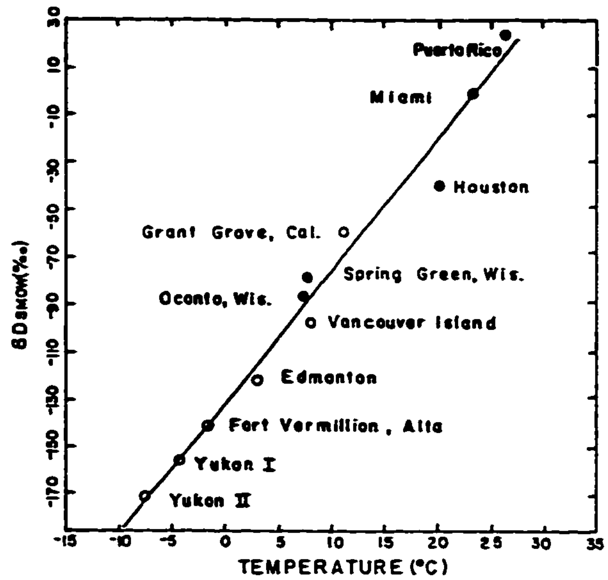


Figure 14. The relationship between δD values of cellulose nitrate and mean annual temperature for tree rings from North America. Datum points represent an average of 15-60 years of growth: o=data from this study; •= data from Epstein et al. 1976. Reproduced with permission from Elsevier Science (Gray and Jong Song 1984:137).

Chapter Summary

Of the five sites initially selected for this study, only two had mires of sufficient depth to core. Cores were taken from topogenic mires at Gjögur (ca. A.D. 1000 to present) in the northwest, and Svalbarð (ca. A.D. 1000 to present) in the northeast. Five cores in all were taken, and each was x-rayed, photographed, and sampled for humification values, loss-on-ignition and radiocarbon dating. Samples were screened through 20 mesh before microscopic separation. This procedure is taken to ensure minimal species-specific effects, which relate to the discrimination against deuterium during photosynthetic processes, and can result in errors in data.

Due to the quantifiable relationship between hydrogen isotopes and environmental temperatures, δD values will be measured. Two factors which affect δD values are temperature dependent fractionation and evapo-transpiration in plants. δ values can be related to altitude, latitude and amount of precipitation, following the work of Dansgaard.

Cellulose is composed of two classes of bound hydrogen, only one of which (carbon-bound) is useful for palaeotemperature data. Oxygen-bound hydrogen can be removed from cellulose through nitration procedures (for example, following Gray and Jong Song 1984).

CHAPTER 5

RESULTS AND DISCUSSION

Description of Cores

GJ-1

The Gjögur core GJ-1 is described in figure 15, and shown in plate 5. The core is 111 cm long, and consists of stratified and humified peat. Two tephras observed at 55 cm and at 91-94 cm remain unidentified.

Loss on ignition (LOI) values are variable, ranging from 27.3% to 90.9%. Slightly lowered values at 50 and 55 cm correlate with Tephra 1 observed at 55 cm, while very low values at 85-90 cm correlate with Tephra 2 (see table 1 and figure 16). Tephra 1 does not show the characteristically low LOI values of Tephra 2, which may be due to dispersion through the immediately adjacent organic sediments, giving relatively high LOI values. Other variations in LOI values most likely represent inconsistent inorganic sediment influxes, including the low value of 38.5% at 20 cm depth. At this time it is impossible to correlate these influxes with human activity in the area.

Radiocarbon dates were measured at the Alberta Environmental Centre (Vegreville) and are uncalibrated (see table 2). The date of 3690 ± 80 years B.P. (ca. 1740 ± 80 B.C.) at 55 cm indicates that the settlement layer would be found significantly higher up in the core than initially expected.

Depth (cm)	^{14}C sample#	Description of sediments
0-9		Present vegetation cover Transitional lower boundary
9-17		Moderately decomposed sedge peat 3/1 5YR Transitional lower boundary
17-55		Strongly decomposed sedge peat 3/1 5YR Transitional lower boundary
55	2036-C	Tephra 1 (unidentified)
55-69		Strongly decomposed silty peat 2.5/1 5YR Sharp lower boundary
69-73		Moderately decomposed silty peat 2.5/1 5YR Transitional lower boundary
73-91		Highly decomposed peat 2.5/1 5YR Sharp lower boundary
91-94	2037-C	Tephra 2 (unidentified) 3/2 2.5YR
94-111		Weakly decomposed sedge peat with wood fragments 2.5/1 5YR
111	2038-C	

Figure 15. Gjögur core 1 (GJ-1) description. Includes humification and Munsell values. Used with permission from Zutter 1996.

Plate 5. Gjögur Core 1, Colour.

TABLE 1
LOSS ON IGNITION DATA, GJÖGUR CORE (GJ-1)

Depth (cm)	Wt (g) (ash/dry)	% LOI
0	0.6 /1.0	60.0
5	0.4/0.7	57.1
10	0.8/1.2	66.7
15	1.0/1.3	76.9
20	0.5/1.3	38.5
25	0.9/1.5	60.0
30	1.1/1.5	73.3
35	0.7/1.4	50.0
40	1.0/1.6	62.5
45	1.0/1.6	62.5
50	0.6/1.4	42.9*
55	0.9/1.8	50.0
60	1.2/1.4	85.7
65	1.2/1.5	80.0
70	1.0/1.2	83.3
75	1.0/1.4	71.4
80	0.6/1.2	50.0
85	0.3/0.9	33.3*
90	0.3/1.1	27.3*
95	0.8/1.1	81.8
100	0.9/1.0	90.0
105	1.0/1.1	90.9
110	1.0/1.1	90.9

* = tephra observed in core

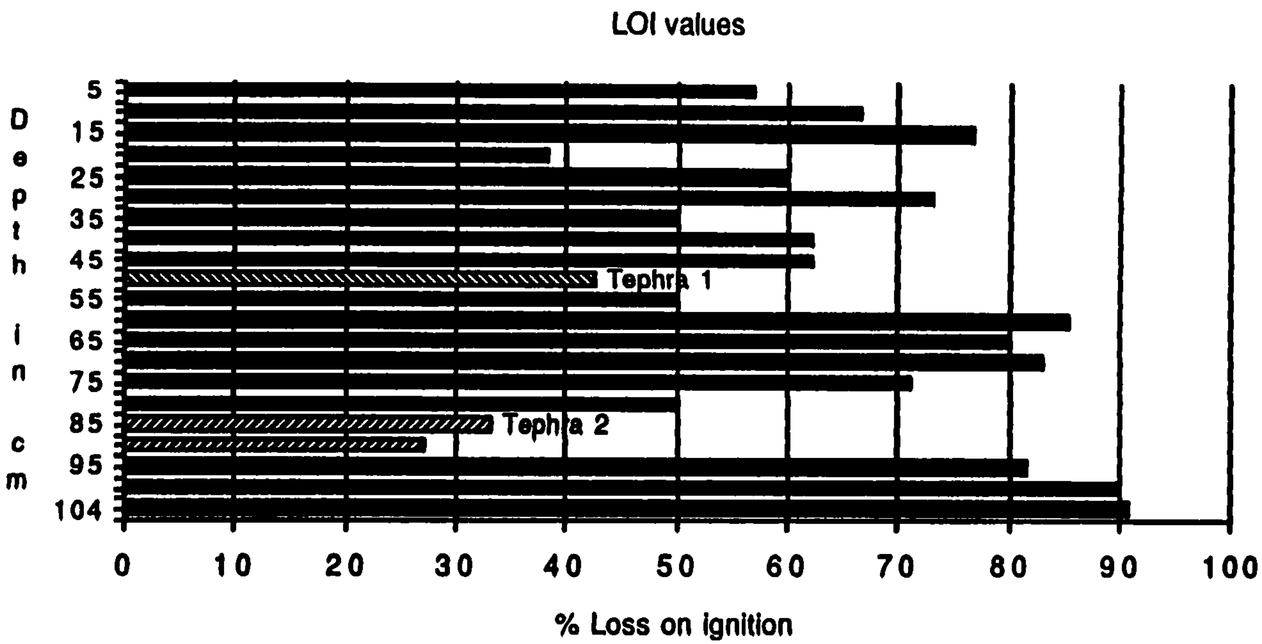


Figure 16. Gjogur Core 1 (GJ-1) loss-on-ignition.

TABLE 2
RADIOCARBON DATES FOR GJÖGUR CORE 1 (GJ-1)
ALBERTA ENVIRONMENTAL CENTRE

Depth	Description of sample	Wt used (mg)	AECV Lab ID#	Age (Yrs B.P.)
55 cm	bulk peat Tephra 1	--	2036C	3690 ± 80
95 cm	bulk peat Tephra 2	--	2037C	5340 ± 100
110 cm	bulk peat basal unit	--	2038C	5910 ± 100

NOTE for Table 2: Ages are $\delta^{13}C$ corrected and are referenced to 1950 A.D. using W.F. Libby's ^{14}C half-life, or $T^{1}/_{2}$ = 5568 years. The Delta C13 age correction = $16(\delta^{13}C - 25)$ years; Delta C13 error is ± 0.3; values are in per mil relative to the PDB standard. Error probability is 1 S.D. All samples are treated with NaOH to remove mobile humic acids and with HCl to remove carbonates, unless otherwise noted. See Taylor (1987:98-99) for a discussion of half life ($T^{1}/2$).

SV-C

The Svalbarð core SV-C is described in figure 17, and shown in plate 6. The core is 133 cm long, and consists of stratified and humified peat. Two tephras have been observed in the core. Banded Tephra 1 at 75-78 cm depth is tentatively identified as Hekla 3 (Dugmore, personal communication 1994). Tephra 2 observed at 110-114 cm was tentatively assigned to Hekla 4 (*ibid.*).

Loss on ignition (LOI) values are variable, ranging from 8.3% to 80% (see table 3 and figure 18). Lowered values at 75 cm depth correlate with Tephra 1. Lowered values at 110 and 115 cm depth correlate with Tephra 2. Other variations in LOI values likely represent inconsistent inorganic sediment influxes, and very low values at the base of the core represent silty layers. At this time it is impossible to correlate these influxes with human activity in the area.

The first radiocarbon data submitted from the cores was a wood sample from the base of the Svalbarð core (SV-C) (133 cm b.s.). The Isotrace Radiocarbon Laboratory (University of Toronto Accelerator Mass Spectrometer Facility) returned a date of 6260 ± 60 yrs B.P. As this gave an unexpectedly early date for the length of the core, wood fragments below the tephras at 77 cm and 114 cm depth were also dated in order to verify their approximate age. These were returned with ages of 3080 ± 60 yrs B.P. (77 cm) and 4110 ± 110 (114 cm) (table 4). In an attempt to date wood concentrations which appeared to be associated with *Landnám*, samples were further taken from 48 and 51 cm b.s. These were returned with dates of 2160 ± 50 B.P. (TO-5786, a bulk peat sample) and 2180 ± 60 B.P. (TO-5242, wood fragments), which still gave a date much too early for *Landnám* by about 1000 years.

Depth (cm)	^{14}C sample#	Description of sediments
0-5		Present vegetation cover Diffuse lower boundary
5-40		Moderately decomposed sedge peat 3/1 5YR Gradual lower boundary
40-75	TO-5786 at 48 cm TO-5242 at 51 cm	Moderately decomposed sedge peat with wood fragments 2.5/1 5YR Sharp lower boundary
75-78	TO-4670 at 77 cm	Banded Tephra 1 (possibly Hekla 3) 4/6 5YR with 6/4 5YR band
78-110		Strongly decomposed silty peat 2.5/1 5YR Sharp lower boundary
110-114	TO-4671 at 114 cm	Tephra 2 (possibly Hekla 4) 4/2 10YR
114-128		Highly decomposed peat 2.5/1 5YR Sharp lower boundary
128-133		Fine grained silt, massive, no apparent bedding 3/4 10YR
133	TO-4431 basal unit	

Figure 17. Svalbarð core C (SV-C) description. Includes Munsell and humification values. Used with permission from Zutter 1996.

Plate 6. Svalbarð Core C, Colour.

TABLE 3
LOSS ON IGNITION DATA, SVALBAR∂ CORE (SV-C)

Depth (cm)	Wt (g) (ash/dry)	%LOI
0	0.2/0.9	22.2
5	0.6/0.9	66.6
10	0.7/2.2	31.8
15	0.6/1.5	40.0
20	0.8/2.1	38.1
25	1.0/2.4	41.7
30	1.0/1.9	52.6
35	0.9/1.6	56.3
40	1.0/2.1	47.6
45	1.2/1.5	80.0
50	1.0/1.4	71.4
55	0.9/1.2	75.0
60	0.9/1.7	52.9
65	0.8/1.4	57.1
70	1.8/1.2	66.7
75	0.3/2.7	11.1*
80	0.9/1.3	69.2
85	0.8/1.1	72.7
90	0.7/0.9	77.8
95	0.7/1.2	58.3
100	0.7/1.2	58.3
105	0.9/1.2	75.0
110	0.5/2.3	21.7*
115	0.3/2.3	13.0*
120	0.6/1.5	40.0
125	0.2/1.3	15.4
130	0.2/2.4	8.3

* = tephra observed in core

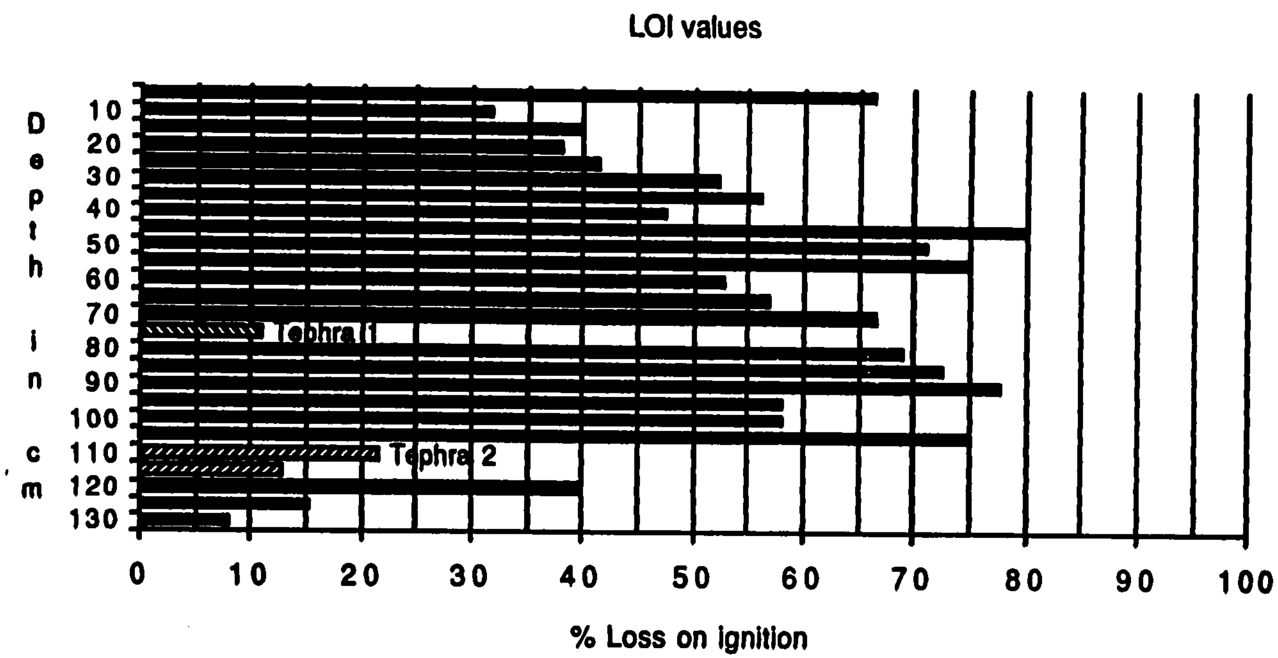


Figure 18. Svalbard Core C (SV-C) loss-on-ignition.

TABLE 4
RADIOCARBON DATES FOR SVALBARD CORE C (SV-C)
ISOTRACE LAB

Depth	Description of sample	Wt used (mg)	Isotrace Lab ID#	Age (Yrs B.P.)
48 cm	peat	377	TO-5786	2160 ± 50
51 cm	*Betula* wood fragments	77	TO-5242	2180 ± 60
77 cm	*Salix* wood fragments	82	TO-4670	3080 ± 60
114 cm	*Betula* wood fragments	136	TO-4671	4110 ± 110
basal unit 133 cm	*Betula* wood fragments	284	TO-4431	6260 ± 60

NOTE for Table 4: Results are the average of the analysis of 2 targets (normal precision) and have been corrected for natural and sputtering fractionation to a base of $\delta^{13}C$ = -25°/oo. The sample ages are quoted as an uncalibrated conventional radiocarbon date in years before present (BP) using the Libby ^{14}C meanlife of 8033 years. The error represents the 68.3% confidence limit. See Taylor (1987:98-99) for a discussion of meanlife.

SV-A

During cellulose extraction procedures on the SV-C separated wood samples (see appendix B), it became evident that there was not enough material to proceed with analysis. The process was attempted again with bulk samples of the peat taken from Svalbarð Core A (SV-A), as per the method of Chatwin (1981).

The core is 107 cm long, and consists of stratified and humified peat. A banded tephra at 60-65 cm and another tephra at 98-101 cm remain unidentified (the same tephras found in SV-C). During initial photography (see plate 7) and description of the core, it was noted that the colours were not the same as those noted for SV-C (see Munsell values given in figures 17 and 19). It was assumed that some changes to the colour of the core sediments had occurred during storage.

In order to maintain the sampling strategy, samples were taken at 5 cm intervals, with the exception of those from 35-45 cm in depth. In this area, samples were taken every centimetre to attain higher resolution in this zone. This was necessary, due to preliminary results by Zutter (personal communication, 1995) which suggested that in core SV-C *Landnám* probably occurred above 50 cm. Inspection of core SV-A also noted a zone of high wood concentration at 40-42 cm, which were thought to correlate with *Landnám*. Samples were taken to 5 cm above and below the noted wood concentrations.

Loss on ignition (LOI) samples are variable, ranging from 3.4% to 77.7% (see table 5 and figure 20). Low values at 60 and 65 cm correlate with unidentified Tephra 1. Tephra 2 is represented by a very low LOI value at 100 cm. Other variations in LOI values most likely represent inconsistent inorganic sediment influxes.

It is expected that the two Svalbarð cores would not show *Landnám* at the same depth, as SV-A was significantly shorter than SV-C (107 cm compared to 133 cm). Waterlogging of the SV-A core was greater (see plate 8), resulting in the 26 cm difference between the lengths of the cores.

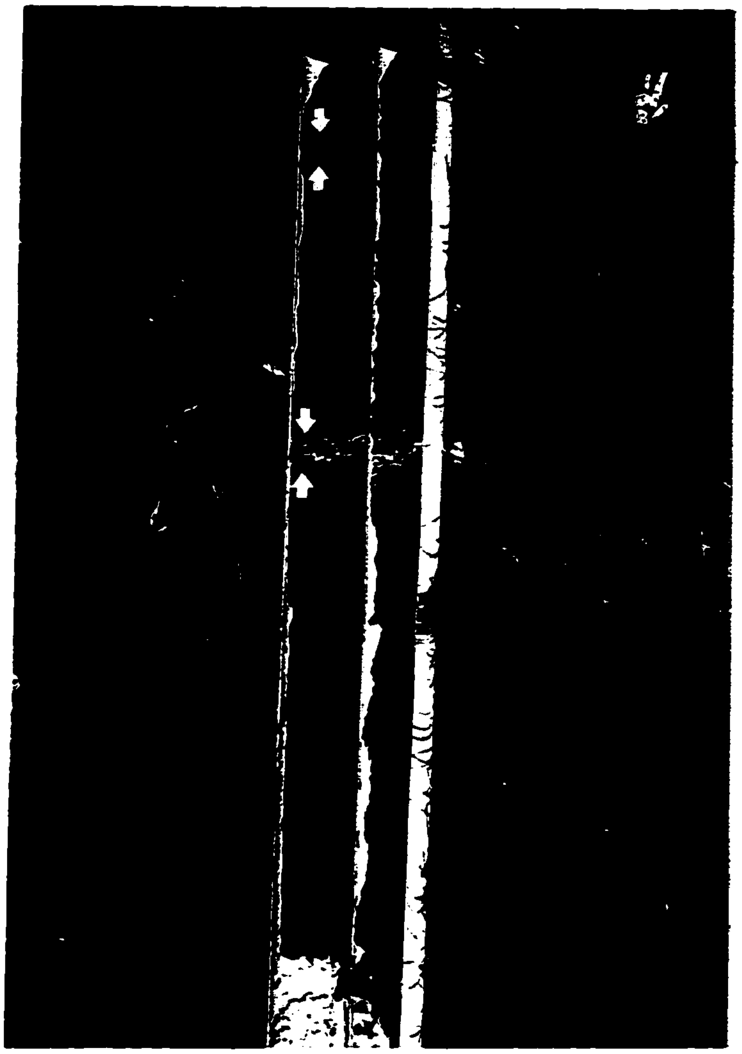


Plate 7. Svalbarð Core A, Colour. Arrows indicate tephras.

Depth (cm)	Description of sediments
0-5	Present vegetation cover Diffuse lower boundary
5-40	Moderately decomposed sedge peat 3/3 7.5YR Gradual lower boundary Angular break in core at 30-32 cm b.s.
40-42	Wood concentration
42-59	Moderately decomposed sedge peat with wood fragments 2.5/2 7.5YR Sharp lower boundary
60-65	Tephra 1 (unidentified) 4/6 5YR with 6/4 5YR band
65-98	Strongly decomposed silty peat 2.5/1 7.5YR Sharp lower boundary
98-101	Tephra 2 (unidentified) 3/2 2.5YR
101-107	Fine grained silt, massive, no apparent bedding 2.5/1 7.5YR

Figure 19. Svalbard Core A (SV-A) description. Includes Munsell values.

TABLE 5
LOSS ON IGNITION DATA, SVALBARD CORE A (SV-A)

Depth (cm)	Wt (g) (ash/dry)	% LOI
5	0.4/0.8	50
10	0.2/1.2	16.6
15	0.3/1.2	25
20	0.3/0.8	37.5
25	0.3/0.9	33.3
30	0.6/1.1	54.5
35	0.3/0.5	60
36	0.6/0.8	75
37	0.7/0.9	77.7
38	0.8/1.0	80
39	0.6/0.8	75
40	0.4/0.6	66.6
41	0.6/1.0	60
42	0.5/0.7	71.4
43	0.4/0.7	57.1
44	0.6/1.1	54.5
45	0.3/0.6	50
50	0.4/0.6	66.6
55	0.5/0.8	62.5
60	0.2/0.9	22.2*
65	0.3/1.0	30*
70	0.5/0.7	71.4
75	0.5/1.0	71.4
80	0.3/0.5	60
85	0.3/0.5	60
90	0.4/0.6	66.6
95	0.4/0.9	44.4
100	0.1/2.9	3.4*
107	0.5/0.7	71.4

* = tephra observed in core

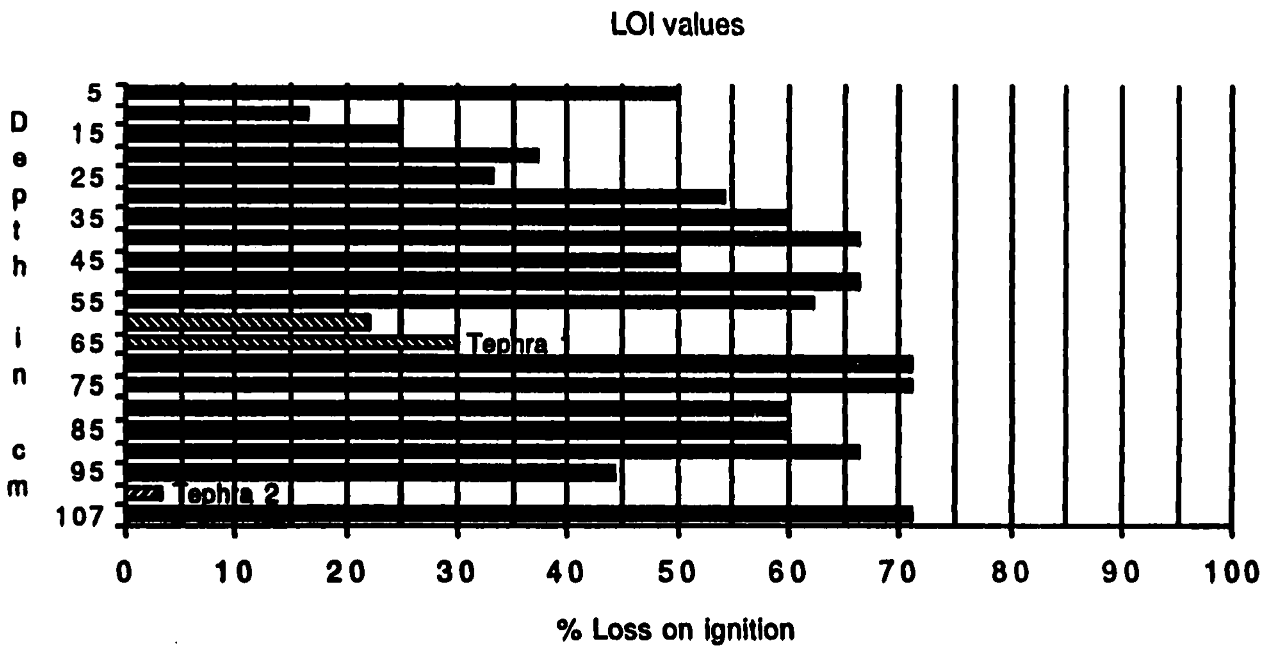


Figure 20. Svalbard Core A (SV-A) loss-on-ignition.

Plate 8. Waterlogging in Svalbard mire.

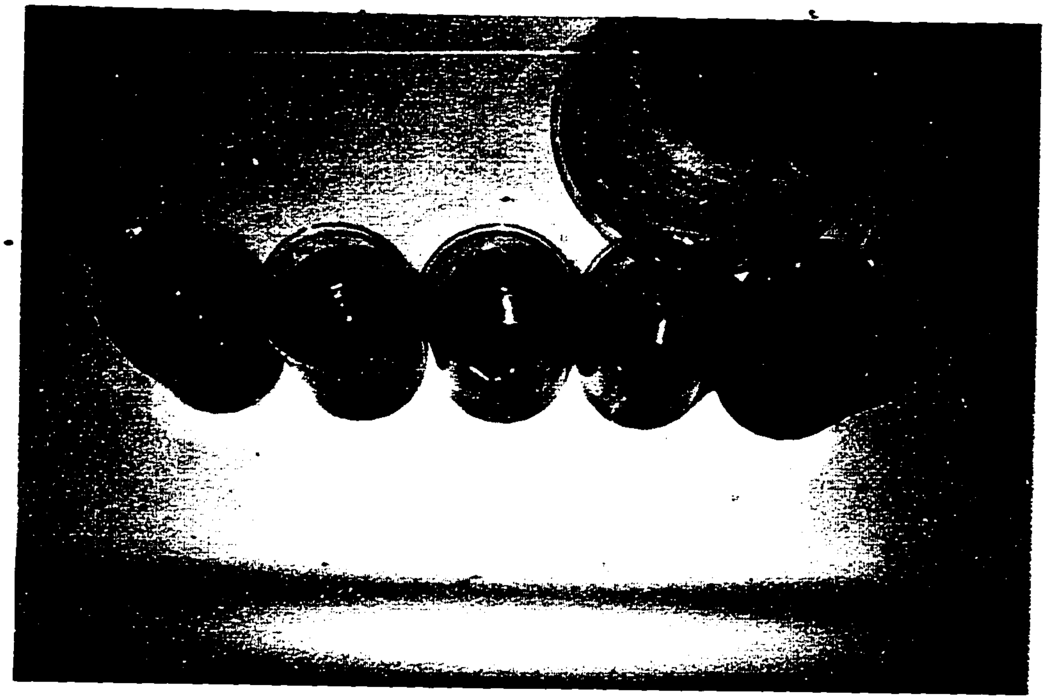
Extraction and Nitration of Cellulose

Extraction and cellulose nitration procedures followed those detailed by Gray and Jong Song (1984) (see appendix B), based on procedures developed by Green (1963b) and Alexander and Mitchell (1949). All extraction processes were carried out under a fume hood.

During the α-cellulose extraction process, it was noted that many of the samples showed different colours, ranging from bright yellow-orange to dark orange-brown (see plates 9 and 10). The assumption was made that colour variation in the samples indicated varying amounts of lignins present, which might affect the results, since samples were treated uniformly.

As noted, initial extraction procedures almost destroyed the samples. Before the nitration process began, samples taken from core SV-C were weighed, and they were too small to continue processing. The recommended weight for samples to begin cellulose extraction is 1.0 g, and after the removal of extractives, their weights ranged from 0.47 - 0.13 g. It was apparent that samples of such low weights would not suffice.

Once samples from SV-A had gone through initial extraction, they were immersed in acetone in preparation for centrifuging (to extract cellulose nitrate from the samples). This was the final step before samples would be taken to the gas extraction lines, and the mass spectrometer. At this point, the samples failed to dissolve into a viscous liquid, and remained solid, even after soaking in acetone for several days. The procedure was abandoned at this point.



Plates 9 (above) and 10 (below). Variation in sample colours.

Failure of Methodology

This study was considered to be a test of stable isotope methodology as applied to palaeoclimatic research in Icelandic peatlands. The work rests on various geochemical/technical assumptions whose validity control its results. These assumptions have been discussed previously, and are summarized below:

- Stable isotopes in precipitation reflect temperature changes (These include effects due to altitude and latitude, as well as the Medieval Warm Period and Little Ice Age temperature fluctuations).
- Hydrogen isotope ratios relating to temperature are incorporated into plant matter (including peaty species) and resulting cellulose provides a permanent record of past temperature.
- Nitration or equilibration of cellulose sufficiently removes the problematic hydroxyl hydrogen signal, and these procedures do not significantly alter the isotopic signals found within the carbonyl-hydrogen fraction of cellulose.
- Separating and identifying different plant species for analysis sufficiently eliminates uncertainty due to species effects or photosynthetic pathway.
- Temperature variations have been meaningful in historic times in northern Iceland due to their direct impact on resources and thus impacting both primarily and secondarily on human subsistence activities.

All of these assumptions appear to be valid. Therefore, the failure of this study was caused by two main factors. First, bulk peat samples could not be processed properly using this procedure: a combination of incomplete extraction of impurities (lignins), coupled with (possibly) insufficient nitration times was the failure of the laboratory methodology. Second, peat failed to meet the criteria of an appropriate study material, and the complexity of its features renders potential results of this method inapplicable.

The Laboratory Analysis and Peat

The first factor is the misapplication of cellulose extraction and nitration to bulk peaty materials. These techniques were initially developed for use on wood species only. The amounts of lignins present in peat-forming species, as well as degree of humification to which peats are subjected, may well be factors which must be accounted for in the initial step of extraction, as well as in nitrification. After Step 1 of the extraction of cellulose (see appendix B), most of the simple lignins should be removed so that only holocellulose remains (Chatwin 1981; Gray and Jong Song 1984). Should this first step not be sufficient to remove lignins from the peaty materials, impurities would remain throughout the process, affecting chemical reactions and results.

Additionally, the length of nitration of the alpha cellulose may not have been adequate. In some studies, extraction times of up to 100 hours for woody species have been needed (Green 1963b). While a three hour nitration may have been sufficient for grassy materials, the in-mixing of woody species may require that the cellulose be nitrated for a longer time. During the processing, it was noted that some samples did not dissolve in acetone (Step 4.1). At this point, samples which were just then being nitrated were left in the acid for a longer period of time (6 hours), in hopes that the error was in the length of nitration times. Unfortunately, this was not the case. Samples which had been left in the acid for six hours displayed the same result when attempts to dissolve them in acetone were made. The laboratory procedure was abandoned at this point.

Concerns with Peat as Study Material

The second factor is a cautionary tale for the application of stable isotope methodology to peat materials. Even had the laboratory procedures not failed, the results would have been suspect. Earlier, I summarized five conditions that Gray (1981), Jacobson and Bradshaw (1981) and Dupont and Mook (1987) proposed for an appropriate study material (page 70). These have not been satisfactorily met.

1. Isotopic ratios must be determined by climatic factors (other factors can be filtered out). In this study, sample size was too small to provide the amount of material needed for the separation of identifiable species before laboratory work to extract and nitrate cellulose was begun. In such cases, results can be erroneous, since the effects of species-specific fractionation and photosynthetic pathway directly affect δD values. Relative frequencies of species change over time due to climate change and anthropogenic affects, so the composition of bulk samples may actually vary without the knowledge of the researcher.

In order to provide enough plant material with which to do species separated analysis, it would be potentially feasible to core a larger diameter of peat (possibly 30 cm), or excavate a 1 m^2 unit. However, the mechanics would be more difficult, and it is not known if the sediments would be undisturbed for sampling. Einarsson (1963:357) suggests that this would not be the case, as stratigraphic levels (demonstrated by tephra layers) above *Landnàm* have been subject to cryoturbation.

2. Isotopes have not been subsequently altered (the record is permanent). It is not known if humification of peaty materials affects isotopic values, although the work of Marino and DeNiro (1987) suggests that it does not. This is a case for further study.

3. The record is continuous. As discussed, turf and peat cutting in the past may render present stratigraphic study of peatlands useless, as huge amounts of time are simply "cut away". It might be possible to search for peatlands located further away from settlements, and thus less utilized. While these might be less disturbed by human activities, they may also be less appropriate for studies which seek to correlate data (like temperature) in the immediate area where such human activities took place.

4. The strata are datable. It is possible to date peat materials, particularly if wood is present. This condition is satisfied.

5. The relatively high accumulation rates provide a time resolution that is appropriate to study parameters. The samples taken were 1 cm in depth. Even in the case of the well-dated SV-C core, if a sample were taken between surface and 48 cm depth, it would amount to a time span of about 45 years. In order to show change over time, at least two samples are required, so a time span of 90 years would be required to show even one change (significantly greater than some of the major fluctuations, which may occur on a decadal scale). Thus, samples are not of small enough time span to allow study of decadal or yearly temperature changes while still providing enough material for chemical procedures.

Further to these points, the nature of peat bogs is extremely complex, and not fully understood. Various factors affect the confidence in sampling peat materials for palaeoclimatic studies:

- Peat cores taken at any location within the mire may not accurately reflect local changes, even at the level of the mire itself. Even extremely minor changes in habitat can affect individual plants and species of plants (Barber 1982).
- Peatlands can be affected by man-made changes in vegetation patterns and changes in local drainage pattern (Moore 1986).
- Comparison between mires may not be possible. Local differences such as plant composition and aspect may result in different thresholds for change (Moore 1986).
- The type of mire (e.g. topogenic vs. ombrotrophic) is determined by water source. Rainfall and runoff may have different isotopic compositions, due to the effects of evaporation on adfluvial waters, so that even small differences between mires (e.g. in the amount of stagnant water) might have significant effects.
- Mossy species which comprise a large part of some mires are not able to close and open stomata like vascular plants; this may lead to variable isotopic values as evapotranspiration is maximized and uncontrolled.

Data Comparison

This study had the potential to produce an isotopic record of δD values for the two northern Icelandic sites of Gjögur and Svalbarð. These records would have served in their turn as independent sources of climatic data with which to compare and contrast data from the GISP2 ice core, Molloy (1993), Amorosi (1992) and Zutter (1989, 1996), and to possibly show general trends temporally consistent with the Medieval Warm Period (MWP) and Little Ice Age (LIA). Additionally, variations which existed between the two northern sites might have provided an opportunity to assess regional differentiation in climate fluctuations which have been noted in other studies (such as Molloy 1993). However, another method of producing a temperature record for such comparisons must be developed.

Chapter Summary

The results of photography, core description, loss-on-ignition and radiocarbon dating is presented for each of the three cores. The failure of cellulose extraction is described and possible reasons are given. Concerns with the assumptions underlying the stable isotopy method in relation to peat are given and specific reasons why this technique is not appropriate are discussed. It will not be possible to compare results with other studies.

CHAPTER 6

CONCLUSIONS

This study had two major goals. The systemic relationships between past climate variations and human activities in Iceland are demonstrated, and are summarized in figure 10 above. The complexity of the changes in the archaeological, historical and palaeoecological records should not be underestimated, nor attributed to only one cause, as many factors are responsible for the Icelandic cultural landscape, including feedback and human intervention in natural systems.

The second aim of this study was to test the ability of hydrogen-deuterium stable isotopy to create a high-resolution record of temperature changes which occurred in two northern Icelandic peatlands over the last millennium. The results indicate that H/D stable isotopy is not suitable for the creation of a temperature profile for northern Icelandic peats. This is due to a variety of factors combining to make the study material (peat) inappropriate for this methodology. The most important of these include the inability to separate species within samples, and incomplete cellulose extraction and nitration, due to the probable presence of impurities.

However, the failure of this method does not negate the need for exact palaeoclimate and temperature data. The need for independent records of climate change has been stressed by many authors concerned about how climatic data has been used in the past in circular arguments, or to support climate determinism. Accurate information from independent sources is required to cross-check archaeological and palaeoenvironmental data.

The use of natural science techniques in multi-disciplinary and trans-national studies has allowed researchers to more accurately portray the lives of the Norse and other archaeologically known peoples. Valuable lessons are continually being learned about the applicability (or misapplication) of these methods. In this way, though this method was inappropriate, this study contributes to the wider discipline and ongoing research.

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APPENDIX A
MICROSCOPIC INSPECTION AND DESCRIPTION OF SAMPLES

Once samples were screened, they were examined microscopically (60X magnification on a WILD M5 dissecting microscope) in order to isolate the different species present in the samples. This was deemed necessary in order to eliminate species-specific effects (see Ziegler et al. 1976; DeNiro and Epstein 1981; Brenninkmeijer et al. 1982; Sternberg and DeNiro 1983; Dupont and Mook 1987). Initially, three major categories of plant tissues were selected for separation and analysis: woody plants of mostly *Betula* and possibly *Salix*, grassy species of *Carex* spp., and possibly *Eriophorum*. It soon became apparent that only the woody remains would be identifiable throughout the cores, and the work focused on isolating woody tissues only.

Once the woody samples from core SV-C had been isolated and reworked to remove remaining filaments of mossy species, samples were removed to the lab, weighed, and prepared for analysis.

TABLE A1
GJ-1 MICROSCOPIC SAMPLE DESCRIPTIONS

Sample #	Wt (g)	Description
GJ-1-0	1.0	much un/semi-degraded material
GJ-1-5	-	
GJ-1-10	1.3	little wood
GJ-1-15	1.1	lots of grass, very little else
GJ-1-20	0.7	insect remains; 5 *Empetrum* leaves
GJ-1-25	1.3	little material
GJ-1-30	0.1	very little material
GJ-1-35	0.3	
GJ-1-40	0.8	little material; little wood
GJ-1-45	0.7	dark colour; some *Empetrum*; no wood
GJ-1-50	0.5	much charcoal/sediment; 1 possible *Empetrum* leaf
GJ-1-55	1.1	
GJ-1-60	1.9	little material; lots of bark
GJ-1-65	1.5	insect remains
GJ-1-70	-	
GJ-1-75	1.6	
GJ-1-80	0.9	little material; possible *Empetrum* or other (?) leaves
GJ-1-85	1.4	very little material; 4 possible *Empetrum* leaves
GJ-1-90	-	
GJ-1-95	-	
GJ-1-100	1.4	
GJ-1-104	0.9	large amount of wood; insect remains; grass very degraded

TABLE A2
SV-C MICROSCOPIC SAMPLE DESCRIPTIONS

Sample #	Wt (g)	Description
SV-C-0	2.5	much undegraded material
SV-C-5	2.5	insect remains; much grass
SV-C-10	1.6	sediment; not very much wood; much grass
SV-C-15	0.4	lots of inorganics; tephra?
SV-C-20	1.2	little wood; much grass
SV-C-25	1.4	some wood; much grass
SV-C-30	2.0	much grass; little wood
SV-C-35	2.0	charcoal?; little wood or bark; much grass
SV-C-40	1.0	little material
SV-C-45	2.0	lots of large wood; insect remains
SV-C-50	2.2	dark sample with sediment; much wood; little grass
SV-C-55	1.0	large wood
SV-C-60	1.3	lots of large wood and grass
SV-C-65	1.2	lots of wood and bark
SV-C-70	1.8	lots of wood and grass
SV-C-75	0.7	less wood, more bark than #70; less grass, more degraded
SV-C-80	1.2	sediments (tephra?); wood and leaves present
SV-C-85	1.3	large amounts of large wood
SV-C-90	-	
SV-C-95	0.6	large wood
SV-C-100	1.1	not very much wood; no leaves
SV-C-105	1.3	wood and bark; little grass
SV-C-110	2.1	sediments; wood but little grass
SV-C-115	0.5	very little material
SV-C-120	-	
SV-C-125	0.1	lots of sediment; bark and wood stained
SV-C-130	-	mostly sediment of dark material; sample useless

TABLE A3
SV-A MICROSCOPIC SAMPLE DESCRIPTIONS

Sample #	Wt (g)	Description
SV-A-5	1.9	1.9 g bulk
SV-A-10	0.9	0.9 g bulk
SV-A-15	3.0	3.0 g bulk
SV-A-20	2.8	2.4 g bulk, 0.4 g wood
SV-A-25	2.2	2.2 g bulk
SV-A-30	3.0	3.0 g bulk
SV-A-35	1.9	1.9 g bulk
SV-A-36	1.3	1.3 g bulk
SV-A-37	1.4	1.4 g bulk
SV-A-38	2.1	2.1 g bulk
SV-A-39	2.8	2.8 g bulk
SV-A-40	2.2	2.1 g bulk, 0.1 g wood
SV-A-41	2.6	1.5 g bulk, 1.1 g wood
SV-A-42	1.7	0.6 g bulk, 1.1 g wood
SV-A-43	1.9	1.0 g bulk, 0.9 g wood
SV-A-44	1.5	1.0 g bulk, 0.5 g wood
SV-A-45	1.4	0.9 g bulk, 0.5 g wood
SV-A-50	1.6	1.6 g bulk
SV-A-55	1.5	1.5 g bulk
SV-A-60	1.3	1.3 g bulk
SV-A-65	3.4	2.3 g bulk, 1.2 g wood
SV-A-70	0.8	0.6 g bulk, 0.2 g wood
SV-A-75	0.6	0.6 g bulk
SV-A-80	0.9	0.9 g bulk
SV-A-85	1.2	1.2 g bulk
SV-A-90	1.3	0.3 g bulk, 1.0 g wood
SV-A-95	0.7	0.3 g bulk, 0.4 g wood
SV-A-100	1.2	0.4 g bulk, 0.8 g wood
SV-A-107	6.7	2.8 g bulk, 2.9 g whole wood; samples very difficult to grind

APPENDIX B
EXTRACTION AND NITRATION OF ALPHA CELLULOSE

This extraction and nitration procedure is described by Gray and Jong Song (1984), and follows standard protocols developed by Green (1963b), Epstein et al. (1976) and DeNiro (1981).

<u>Step 1: Removal Of Extractives</u>

1.1 Grind sample to pass 40 mesh
1.2 Soak in 1:1 Benezene:Methanol solution for 24 h
1.3 Acetone wash for 24 h
1.4 Dry in vacuoo at 40°C for 72 h

<u>Step 2: Extraction Of Alpha Cellulose</u>

2.1 A 1g sample is placed in 300 mL of hot water in 1L flask containing 3 mL acetic acid
2.2 Add 10 g technical grade sodium chlorite, heat at 90°C for 1 h
2.3 Repeat twice more with 10 g sodium chlorite and 3 mL acetic acid
2.4 Filter residue, wash with hot water and then with large amounts of cold water (holocellulose now remains)
2.5 Stir in 50 mL of 17% NaOH with holocellulose at room temp for 40 min
2.6 Filter and wash with 17% NaOH, then 10% acetic acid, then with large amounts of distilled water
2.7 Dry alpha cellulose by solvent exchange with acetone, dry in vacuoo for 72 h

<u>Step 3: Cellulose Nitration</u>

3.1 404g of phosphorus pentoxide added to 100g of cold 90% nitric acid (yields 64% HNO_3/ 26% H_3PO_4/ 10% P_2O_5)
3.2 Milled wood rapidly immersed in nitrating acid at -16°C and left to react at 0-5°C for 3 h (if cellulose extracted)
3.3 Cooled to -16°C, filtèred, washed with 1:1 glacial acetic acid and water
3.4 Immersed in 0°C water, neutralized with sodium carbonate
3.5 Washed with water, stabilized by 3 x 5 min boiling water treatments
3.6 Filtrate cooled 5 min in methanol, drained by suction
3.7 Dried in vacuoo at room temperature

Step 4: Extraction Of Cellulose Nitrate

4.1 Nitrate dissolved in acetone, giving viscous liquid

4.2 Centrifuge

4.3 Clear solution added to a large amount of cold water; nitrate precipitates

4.4 Wash precipitate with large amounts of water, followed by methanol

4.5 Dry in vacuoo 2 days