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Annual Speleothem Laminae: Indicators of Paleoclimate in Ireland

Martin Marek Vesely, B.A.

A thesis submitted to the Faculty of Graduate Studies and Research as partial
fulfillment of the degree of

Master of Arts

Department of Geography
Carleton University

Ottawa, Ontario

March 1st 2000

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Acceptance of the thesis

Annual Speleothem Laminae: Indicators of Paleoclimate in Ireland

Submitted by Martin Marek Vesely

In partial fulfillment of the requirement for
the degree of Master of Arts

Thesis Supervisor

Chair, Department of Geography

Carleton University

July 27th 2000

Abstract

Three stalagmites and one flowstone were collected in the Burren District, County Clare, Ireland, a temperate region of north-west Europe. The speleothems were dated using U-Th thermal ionization mass spectrometry (TIMS) and found to be Holocene in age, free of hiatuses and alteration.

They were cut vertically, polished and then imaged using a confocal laser microscope to produce images of luminescent laminae. Determined to be annual, these laminae were developed into width chronologies in order to identify growth trends.

Average, annual laminae growth rates are 0.024-0.034 mm. Regionally, the laminae growth trends from various caves show a coherent pattern. This pattern correlates with other paleoclimatic proxies such as ice core δO^{18} , sunspot events, dendrochronological records, bog humification and historic records. Certain volcanic events are indicated by abnormally wide bands.

The laminae widths time series were analyzed using a single series Fourier spectral analysis. Major cycles at ≈ 11 and 80 years were identified. These are interpreted to denote solar influence on growth corresponding to sunspot and Gleissberg cycles respectively. Cycles in the order of ≈ 200 and 600-800 are also present, though less reliable.

I would like to acknowledge the contributions of the following people who helped make this thesis possible. The people listed here contributed in their individual way to the completion of this thesis, from accommodations in the field to technical expertise. Omissions of any person(s) in this regard are accidental.

Philip, Helena and Ladislav Vesely, for their support and comic relief through my schooling process.

Joyce Lundberg, for her support both financially and intellectually and for being the most patient and interesting supervisor a student could hope for.

Steve Turgeon, for his advice and level-headed guidance.

Alfonso Ribes and the staff at the Con-focal Laser Microscopy lab at the University of Waterloo, for their help with imaging the speleothem.

David Drew of Trinity College in Dublin, for the accommodations and the caving experience in the Burren.

J. Pilcher and D. Brown at Queens University in Belfast, for the insightful conversation and advice regarding this thesis and paleogeographical studies in Ireland.

Andrew Williams, for his advice regarding spectral analysis.

Arwen Cowley-Owen, for her understanding and advice regarding the past two years.

Scott Nichol and David Schroeder who discussed with me this project, over Waterloo's finest brew.

Amy Goudie and Jennifer Carl, for the use of the couch in Dublin.

Lisa-Marie Gagné and Karen Foran, for their company and patience in Ireland.

Colm Conneelly and Philip Stewart at An Aharla on Inishmore, for the conversation and hospitality.

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1.0 Introduction

1.1 Background

Speleothem, a cave deposit usually made of calcite, is formed when percolation water dissolves CO₂ in the soil zone, enters a cave where the CO₂ degasses into the cave atmosphere, causing precipitation of calcite over time (Hendy, 1971). Common growth forms include stalagmites, stalactites and flowstone. Speleothems are often very well preserved in geologic history because their location in caves provides comparatively more protection from erosion than at the surface. Their growth constitutes a 'closed system' in which their chemical constituents are usually not altered from the time of initial deposition (Baker, 1993a). Speleothems can usually be reliably dated by radiometric dating methods. The most prominent of these methods is uranium-thorium dating, which allows speleothem to be dated up to 350 ka (by alpha counting-spectrometry) or 500 ka (by mass spectrometry) (Edwards, 1986). Because of these properties, speleothems have been used for paleoclimatic reconstructions (Lauritzen and Lundberg, 1999a). Isotopic and petrographic analysis have been used (Baker, 1993a; Baker, 1998; Ming *et al.*, 1998), and, less commonly, pollen and volcanic materials have been extracted and used to mark and determine past climatic progressions (Genty, 1993).

As they accumulate incrementally, many speleothems show various types of laminae or bands, which also can potentially give paleoenvironmental information. Paleoclimatic banding studies have already been undertaken in dendrochronology, dendroclimatology and coral studies. The use of dendrological bands as a base for paleoclimatic study is regarded as the pioneer of all subsequent banding or laminae-

focused paleoclimatic interpretations. The paleoclimatically significant information from tree rings includes ring-width, density and isotopic composition (Lowe and Walker, 1997). Paleoclimatic information from coral bands also includes band-width density and isotopic composition (Lundberg, pers. comm.). In addition, variations in the detrital content and luminescence from humic and fulvic acids can provide paleoenvironmental information. Isdale (1984) made the first observation of luminescent coral banding. It was determined by Isdale and Boto (1985) that terrestrial fulvic acids, transported by rivers into the nearshore environment, were incorporated into corals, causing luminescent banding variation.

In the late 1980s the presence of microscopic luminescent banding structures within crystals of speleothem was reported (Shopov, 1989; Shopov 1990; Shopov, 1991). This luminescence has been attributed to the excitation of humic and fulvic acids derived from the overlying soil and subsequently incorporated into the calcite through the drip water forming the speleothem (Baker, 1993). Although calcite itself luminesces due to ionic impurities, Shopov *et al.* (1994) attributes the dominant cause of luminescence to the presence of humic and fulvic organic acids, as they luminesce much more strongly than calcite alone.

It was postulated by Shopov (1991) and proven by Baker (1993) that these structures were annual growth layers similar to the growth rings of trees. Baker (1993) and Shopov *et al.* (1994) tested the annual banding theory by using high-precision thermal ionization mass-spectrometric (TIMS) $^{230}\text{Th}/^{234}\text{U}$ ages from banded sections of a stalagmite and compared the dates with those of the physically counted bands. In both studies the two methods agreed with each other within the

respective error limits.

Not all stalagmites display visible or luminescent banding. Baker (1993) states that of 43 samples initially studied, only five displayed visible banding, due possibly to the use of a low-energy, broad-spectrum UV lamp not capable of exciting weak luminescent banding. Shopov (1991) used a stronger ultraviolet light source, but noted the absence of banding in some sections of samples as well. This observation could be attributed to a decrease in concentration of humic and fulvic acids, or to an increase in detrital components, or to year-long growth with no seasonality. Baker's (1993b) study used stalagmites from various karst localities in the United Kingdom and also discovered that banding was not present throughout the whole of each sample.

Baker's (1993b) initial demonstration that banding could be annual illustrated the potential of speleothems as a resource for paleoclimatic reconstruction in which paleoenvironment can be estimated from stable isotopes, band-width, and luminescent intensity (Baker, 1993b). Isotopic studies at the resolution of the annual bands are rarely feasible except for very fast growing samples. Band-width can be used to indicate growth rates. It is important to note that absolute growth rates from an individual stalagmite cannot always be used to determine a paleoclimatic signal, since the growth rate is a function of flow routing (drip route changes) and aquifer characteristics, rather than paleoprecipitation (Baker, 1993b). Relative changes or trends within a single sample, however, could disclose valuable paleoclimatic information.

Microscopic observations of bands under a luminescent source often show two crystalline fabrics which correspond to two types of laminae. Under observation using a normal light microscope, the darker brown translucent laminae were determined to be palisadic calcite with structure perpendicular to the stratification and having low porosity, while the light coloured opaque laminae were formed of palisadic calcite with higher porosity (Genty, 1993). White (1981) attributes the dark portions of calcite, which fluoresce strongly, to growth related to waters rich in organic acids during summer months and white layers (non-fluorescent) to growth during fall to winter months when organic activity is minimal. The two types of laminae are not necessarily universal and generally appear only in areas with distinct seasonality. Ribes *et al.*, (2000) observe that it is quite common for the visible and luminescent images to be exactly opposite, as the darker coloured banding is caused by a concentration of organic matter which gives the greatest luminescence (Figure 1.1).

Deposition of the laminae depends on the volume and chemistry of drip water that form speleothem, which in turn are dependent on water supply from the surface as well as organic activity in the soil above the drip site. Fluctuations in precipitation levels, temperature and organic activity will affect the growth of a speleothem and will be recorded in the laminae. Baker (1993a) illustrates that growth rate is dependant on temperature. In his study, Baker (1993a) kept all depositional variables, such as CO₂ concentration, water film thickness and calcium concentrations, constant and varied only the temperature. This proved that temperature alone affects growth rates, in addition to the more obvious temperature

control on biological activity, soil CO₂ levels and drip water saturation levels. Thus, laminae and petrographic studies could yield valuable paleoclimatic information. Presumably, the larger the amount of supersaturated drip water supply, the larger the amount of speleothem growth and the thicker the laminae width, as discussed by Tan *et al.* (1997).

On the larger scale, the thickness and shape of the laminae are reflected in the shape of the stalagmite which in turn reflects paleoenvironmental conditions. Franke (1965) divides stalagmites into three categories. Those of uniform diameter that add almost all new growth at the top (not down the sides) are considered to be created by a uniform supply of feedwater with uniform solute concentrations. Curl (1973) modeled their diameter by the relationship between CaCO₃ available for deposition and flowrate: the theoretical minimum diameter is ≈ 3 cm. Stalagmites with variable, terraced thickening are Franke's second classification, where periodic variation in growth rate and greater fall height of drip water has caused a greater splash. The third type of stalagmite is a conical form whose the shape has been attributed to a decreased growth rate.

Fluctuations in luminescent property of speleothems have recently been used as a proxy of paleoclimate. Luminescent intensity can be scanned automatically with relative ease. Baker (1993b) used laminae chronologies, and assuming a constant, linear growth rate to model the length of gaps in the record, spectral analysis was applied to the banding intensity signal to determine its periodicity. A

Figure 1.1: Dark and light laminae luminescent in banded flowstone from Aillwee Cave, Burren District, Ireland. The sample shown is 2x2mm section, under 532 nm excitation, > 555 nm emission. White spots are dust particles on sections of calcite.

linear model was used as the gaps in the data were quite small . A weak 11-point periodicity was found, which was attributed to the 11-year sunspot cycle.

Changes in solar intensity affecting climate over time may affect plant productivity and humic and fulvic acid concentrations in the soil and groundwater; thus the intensity of the luminescent banding preserved in speleothems can vary over time (Baker, 1993b). Annual luminescent banding was thus shown to be useful in paleoclimatic study.

1.2 Statement of Problem

The value of the banding of speleothems as paleoclimatic proxies has been established in previous papers such as Baker (1993) and Genty (1993). Most studies have focused on the petrographic and luminescent properties of the laminae rather than the banding width itself. The use of laminae width as a paleoclimatic proxy has only recently been addressed in paleoclimatic research. For example Tungsheng *et al.* (1999) compared instrumental records and historical records to show that the thickness of annual layers of stalagmites can be taken as a proxy of precipitation in China. Recently, Qin (1999) have used spectral analysis on a laminae thickness record to identify solar influenced growth cycles from a cave close to Beijing.

The focus of the present research was to establish a paleoclimatic study of a region using the laminae width of speleothems. This research was conducted to answer the following questions:

- 1) Are speleothem growth trends, as indicated by laminae widths, consistent within different caves of the same geographical region?
- 2) Are speleothem laminae widths an indicator of paleoclimate over the course of the Holocene in the study area?
- 3) Are cycles of growth present in the speleothems?
 - a) If so, what is their periodicity?
 - b) What causes the cycles?
- 4) How do the derived growth trends in the speleothem compare to known proxies of paleoclimate?

General methods used in addressing academic questions:

(Details of each procedure are given in each respective relevant section.)

- 1) The Burren District, County Clare, Ireland, an area covering approximately 800 km² with established paleoclimatic proxies such as peat and dendrochronology, was chosen as a field site. Speleothem samples were gathered from a variety of caves in the region.
- 2) TIMS dating and laminae counts from confocal laser macroscopic images were used to determine if laminations are annual.
- 3) Upon identification of annual banding, speleothem band chronologies were established using the widths of the bands as well as their number as growth proxies.

- 4) Speleothem chronologies were compared to determine if the speleothems show a similar pattern of growth during the Holocene and to determine if the signal is local or regional. Comparisons to other proxies were made for individual records and for composite records.
- 5) An identification of the laminae growth trends in relation to climatic oscillations and variations during the Holocene was investigated by spectral analysis and by comparing the speleothem chronology to other proxies of paleoclimatic information.

Laboratory work involving the investigation and imaging of the banding properties of two Irish samples from Aillwee and Cullaun cave was undertaken in May 1999. These samples were donated by D.C. Ford of McMaster University, Hamilton, Ontario. The samples were imaged at the University of Waterloo where the Confocal Laser Microscopy Group configured and demonstrated the use of the confocal laser microscope for digitally imaging fluorescing geological samples (Ribes, 1995). The author under the supervision of Dr Alfonso Ribes conducted imaging.

From July 1999 to August 1999, fieldwork was undertaken in the Burren District of Ireland to gather speleothem samples from four separate cave systems. This fieldwork was done under the supervision of Dr Joyce Lundberg (Carleton University) and Dr David Drew (Trinity College, Dublin). As well, the Paleoecology Centre of Queen's University in Belfast was consulted in order to gain

knowledge of the logistics and statistical methods used in constructing chronologies.

Finally, in August 1999 and again in October 1999, the samples were brought to the University of Waterloo, for final imaging using the confocal laser microscope.

1.3 Organization

This research paper is organized in the following manner: Chapter Two discusses the regional setting, geological history and Holocene climatic history of the Burren District and Ireland. Chapter Three discusses the nature of Holocene climate change, the events and the cycles. Chapter Four presents a discussion of the methodologies used in conducting research for this thesis. Chapter Five is a presentation and interpretation of the laminae chronologies with respect to correlation of the four stalagmites used in this thesis. A comparison to mire humification, sunspot records, dendrochronology and ice core data is provided. Chapter Six discusses the spectral characteristics of the chronologies and also documents findings related to the study of laminae structures in the speleothem and compares growth trends to sunspot variability. Chapter Seven synthesizes and concludes the findings of the research discussed in this thesis.

2.0 Regional and Geological Setting

“While rocks form the basis of any landscape, the very bones are visible in the Burren.”
(Drew, 1997)

2.1 Physiography

The western part of County Clare, Ireland is a karst region. Ford and Williams (1989) describe this area as one of the major carbonate outcrops in Europe. The study area lies within the boundaries of the physiographic region of Ireland known as the Burren District (Figures 2.1 and 2.2). The region is encompassed in the northwest of County Clare and is bounded by the Atlantic Ocean. As a result of the rock's solubility and secondary porosity, the Burren region is the site of many cave systems, some of which have speleothems. The Burren contains caves in all stages of formation and decay. Most are very simple vadose canyons in equilibrium with modern sea level. Cave resurgences off the coast of the Burren, which cause upwelling of calm water columns into the turbulent Atlantic Ocean indicate that the caves must have formed in equilibrium with a lower, probably glacial, sea level. Although most caves in the Burren are regarded as Late Quaternary and more commonly, post-glacial features, recent alpha dating evidence suggests that Aillwee cave could be a pre-Quaternary feature (Drew, pers. Comm. Unpublished data).

The Burren District is a plateau developed on Carboniferous strata formed 325-345 million years ago (Figure 2.1 and 2.2). Approximately 60% of the area is either bare rock outcrops or rocky pasture. The soil of the Burren, if present at all, is formed from glacial till. Human agricultural activity has deforested the area causing

massive soil erosion. The hills overlooking Galway Bay rise in tiers of cliffs and terraces where horizontal planes of weakness in the rock have been exploited by erosive groundwaters and the loosened rock has been subsequently scraped away by glaciers (Drew, 1997), (Figure 2.3). Below these terraces, massive unfractured limestone forms smooth slopes (Drew, 1997). The uppermost layer of limestone is interbedded with siliceous, chert layers. Chert does not readily dissolve in water and prevents rainwater from percolating downwards through limestone fissures. Chert is a prevalent feature within the caves of the Burren and can cause erosional, shelf-like formations (Figure 2.4). The insoluble chert layers cause occasional springs to surface, but then sink again a short distance away. These springs provide the only sources of open water in the otherwise vadose karst (Drew, 1997). Despite receiving an average annual rainfall of over 1500 mm, rivers and reservoirs remain scarce as the rain is drained into countless fissures. Only where limestone meets impermeable shale do valleys containing rivers exist.

The limestone also has smaller features visible upon close inspection. The limestone pavements are peppered with depressions and channels where acidic rainwater has been the primary influence on the selective dissolution of limestone. These small depressions, as well as clint and grike topography, serve as a refuge for small flora and fauna. This characteristic *epikarst* acts as the major feeding source of cave drip water.

2.2 Quaternary Evolution

Ireland has been affected by recurrent glaciations, of which only the last two

have been well documented. At the peak of the last glaciation (20 ka), most of Ireland and much of northwest Europe were covered by ice (Figure 2.5). Maritime influences limited the grip of the ice in the southwest of Ireland where an ice-free zone existed. The environment and coastal outlines of Ireland changed substantially as the ice sheets retreated and sea levels started to rise around 12 ka (Aalen, 1997). The lowland regions have glacial deposits, which serve as the basis of productive soils in the country. Eskers and glacial till deposits are numerous and used to trace direction and conditions of ice advance and retreat (Warren, 1991).

2.3 The Munsterian and Midlandian glaciations

The Munsterian is the earliest known general glaciation (≈ 140 ka) and involved the expansion of ice from a number of centres from the middle of Ireland and advance from Wales and Scotland (Figure 2.6). An ice sheet advanced across Ulster in a southwesterly direction. This ice deposited marine fragment till (Davies and Stephens, 1978). The glaciation was more extensive than the later Midlandian ice advance. Regional ice which expanded and advanced from Cork and Kerry is known as the Greater Cork-Kerry glaciation (Davies and Stephens, 1978) (Figure 2.6).

The Midlandian glaciation (≈ 70 ka and ≈ 22 ka) repeated the pattern of glaciation from a number of different centres. It consisted of two phases of glacier advance corresponding to the Eowisconsinan (Early Wisconsinan, ≈ 70 ka) and Late Wisconsinan (≈ 22 ka) periods in North American stratigraphic units and the early Devensian and Late Devensian in British stratigraphic units (Figure 2.7). The ice

Figure 2.2: Burren District study area, Caves visited in this study are marked numerically (after Aalen, 1997).

Figure 2.3: View of Burren towards the Atlantic Ocean. The rocky limestone, characteristic of the area, is visible. Horizontally bedded, the uplands are characterized by very well developed pavements.

Figure 2.4: Chert layer shelves (protruding from limestone below caver's hands) in Faunarooska Cave.

mass was thinner and less extensive than the Munsterian glaciation. The Midlandian glaciations flowing southwest, covered the Burren but did not extend to South Clare.

During the Midlandian glaciations, regional ice advance from Cork and Kerry also occurred and is known as the Lesser Cork-Kerry Glaciation (Davies and Stephens, 1978). Regional ice also expanded and advanced from Cork and Kerry and is known as the Greater Cork-Kerry glaciation (Davies and Stephens, 1978) (Figure 2.6).

The Midlandian glaciations (≈ 70 ka and ≈ 22 ka) repeated the pattern of glaciation from a number of different centres. It consisted of two phases of glacier advance corresponding to the Eowisconsinan (Early Wisconsinan, ≈ 70 ka) and Late Wisconsinan (≈ 22 ka) periods in North American stratigraphic units and the early Devensian and Late Devensian in British stratigraphic units (Figure 2.7). The ice mass was thinner and less extensive than the Munsterian glaciation. The Midlandian glaciations flowing southwest, covered the Burren but did not extend to South Clare. During the Midlandian glaciations, regional ice advance from Cork and Kerry also occurred and is known as the Lesser Cork-Kerry Glaciation (Davies and Stephens, 1978).

The ice sheets covering the Burren played a mainly erosive role, removing the upper layers of partly weathered rock and deepening valleys and depressions. This is particularly evident where they paralleled the direction of ice movement from the northeast, during the last glaciation. Glacial deposits were laid down in the larger valleys and depressions enabling the development of deeper soils. These areas now form green islands of agriculture such as Ballyvaghan and Turlough (Figure

2.2) (Drew, 1997). Interglacial deposits provide sources of arable land for agriculture in Ireland.

2.4 Post Glacial Evolution

As the majority of caves in the Burren District are Holocene in age, the following pages trace the post-glacial climatic chronology of Ireland to provide context. This chronology has been adapted from Holland (1981) and Mitchell (1981).

15 ka: The Late Midlandian sheet began to retreat exposing glacial till and scarred outcrops.

14 ka: The climate began to shift to Woodgrange Interstadial, plant cover began to develop a tundra meadow-like aspect with prevalent sedges and grasses.

13 ka: Junipers began to appear. This tough, low-statured evergreen survived well on poor soils and thrived in the warming climate. Other plants and animals, including the Giant Deer and Reindeer also arrived, crossing land bridges from what was to become Scotland and the English mainland.

10.5-10 ka: The temperature dropped and Nahanagan Stadial began. Due to loss of food supply, primarily grasses, sedges and lichens, the Giant Deer became extinct and the Reindeer disappeared from Ireland.

Figure 2.5: Glacial maxima of Europe at 22 ka (Aalen, 1997).

Figure 2.7: Climatostratigraphic Units and marine isotope stage record of the Late Pleistocene and Holocene from marine isotope record (after Martinson *et al.*, 1987).

10 ka: The climate warmed commencing the Littletonian Warm Stage. The juniper spread and the birch appeared in large numbers for the first time. Pine, elm, and other forest trees also appeared, and Ireland began a long-term process of forestation. Other plants and animals crossed the land bridges as well. Red deer, wild boar, bear, red squirrel, pine marten, wolf, fox, stoat, and eagle and other birds of prey became established. Fish and game birds were present in abundance.

8.5-7.7 ka: Sea level rose and permanently severed the land bridges with England. Long after the connection between England and Ireland was disrupted, England was still a peninsula of Europe, and so the migration of plants and animals moving northward into the lands abandoned by the ice continued to enter England for some time after the flow to Ireland had been cut off. As a result, England developed a much greater variety of plants and animals than Ireland.

The rise in sea level and the consequent severing of land bridges to the mainland was the result of interplay between two forces: the isostatic rebounding of the earth as the immense weight of the glacial ice was removed (isostatic recovery), and the increase in sea level (eustatic rise) resulting from the melting of that glacial ice. At first the melting ice sent waters over previously dry land, but then the lessened weight of the islands resulted in a slow rebound, forcing the encroaching water off the temporarily submerged land, in turn increasing the eustatic rise, so that eventually the lower levels connecting first Ireland and England and then England and the European continent were submerged.

8.5 ka: Human beings appeared for the first time in Ireland arriving by way of the still-existent land bridges from Scotland and England. They made their initial

appearances in the far north in the lower Bann valley near present-day Coleraine, from Scotland, and in the southwest in the Shannon estuary from England. Later they spread northeast along the coast of Antrim and followed the Bann upstream to Lough Neagh. They also settled into an industrious existence on the shore of Larne Lough just north of present-day Belfast, where they chipped flints for implements. These people, mesolithic hunter-gatherers without domestic animals or farming skills, lived for the most part along the coasts and waterways. Consequently, these early arrivals had little impact on the environment

The climate which they found upon their arrival was warmer and wetter than was prominent further inland, away from what was then the Anglo-Irish peninsula. The warming which began about 10,000 years ago was accompanied by high rainfall and high humidity. The effects of these factors were accentuated by the topography of the island. Because Ireland is bowl shaped, that is, ringed with mountains on its perimeter and with a large, low-lying interior plain, much of the drainage, as today, instead of flowing more-or-less directly into the sea, flowed into the interior where low-lying parts of the Midlands were covered by shallow lakes.

The high humidity kept much of this water, constantly augmented by the abundant rainfall, from evaporating. As the run-off from higher ground filled these lakes with mud, reeds and other water plants extended over their surfaces. As they died they formed the first layer (fen-peat) of the bogs which are so extensive in the Midlands. On top of this quaking and saturated vegetable mattress, sphagnum moss found growing conditions ideal, while other forms of vegetation, grasses and trees, found them exceedingly uncongenial. The sphagnum moss, not dependent on the

soil for its nutrients, piled itself higher above the surrounding ground level, forming raised-bogs, which dammed up natural channels for the flow of water. This, in turn, caused saturation of surrounding land and the formation of yet more bogs. As a consequence, the extensive forestation which had taken place in early post-glacial Ireland was partly reversed as the growth of the bogs pushed the forests back from their margins or submerged them, as countless examples of bog-preserved trees demonstrate.

The natural growth of the bogs was not the only force that limited or threatened the expansion of the Irish forests. Sometime between 7,500 and 7,000 years ago, a new influx of human beings occurred. Crossing the Irish Sea in boats and bringing their domestic animals with them, these Neolithic farmers were destined to have a much greater impact on the natural history of Ireland than the Mesolithic hunter-gatherers who had preceded them. They prepared their fields by either cutting down trees or more often simply girdling the trees to kill them. This latter strategy had the effect of destroying the canopy of shade afforded by the tree and allowing enough sunlight to reach the forest floor to sustain crops. Working the soil with their stone implements, these farmers worked their fields until the nutrients were exhausted, when they moved on and cleared other fields. Thus, the forests, under attack by the bogs and the farmers, began to contract on both high and low ground.

Another phenomenon also occurred which apparently had natural causes but was probably accelerated by the clearing of the forests. This was the development of blanket-bog on highlands and hillsides, principally in the wetter northern and

western parts of the island. In these areas of the island where rainfall was high and the evaporation rate was low, even soil on high and sloping ground became permanently saturated (Watts, 1971). As nutrients leached away from the surface of the soil, spores of sphagnum moss once again found a refuge, and the process of bog formation started. The clearing of these forests by farmers may well have accelerated the process in some places. Tree stumps have been found in the normal soil under some blanket bogs but not under others.

As the human residents of Ireland developed their skills, their influence on the environment increased dramatically. The arrival of the Bronze Age in Ireland around 4,000 years ago had no great effect on the island's natural history since cutting implements made of bronze, while superior to stone, still lacked the effectiveness of iron and steel. Around 1,700 years ago (300 AD), two crucial and related trends combined to increase the human impact on the environment; the widespread use of iron implements, and the introduction of more advanced methods of agriculture, including animal-drawn ploughs and ploughshares. The arrival of the Iron Age, which may have begun as early as 2,500 years ago (500 BC), and this new farming technology, vastly accelerated deforestation, which continued at a high rate until the beginning of the seventeenth century. At this time, British merchants, now part of the ruling group in Ireland, virtually stripped the island of its remaining trees. From 2500-2600 BC, an island once 80 percent forested became as treeless as the great central plains of the United States. Around the beginning of the eighteenth century a modest reversal began as British landlords reforested their estates for aesthetic reasons, and by 1850 some 3 percent of the land was tree-covered. This

percentage fell again to one percent by 1920, but in response to determined efforts by the Irish government has since climbed to four percent, a very small figure, given the natural conditions of Ireland (Holland, 1981).

Since deforestation, the characteristic Burren flora is now wildflowers, shrubs, sedges, thickets of oak, ash, hazel, and Mediterranean species. This flora is absent proximal to Lisdoonvarna (Figure 2.2), where the shales produce heavy damp soil and peat accumulations. In recent decades, reduced agricultural pressure has allowed various shrubs to invade limestone pavement and rocky pasture areas. Since prehistory, the main land use practices in the Burren have centered on agriculture. For this reason, the landscape visible today reflects the past and current pressure of agricultural demand. In 1841, the Burren area was heavily settled, with pockets of glacial drift exploited for small pastures. At present, there is a concentration of humans in a region which currently has a limited resource base (Drew, 1997). Problems such as water supply and effluent disposal are prominent as surface supply is scarce and groundwater pollution from cattle waste is serious. Anthropogenic stress has increased due to agri-tourism and the encouragement of outdoor pursuits such as caving and hiking, which inflict pressure on cave systems and floral refuges (Drew, 1997).

The Burren District is a unique environment that has been forged and altered by environmental influences and climate changes. It seems as though the post-glacial, anthropogenic influences might be the most severe of all the natural climate changes.

This chapter has illustrated the environmental changes naturally occurring in post-glacial times. The next chapter explores the nature of these changes.

3.0 Climate change and cyclicity during the Holocene

3.1 Introduction

This chapter addresses changes and cyclicity of climate conditions, with a focus on the Holocene, so that a basis for analyzing and interpreting the speleothem samples in this study is established. The last twenty years have seen the establishment of high-resolution proxy records from ice cores and ocean cores. Various oscillations have been identified from various proxies during the Late Quaternary as well as the Holocene. Given general studies of patterns of cycles and events it becomes apparent that some climatic changes are linked to cycles and some are singular events.

The last glaciation began ≈ 75 ka with the ice advance of the Early Wisconsin (Early Devensian). The climate then warmed to the Mid Wisconsin (Middle Devensian) interstadial (≈ 55 ka) and then cooled and peaked during the Late Wisconsin (Late Devensian (≈ 22 ka) (Figure 2.7). Superimposed on these large-scale oscillations are smaller-scale cycles and events, the most marked of which occurred during the Late Wisconsin.

During the last ice age between 75 ka and 14 ka, Bond Cycles operating on 10-15 ka timescales can be attributed to shifts in ocean-atmosphere temperatures. The conclusion of these cycles causing massive iceberg discharges are known as Heinrich events (Lowe and Walker, 1984). Superimposed on the Bond Cycles is evidence from ice core isotopes of temperature fluctuation with a period in the order of 1500 years (Bond and Lotti 1995). Such oscillation was also demonstrated by

evidence in the marine foram oxygen isotope records, illustrating a temperature change of up to $\approx 5^{\circ}\text{C}$ in a matter of decades. These “Dansgaard-Oeschger events”, as they have come to be known, were relatively short cycles of between 500-2000 years (Lowe and Walker, 1984).

Cyclicity and associated events seem to have characterized climate change during the glacial. However, sometimes climate change was not obviously cyclical. For example, at the end of the Wisconsin glacial, the late glacial Interstadial ($\approx 18-15$ ka) was interrupted by the Younger-Dryas cold event (Figure 3.1). The Younger-Dryas cooling caused renewed ice accumulation in the British Isles and has been termed the Loch Lomond stadial. During this period, ice caps up to 400 m thick developed in the English Lake District, North Wales and South-East Ireland (Dawson, 1994). The Younger-Dryas event does not relate to any identified cycle and is regarded as a singular event. Following the end of Termination I (Figure 2.7), the Holocene Interglacial commenced following a rapid climate change in the British Isles about 10 ka and peaked during the Hipsithermal (8000-4000 BP) (Dawson, 1992).

3.2 Holocene Cyclicity:

In general, the Holocene has had a stable climate compared with the large-scale oscillations of the glacial. Cyclicity, however, is still apparent in many records.

Climate cyclicity is potentially controlled by ocean circulation, in particular thermohaline circulation, by air circulation, particularly the North Atlantic Oscillation and by solar forcing. Of the three aforementioned controls, solar forcing

seems to be the most common. Small oscillations of temperature with periods in the order of 1000, 500 and 80 years attributed to solar climate forcing have been noted by Schove (1955) and Cole (1973) and more recently by Baker (1997). In early studies, Schove (1955) and Cole (1973) mathematically calculated occurrence of sunspot cycle activity and linked this cycle to climatic variability. Recently, Baker (1999) solidified the climate/sunspot relationship by reporting the emergence of solar cycles evident in luminescent banding in a Scottish stalagmite, with a periodicity of 80-125 years. It is thought that this may correlate with solar output variations, or more specifically the Gleissberg Cycle of solar activity which has a periodicity of 80-120 years (Frick *et al.*, 1997). The Gleissberg Cycle is thought to be a modulating factor of the 11-year sunspot cycle which possesses a considerable potential to accumulate an effective surplus of irradiance. The Gleissberg Cycle consists of seven sunspot cycles. Recent minima in the Gleissberg Cycle emerge in the years 1670, 1810 and 1895 AD. Each of these sunspot minima coincides with cool climate in the Northern Hemisphere; the deeper the level of solar activity fell, the lower the temperatures sank. Schove (1955) and Cole (1973) describe a cycle of 554-560 years of solar irradiance as affecting temperatures and humidity. This cycle consists of two Gleissberg Cycles as well as two 78-year cycles of humidity.

Cycles of productivity ranging between 200-300 years have been identified in the Antarctic peninsula from sediment cores for the last 3700 years. Spectral analysis of foram assemblages from Venezuela also demonstrate spectral peaks at 200 and 136 years (Leventer *et al.*, 1996). This productivity has been attributed to solar forcing and is believed to be related to sunspots. Discontinuous time series,

primarily from glacial moraines, point to a 200-300 year periodicity in high northern latitudes. Frequencies of 92 and 202 years have been observed in Scandinavia from tree ring activity (Leventer *et al.*, 1996). Evidence of solar forcing of climate also appears in the GISP2 ice core in which the timing of $\delta^{18}\text{O}$ and $\delta^{14}\text{C}$ fluctuation has been shown to have a solar component and periods of 420, 200 and 140 years. (Stuiver *et al.* 1997).

Variations in ocean circulation are another factor which has been identified as an influence on climatic cycles. Moberg (1997) discusses a 22.8-year spectral peak cycle in temperature fluctuation from Stockholm historical temperature records. This 22.8-year cycle has been attributed to sunspot cycles coupled with quasi-stable North Atlantic thermohaline circulation. Stuiver and Braziunas (1993) propose that the solar variation at 206 years is linked with an amplification influence of ocean salinity in the North Atlantic affecting the "Great Ocean Conveyor" system.

Bond and Lotti, (1995) have recently reported that the North Atlantic region has seen the effects of an influential 1500 year cycle during the Holocene, characterized by sudden cold events in the order of one century or two within the low part of each cycle. The coldest region of this cycle was about 2 °C cooler than the warmest portion, indicating a substantial shift in climate. It is not known whether these cycles extended around the world or were generally confined to the North Atlantic region.

The North Atlantic Oscillation (NAO) is another phenomenon regarded as causing cyclical climatic variation. The NAO is a large-scale alteration of atmospheric mass between the Icelandic Low and Azores High. Spectral analyses of

tree ring chronologies from northwestern Europe have indicated that oscillations with periods of 24, 8 and 2.1 years are apparent and consistent features of the NAO (Cook *et al.*, 1998).

3.3 Holocene Events

Sudden and widespread changes to cooler and less humid conditions have been noted in many parts of the world for the Holocene. The most apparent of these is a rapid cooling event at about 8.2 ka (Adams, 1999). This event saw the rise of dry, cool conditions globally lasting about 200 years before a sudden return to warmer, moister conditions. This event is visible in the Greenland ice cores, where the cooling has been interpreted as being at half the magnitude of the Younger-Dryas cooling at ≈ 11.5 ka (Figure 3.1).

Palynological records from the British Isles show that pines (*Pinus*) which had colonized the area between 9.5 and 8 ka had died out in almost all areas by 4 ka. This period is known as the Pine Decline (Pilcher *et al.* 1995). Bridge *et al.* (1990) showed clearly that the main decline was over by about 4.5 ka with the majority of decline occurring between 5.3-4.5 ka. Pilcher *et al.* (1995), mention that a single explanation for the Pine Decline is unlikely to be found but it is likely to represent a time of climate change in the British Isles.

Possibly related to the aforementioned Pine Decline, or to a later cold period, a particularly strong arid event occurred about 4000 years ago and has been noted in Northern Africa (Adams, 1999).

Figure 3.1: Composite ocean sediment and ice core proxies showing Younger-Dryas and the 8.2 ka year cooling event (after Berger, 1990 and Dansgaard *et al.*, 1989).

Climatic events of shorter duration are indicated by the narrow ring events documented in dendroclimatological studies. Narrow ring events or periods of minimal growth that can span decades have been discovered in Irish *Pinus* and *Quercus*. The dates of these events are ≈ 4.35 ka, 3.12 ka, and 1.54 ka (J, Pilcher, pers. comm.). The narrow ring events of 4.35 ka and 3.12 ka have been attributed to the eruption of the Heckla 4 and Heckla 3 volcanoes in Iceland and their effect of introducing aerosols into the atmospheric circulation causing a poor growing seasons (Baillie and Munro, 1988).

The most recent Holocene climate event is the Little Ice age. This event began during late medieval times (700 BP or 1300 AD) and ended 200 BP or 1800 AD. This may have been the most rapid and largest change in polar circulation during the Holocene (O'Brien *et al.*, 1997). The Little Ice Age began and ended suddenly according to evidence from the GRIP2 ice core.

3.4 Links to speleothem growth:

The aforementioned climate oscillations and events have in some manner affected the biological activity of flora and fauna, either through direct temperature influence or through solar intensity variance. As previously discussed, speleothem growth and luminescence are dependent on organic activity in the soil zone above the cave and drip water supply. If these climate change cycles and events altered the organic constituents and supply of cave drip water then presumably their occurrence will be recorded in the laminae of the speleothem.

4.0 Methodology

4.1 Introduction

This research consisted of field sampling and image analysis. The field work in Ireland consisted of sampling stalagmites from various caves in the Burren District of County Clare. The sampling was carried out between July and August 1999. Cave selection was based on prior investigation of geochronological laboratory records, by Dr Joyce Lundberg, of various speleothem samples at McMaster University (Hamilton, Ontario). David Drew (Trinity College, Dublin) and Derek Ford (McMaster University, Hamilton) sampled many Irish speleothem in the 1970s and 1980s. McMaster University has established a speleothem database. The database contains alpha dated ages and uranium content information which could be used to identify suitable caves with Holocene speleothem that have a uranium content of at least 1 part per million (ppm). The samples with the highest uranium contents ($> 1\text{ ppm}$) and Holocene ($< 10\text{ ka}$) in age, were selected for this study (Table 4.1).

Samples from Aillwee cave and Cullaun cave in the McMaster University collection proved to be Holocene in age and had high levels of uranium, which makes them suitable for TIMS dating. The samples still remained intact and were used for this study. The speleothem database suggested that Faunarooska, Fergus River and Glen Curran caves also had speleothem of Holocene age with high uranium content. The samples from these caves had long disappeared from

McMaster University, thus the caves were sampled for this study. The field sampling methodology was focused on collecting samples of the same size (diameter), shape and age. Sampling was done in such manner as to minimize the environmental impacts on the cave and surroundings. This was accomplished by selectively sampling in areas which were not visible from the main channel of the cave and/or by choosing stalagmites that had grown on mud banks which would erode eventually.

A trip was made to the Queen's University of Belfast to consult with Dr Jonathan Pilcher and David Brown of the Paleoecology Centre. This consultation was used to seek advice and insight into the construction of chronologies, techniques of paleoecological analysis and regional information pertaining to Ireland, especially on the dendrochronologies that they had constructed.

4.2 Sample Imaging

The data collection portion of the study consisted of cutting the speleothem along the central axis of growth. One half of the sample was sub-sampled for TIMS dating. A dentist's drill was used to sample approximately 1.5 gram sections from the base of the samples (Figures 5.1-5.4) which were dated using Thermal-ionization mass spectrometry (TIMS) U-Th series dating. The use of TIMS dating has become a well-established and accurate way of dating speleothem samples as documented by Baker (1993). Dating of the speleothem was performed by Dr Joyce Lundberg at Bergen University (Table 4.1), Norway, after the field-work sampling and prior to the analysis portion of the study

During August and October 1999, the remaining half of the samples were then polished using a polishing wheel and diamond paste to $0.25\ \mu\text{m}$. The samples were then imaged using a confocal laser microscope at the University of Waterloo (Figure 4.1). The confocal laser microscope uses an excitation laser source to strike a specimen. The resulting luminescent emission strikes a detector lens and is interpreted as an image (Figure 4.1). The samples were individually mounted onto the microscope stage and imaged using the confocal laser. Laser excitation sources were chosen based on availability and previous experimentation by Joyce Lundberg and the Confocal Laser Microscopy Group on speleothems. Initially, a blue 442 nm laser was used as the excitation source as the spectrum between 320-600 nm is known to generate a strong luminescence from organic matter (Baker, 1993b). After the first four hours of imaging the reflective mirrors being used had been burned. This eventually caused the striking laser beam to become too weak to use. A green laser at a wavelength of 532 nm and new mirrors were commissioned and used afterward. Under the laser light, the humic and fulvic acids luminesced at a ≈ 555 nm emission, causing the laminae to become more visible and readily captured digitally.

The samples were imaged at a resolution of 1024×1024 pixels, in 5×5 mm sections along the centre of the vertical axis of growth. The 5×5 mm imaged sections represent approximately 10% of the total sampleable area. It had been discovered that an increase in scanning speed caused an apparent periodicity related to aliasing. To eliminate the aliasing effect a slower scanning speed was selected. If the images along the axis of growth did not produce distinguishable banding then

Sample	Age(Ka)	$^{230}\text{Th}/^{234}\text{U}$ Act.	$^{234}\text{U}/^{238}\text{U}$ Act.	U ppm	$^{230}\text{Th}/^{232}\text{Th}$	$^{234}\text{U}/^{232}\text{Th}$	Corrected Date(Ka)
80012 Aillwee Base	5.710 +/-0.018	0.05125 (16)	1.316 (2)	0.6973	7	142	
80012 Aillwee Top	2.695 +/-0.010	0.0245 (9)	1.295 (17)	0.9397	8	327	
80019 Cullaun Base	6.457 +/-0.071	0.0577 (6)	1.088 (2)	0.0949	4	73	4.196 +/- 0.075
Fergus River GG-H Base	12.570 +/-0.26	0.109 (2)	1.227 (19)	0.5330	8	78	10.461 +/- 0.026
GC1 B Glenn Curran Base	9.166 +/-0.081	0.0809 (7)	1.106 (9)	0.8630	454	5616	

Table 4.1: TIMS dating results of Burren speleothem samples used in this research. All ratios are activity ratios. All errors are 2σ . "Corrected date" indicates a correction for detrital ^{230}Th input using an assumed initial $^{230}\text{Th}/^{232}\text{Th}$ activity ratio of 1.5.

the transect line was shifted laterally to search for more easily identifiable laminae. This was done only six times for this study.

McGarry and Baker (in press) suggest that laser technology is problematic and obsolete as porous calcite can cause scattering of the laser beam. This results in a signal that is a function of calcite porosity as well as organic content, thus skewing luminescent values. Although deemed obsolete for generic luminescent studies on poor quality samples, the use of laser imaging through a confocal system is still valuable for carefully chosen samples. The samples used in this study were gathered in a 100% humidity cave where calcite porosity from evaporation could be ruled out. As aforementioned, the samples were polished to a very high grade greatly reducing imperfections in the calcite surface. The resulting laser images showing banding were of high quality and resolution, which showed no evidence of calcite porosity or porosity scattering (Figure 1.1). It is also important to note that the luminescent intensity was not the basis of this study, rather the laser technology was used simply as an imaging tool.

4.3 Data Generation and Analysis

The digital images were enlarged and printed using a laser printer at 1200 dpi resolution. Transects were drawn onto the images and the banding number and width was measured manually. The measurement of the laminae was done similar to tree ring documentation where the band was recorded as a position from the base of the growth axis. The band width was then calculated and the bands

counted. Transects were chosen by virtue of areas where the most easily visible banding occurred. One band was defined as the distance from the top of a white band to the top of the next following white band. In sections of the images where measurements were difficult to obtain two transects were used and the average laminae width was taken to minimize measurement error (Figure 4.2). These measurements were entered into a spreadsheet application.

The information on position from the base of the growth axis had to be transformed into age for each band. Where bands are continuous, each band represents a single year added incrementally (see discussion in section 5.2). The duration of band-free intervals had to be estimated using assumptions about average growth rates. Linear growth models were constructed by using average growth rates for each respective sample to account for sections where no banding could be distinguished (Table 4.2). The average growth rates of each sample were calculated from the continuously banded sections and used to estimate gap length. Clearly, not all speleothem growth should be assumed to be linear. There is evidence to suggest that linear growth is quite common in Holocene stalagmites North-West Europe. Recently, McDermott *et al.* (1999) and Linge (1999) demonstrated linear growth in speleothems from Ireland and Norway respectively. Baker (1993b) notes a slow decrease in growth over time of a stalagmite from England, which otherwise has almost linear growth. The linear growth model is a simplistic transform function that was used in this study.

The results for each individual sample (i.e. width and age for each band) were plotted and then were compared to the other samples in overlapping time ranges as indicated by the TIMS dating. Sections of identically aged portions resulting from TIMS dating and chronology construction of each sample were compared through regression, correlation, curve fitting and spectral analysis techniques (Chapter 5 and 6). These results coupled with data from other proxies such as sunspot data, ice cores and dendrochronology served as the basis for the comparison and analysis of the chronologies (Chapter 5).

Sample	% Banded	% non-banded	# of gaps	Avg. growth/mm	Top of sample TIMS (Ka)	Actual TIMS (Ka)	Modelled basal age(Ka)
Aillwee	56	44	5	55 years/mm	2.695 +/- 0.010	5.710 +/- 0.018	5.72
Cullaun	22	78	5	37.4 years /mm	0(active when collected)	4.196 +/- 0.075(corrected)	4.032
Fergus River	13	87	7	81 years/mm	0(active when collected)	10.461 +/- 0.256 (corrected)	10.125
Glen Curran	12	88	8	62.7 years/mm	0(active when collected)	9.166 +/- 0.081	9.1542

Table 4.2: Data used to compile linear growth models. Modelled basal ages derived from speleothem laminae chronologies.

Figure 4.1: Schematic representation of the confocal Microscope/Macroscopic. Light from the laser source fills an objective lens which focuses it to a point on the focal plane. Light reflected from the focal plane will be partially reflected by the beam splitter and focused through a confocal pinhole into a detector (Ribes et al. 1999).

Figure 4.2: 2x2 mm scan of Aillwee sample at 2cm under 532 nm laser excitation source, >555 nm emission. Laminae were measured from the top of the white portion of the couplet to the top of the next white band on the luminescent images. Transects 1 and 2 are marked and variability between laminae measurements in each transect appears in graph below image. Case #1 is highlighted on the image with dark lines. Case numbers refer to the number of bands counted.

5.0 Growth Signals in Speleothem Laminae from Four Irish Caves: Presentation and Interpretation of Results

5.1 Introduction

The purpose of this section of the study is to correlate annual laminae growth trends of speleothem from four different caves. Baker (1993b) infers that absolute growth rates of different samples cannot be compared due to absolute growth rate being a function of drip flow route changes and aquifer characteristics. However, relative growth rates in a single sample vary in response to flow volumes, biological activity, temperature and other paleoenvironmental variables, which might be expected to vary regionally. In this study comparison of relative growth trends was analyzed to see if they demonstrated a regionally coherent signal.

5.2 Methods

If all samples were the same age as determined by thermal-ionization mass spectrometry (TIMS) and displayed annual banding then it is postulated that they would show the same patterns in growth. One flowstone sample and three stalagmite samples were used. They originated from the Aillwee, Cullaun, Fergus River and Glen Curran caves. In order to minimize non-climatic influences on growth such as variations in drip water supply, samples were chosen for their simple shape. Samples chosen had to be the same age, so only those that appeared to be still active were collected. Cave locations are shown in Figure 5.1 and sample sketches in Figures 5.2-5.5. Qualitatively, the samples

were compared to see if any visible patterns could be distinguished and identified. This initial identification helped find the axis of growth and to identify landmark growth events as well as facilitating scale placement. From initial qualitative observations, it appears evident that the samples have varying patterns of growth. The changes in axis of deposition in two samples where the growth had shifted to an offset axis (Figures 5.3, 5.5) show no detrital pitting or dissolutional surfaces and apparently are not hiatuses. They could be accounted for by changes in drip water supply, shifting of a mud bank on which the speleothem was growing or a combination of these and other factors (J. Lundberg, pers. comm.). Qualitatively (Figures 5.2-5.5), it appears that the samples demonstrate some variability, expressed as changes in laminae width and colour, which might indicate climatic influence. All of the polished surfaces were examined under a binocular microscope. No evidence of alteration or dissolution surfaces were found, suggesting continuous uninterrupted, growth. The samples were then imaged using a confocal laser microscope.

The testing of the growth laminae in order to establish annual occurrence was necessary in order to proceed with the study. The Aillwee (80012) sample served as a basis for this verification and future work. The sample was dated twice close to the base and top (Figure 5.2) using TIMS. The sample was then imaged and the laminae were counted in order to determine if the two methods agreed, similar to Baker (1993b). The Aillwee sample was found to have an age span of $2.69 \pm .06$ ka to $5.71 \pm .18$ ka an overall range of 2780 to 3260 years while yielding approximately 2800 bands (Figure 5.2). It was concluded that the banding in the Aillwee sample is annual. The other

samples could not be tested so easily because of the higher number of band-free gaps. When the visible bands were assumed to be annual and the length of the gaps modelled using the average growth rates, then the basal date was within the error limits of the TIMS basal dates (Table 4.2). Two of the samples had relatively high detrital contents, so the TIMS results were corrected for input of detrital thorium, according to the standard adopted by McMaster University Geochronology Laboratory where an activity ratio of 1.5 is assumed for initial $^{230}\text{Th}/^{232}\text{Th}$ activity. This correction is shown as “Corrected Date” in Table 4.1. It was concluded that all samples displayed annual banding as TIMS dates and band counting agreed (Table 4.2).

Example images of each of the samples used in the construction of the chronologies appear in Figure 5.6. Chronologies were constructed from the laminae width measurements and growth modelling (discussed in Chapter 4). To facilitate comparison all chronologies were plotted with identical age scale (Figure 5.7). From the chronologies, when the four records are aligned on the same time scale, it becomes noticeable that once these gaps are taken into account only a few sections of each respective sample overlap, in terms of time scale, with those of other samples. These overlapping portions serve as the basis for comparison of the four records.

Peat bog humification, ice core isotope, annual accumulation and dendrochronology proxy data were used for comparison of the trends visible in the speleothem chronologies. These proxies have been identified as substantial paleoclimatic archives, especially of rainfall variation and solar influenced climate oscillation (Baker *et al.*, 1998). A

composite speleothem chronology graph using all chronologies was constructed by joining previously separate banded sections and plotting them on an identical time scale.

5.3 Results:

It can be seen that all samples had comparable average laminae widths as their ranges overlap within 2σ :

Time Series Name	Average Band Width (mm)	2σ Std (mm)
Aillwee	0.024	0.022
Cullaun	0.028	0.016
Fergus River	0.032	0.018
Glen Curran	0.034	0.032

Figure 5.7 shows the laminae widths of each chronology plotted against time.

The use of varying frequencies of filters helps to identify either small scale or large-scale trends in the chronologies. A *low-pass filter* retains the long-term or low frequency variations. *High-pass filters* transmit high frequencies and block variances that have low frequencies. For example, Baker (1993b) used 11-year and 22-year (*low pass*) weighting of moving averages to emphasize sunspot activity in speleothem.

Hence, an 11-year moving average was used to filter the small variations in order to clarify trends in the inter-sample comparison (Figures 5.8-5.9). (Baker 1993). The results, visible in Figure 5.8-5.9, indicate similarities in the pattern of variation at both high (≈ 11 -year) and medium (≈ 60 -year) frequencies. The variable lags in time between each respective series when compared to another can be attributed to an “accordion” effect caused by either a miscounting or inaccurate measurement of laminae in barely visible sections.

Figure 5.1: Burren District study area. Caves visited in this study are marked numerically (after Holland, 1981).

Figure 5.2: Aillwee (80012) cave sample (visible light scan) and a sketch indicating major visible banding and sections dated by TIMS and alpha methods. The lower surface is broken and does not represent the beginning of deposition. Similarly, the upper surface is an erosional surface and does not represent the cessation of growth. Sample donated by D. Ford.

Figure 5.3: Cullaun (80019) cave sample (visible light scan) and a sketch indicating major visible banding and section dated by TIMS. The shift in deposition does not represent a hiatus, cessation of deposition or erosion. Broken basal surface is not the beginning of deposition. Sample donated by D. Ford.

Figure 5.4: Fergus River (FR-GG-H) cave sample (visible light scan) and a mapped sketch indicating major visible banding and section dated by TIMS. The base represents the beginning of natural deposition-post glacial or post Younger-Dryas. Sampled in 1999.

Figure 5.5: Glen Curran (GC1) cave sample (visible light scan) and a sketch indicating major visible banding and section dated by TIMS. Base of sample represents beginning of natural growth. Sampled in 1999.

The variable lag in the Figures 5.8-5.9 ranges from 3-15 years for a 50 to 400 year span respectively.

Despite the aforementioned lags, it can be seen that the various samples show similar patterns of peaks and troughs in laminae growth (Figure 5.8-5.9). Although the standard r^2 is very sensitive to slight offsets in curve chronology comparison, it is commonly used to express a degree of similarity.

A quantification of the correlation coefficient (r^2) between samples ranged from $r^2=0.31$ to $r^2=0.50$ for the entire respective regions of overlapped chronologies (Figures 5.8-5.9). The results of the correlations are:

Caves Compared	r^2
Aillwee/ Glen Curran	0.50
Cullaun/ Fergus River	0.41
Cullaun/ Aillwee	0.31
Glen Curran/ Fergus River	0.34

The compared sections visible in Figures 5.8-5.9 were aligned based on the results of the TIMS dating and chronology construction. There is a potential for error in correctly overlapping the sections. These correlation values and visual inspection of the overlapped chronologies illustrate the common growth trends experienced by the stalagmites in all caves.

Figure 5.6: Samples of confocal images, clockwise from top left: Aillwee (80012) .75-1.25 cm from top, Cullaun (80019) 2.75-3.25 cm from top, Glen Curran 5-5.5 cm from top, Fergus River 5.5-6 cm from top Images are 5x5 mm sections. Scratches (as visible in Fergus River image) are artifacts of polishing.

Figure 5.7: The four chronologies used in this study plotted on identical timescale.

Figure 5.8 a) and b): Sections of time overlapped chronologies compared showing correlated peaks .

Figure 5.9 a) and b): Sections of time overlapped chronologies compared showing correlated peaks. Lags in correlated peaks can be attributed to “accordion” error caused by slight deviations in growth rate affected by climatic oscillation.

This portion of research only investigates to see if the chronological records compare at smaller scales and is limited greatly by the infrequency of overlapped sections and by the lack of numerous TIMS dating sections. This study demonstrates that all four records seem to be affected by the same small and medium scale cycles.

The identification and comparison of large-scale patterns is the focus of the next stage of this study where the records were compared with other proxies of paleoclimate.

5.4 Comparison to other paleoclimatic proxies:

Ireland has been the focus of many paleoclimatic reconstructions. In order to compare and investigate long-term trends in the speleothem chronologies, proxy paleoclimate records from Ireland and similar regions of NW Europe were sought. The proxies chosen would have to show the influence of temperature and/or rainfall and/or solar activity variation as speleothem growth is affected by these factors (Baker 1993a, b). Peat bog humification, pollen cores, dendrochronology and speleothem isotopic analysis would be suitable for comparison.

Investigations into Ireland's Quaternary vegetation began in the 1930s when K. Jessen commenced a program of pollen-analytical research on Irish bogs and lake deposits (Watts, 1985). From bog investigations, more recent research has focused on pollen extraction from lake sediments.

In other regions such as Scotland, Chambers *et al.* (1997) have used blanket peat humification records and pollen analysis to construct a proxy-paleoclimate record which identifies major shifts in climate to wet periods at 3.4 ka, 2.6 ka and 1.9 ka.

Well-documented climatic fluctuations do not always appear consistently throughout Europe or, for that matter, the world. For example, it has been documented by Watts (1985) that the period between 7000 and 5100 BP is thought to be the warmest part of the interglacial in Ireland, yet the evidence in Ireland from lake or bog deposits is slight while terrestrial carbonate (tufa) deposits from England have shown the climatic optimum as being between 8000 and 4500 BP (Andrews *et al.* 1994). This discrepancy indicates the limitations of proxy use. The proxies used for comparison in this study were chosen on the basis of the type of proxy data available and geographic region of the proxy.

In order to establish the significance of seemingly climate-influenced trends in the chronologies (Figure 5.8-5.9), the paleoclimatic proxies of ombrotrophic mire cores from County Galway, Ireland were used as basis of comparison. Dendrochronology, sunspot records, ice core data and known historical climatic events were also used to identify trends in paleoclimatic activity. Blackford and Chambers (1997) have identified a sunspot-related trend in paleoclimate affecting humification of mires in Ireland (Figure 5.10), which coincides with the findings of Schove (1955) and Cole (1973). Sunspots are central portions of active regions on the solar surface. Their presence indicates convectional activity. A decrease in sunspot number as occurring during the Maunder, Spörer and Wolf minimums (Figure 5.10) has shown to have had a .5 °C cooling effect. Sunspot influencing speleothem growth is visible in the speleothem record as Baker (1998) notes that Scottish speleothem, with a TIMS dated range of 2500-0 BP, exhibited solar-influenced luminescent variability.

Blackford and Chamber's (1997) record (Figure 5.10) spans the last 1000 years and so only the Cullaun chronology could be compared to sunspot trends which correspond to the humification trends presented in peat humification records. The Cullaun chronology spans the time when the sunspot minima of the Sprer and Wolf periods occurred: ≈ 475 BP and ≈ 650 BP. The Cullaun series shows that during this period of time two periods of reduced laminae growth with widths of 0.022-0.024 mm compared to 0.026 mm occur, which correspond to the Spörer and Wolf minima in solar activity (Figure 5.10). As previously discussed, periods of cooler climate can affect organic activity in the soil layer above the cave drip site which causes an organic deficit (i.e. less luminescent intensity) in speleothem laminae. Due to lack of organic activity in soil, soil CO₂ levels would be reduced causing a lower deposition rate and thinner laminae. According to Blackford and Chambers (1997), sunspot minima influence on the peat humification record does not show the Wolf minimum due to problems of estimation of peat growth rate between ¹⁴C determinations.

The next period of time adequately covered by the speleothem chronologies is $\approx 2400 - 5200$ BP. The Aillwee series chronology contains growth spikes and lack of banding sequences which seem to correspond to the narrow tree ring event of ≈ 3129 BP and the pine decline of $\approx 5300-4500$ BP respectively (Figure 5.12). Baker (1993 a) notes that the ≈ 3129 BP narrow ring event caused by the Heckla 3 volcanic eruption in Iceland has been observed in Scottish tree rings and pollen cores and in the Greenland ice core record the event's effects spanned almost 20 years. The ice core record indicates that 60×10^6 tons of H₂SO₄ were deposited by this event. The role of acidic ash from volcanoes on

speleothem growth is not known. It has been postulated by Baker (1993) that the acidity of the ash may cause increased dissolution of limestone thereby greatly increasing subsequent precipitation of calcite. The Aillwee series (Figure 5.12) showing a significant spike in growth at the time of the Heckla 3 eruption which corresponds with the observations of Baker (1993a), who also noticed a significant growth spike in laminae widths corresponding to the timing of Hekla 3 in a British stalagmite. Other peaks of unusually rapid growth in the chronology at 3402 and 4907 BP, correspond to high sulfate concentrations in the GISP2 ice core. The general patterns of shifts to wet, cool climate at $\approx 4.0, 3.4, 2.6$ Ka as indicated in Chambers *et al.* (1997) correspond with reduced laminae growth in the Aillwee series (Figure 5.12).

From the laminae width chronologies a composite chronology was created and compared to the GISP2 $\delta^{18}\text{O}$ and annual accumulation curve. Landmark events such as the sunspot minima and Heckla 3 eruptions, as well as general growth or climate pattern as denoted by polynomial curve fitting were identified. Figure 5.13 compares the composite speleothem laminae chronology with GISP2 $\delta^{18}\text{O}$ and annual accumulation data. The general pattern of temperature fluctuation exhibited by $\delta^{18}\text{O}$ and laminae width, as traced by the polynomial curves correspond. Individual events indicated by various aforementioned proxies appear consistent in both the ice core record and the speleothem chronology.

The general pattern of laminae width and the general pattern of temperature fluctuation exhibited by δO^{18} of ice, as traced by the polynomial curves, correspond. This suggests, that temperature is the dominant control on lamina width. Individual events

confirm the dominance of temperature control; shorter periods of reduced temperature, eg: the sunspot minima and the pine decline, correspond to decreased laminae width or an absence of laminae.

Theoretically calcite growth should also be affected by water supply. There is no simple correspondence of laminal width and the general pattern of precipitation as shown by the GISP2 accumulation curve. However, in shorter time scales, water has some influence. The following table documents short-term climatic conditions and corresponding laminae widths.

Conditions from GISP δO^{18} and annual accumulation	Time Period	Laminae Width Growth
Warm and Wet	≈ 3.5 Ka	Increased Laminae Width
Warm and Dry	≈ 4.0 Ka	Decreased Laminae Width
Cold and Wet	$\approx 0.7-0.2$ Ka	Decreased Laminae Width
Cold and Wet	$\approx 5.3-4.5$ Ka	No Banding, Gap Present
Cold and Dry	≈ 3.7 Ka	Decreased Laminae Width

It can be seen that dry conditions, whether warm or cool, always give reduced laminae widths. Otherwise water supply is not limiting and temperature control dominates, cold conditions giving narrow bands and warm conditions giving wider bands. Even during the period of high precipitation in the last 1000 years the laminae are small. The conclusion is that temperature seems to govern laminae widths except during periods of drought.

5.5 Conclusion:

The fact that all samples had similar average laminae widths; Aillwee- 0.024 mm, Cullaun-0.028 mm, Fergus River-0.032 mm, Glen Curran-0.034mm (Figure 5.7) seems to contradict Baker (1993b), who suggests that growth rates cannot be compared. Growth rates in this study could be compared as a result of the sampling methodology, which sought speleothem of similar size, shapes and age. The chronologies constructed give evidence of annual laminae sequences, which are indicative of paleoclimatic activity.

Based on the identification of annual banding sequences this research sought to investigate laminae growth patterns in various speleothems. Small overlapping chronological sections were compared and correlated. This study has shown similarity between laminae growth trends from the comparisons of small sections Aillwee/Glen Curran and Cullaun/Fergus River samples (Figures 5.8-5.9). A slightly weaker relationship was yielded from Cullaun/Aillwee and Glen Curran/Fergus River sample comparisons. From Figure 5.1, it can be seen that these caves lie at a distance of up to 8.5 miles or 13.6 km from each other yet the patterns of growth are indicative of similar influence. This suggests that if the chronologies in their entirety could be compared, they would be similar as well. The inherent TIMS dating error, as well as the aforementioned, "accordion" error has skewed this relationship, due to potentially missed or miscounted bands.

The patterns of growth exhibited in the speleothem chronologies were analyzed and compared to other proxies. While self-similar, these trends also coincide and show an indication of paleoclimatic sunspot activity, singular climatic events such as volcanic

eruptions (rapid growth), with sections of narrow band growth corresponding to sunspot minima, dendrochronological evidence, sunspot data and ice core data. (Figures 5.10-5.13).

It was concluded that speleothems from various locations in the Burren District, Ireland, show similar variations of annual banding growth caused by variations in climate.

Figure 5.10: Let 1 (top) and Let 2 (middle) mire cores from County Galway, compared to sunspot records. Residual between smoothed and observed depth decay value (*rm-h*) data showing dry periods as positive and wet as negative. M= Maunder minimum; S= Spörer minimum; W= Wolf minimum. (Blackford and Chambers, 1997).

Figure 5.11: Cullaun series identifying Spörer (400-550 BP) and Wolf (600-675 BP) minima. Similarity to Figure 5.10, more specifically the sunspot data presented by Stuiver and Quay (1980) is remarkable (after Blackford and Chambers, 1997).

Figure 5.12: Aillwee series identifying possible rapid growth events and Pine Decline influence. Proxy data for Heckla 3 from Pilcher *et al* (pers. comm.) and Baker (1993a). Proxy data for Pine Decline from Bridge *et al* (1990). Proxy data for ~2600 and ~3455 BP wet periods from Chambers *et al.* (1997).

Figure 5.13: GISP 2 ice core $\delta^{18}\text{O}$ and annual accumulation compared with composite chronology from Ireland. M= Maunder minimum, S= Spörer Minimum, W=Wolf minimum. GISP2 Data courtesy: NSIDC, University of Colorado at Boulder.

6.0 Spectral Analysis of Annual Laminae in Speleothems from the Burren District, Ireland: Sunspot-Influenced Climate Oscillation

6.1 Introduction:

Speleothem laminae growth is affected primarily by precipitation and biological activity in the soil layers through which the drip water supply percolates (Baker, 1993a). Many recent studies such as Baker (1993b), Baker *et al.* (1996), McDermott *et al.* (1999), Qin *et al.* (1999) and Lauritzen and Lundberg (1999a) have documented the effects and study of paleoclimate on speleothem growth and laminae.

An increase in biological activity and temperature leads to an increase in soil CO₂ concentration causing increased dissolution and an increase in laminae width upon deposition. If climate conditions change (i.e. temperature or precipitation), the percolation of water as well as biological activity in the over-lying soil may be altered causing an effect on magnitude and constituents of drip water supply affecting laminae growth. For this reason, it is thought that the growth of laminae in the stalagmites used in this study will have been affected, albeit indirectly, by climate over the course of the Holocene. This has been shown to be the case in the previous chapter. This chapter continues the search to explain the variability of laminae widths observed by the analysis of their cyclicity.

This study involved a single Fourier spectral analysis of four speleothem laminae width chronologies from the Burren District, Ireland. The construction of the chronologies has been documented in the methods chapter. The time-series (spectral)

investigation was performed using spectral analysis as documented by Warner (1998). Spectral analysis is a means to identify trends in data which might otherwise not be visible from statistical practices such as standard curve fitting techniques. Spectral analysis is concerned with the exploration of cyclical patterns of data. The purpose of the analysis is to decompose a complex time series with cyclical components into a few underlying sinusoidal (sine and cosine) functions of particular wavelengths.

A commonly cited reference where spectral analysis is used is the nature of sunspot activity as being an 11-year cycle and multiples thereof (Bloomfield, 1976). Baker *et al.* (1998) have documented oscillations with a clear periodicity of 80-125 years in Scottish stalagmites. This trend was attributed to solar output variations and ascribed to the 80-100 year sunspot related cycle called the “Gleissberg Cycle” coupled with depression tracks of the North Atlantic Oscillation (NAO). The NAO is the major climate control in the region thus any variations from the Gleissberg cycle in the Scottish speleothem were attributed to its influence. The Qin *et al.* (1999) have used spectral analysis of speleothem laminae thickness to analyze dominant cycles that influence growth in China and note sunspot-related cyclicity as commonly found in other climate indices.

Using the constructed speleothem laminae chronologies from Chapter 5, a spectral analysis was performed to identify common cycles in each of the four speleothem samples. Through spectral analysis, a periodogram was generated which separates the entire chronology into frequency of occurrence categories. The sine and cosine values of each peak are calculated. Once significant peaks are selected then the

sine and cosine values can be programmed into a sinusoidal curve that the researcher determines from the given sine and cosine values.

This curve fits the general format of:

$$\text{Curve} = A_{\text{period}} \cos(2\pi\tau / \text{period}) + B_{\text{period}} \sin(2\pi\tau / \text{period}) + F$$

Where $\tau = x$, $\text{period} =$ value from periodogram selected as significant and $F =$ constant on y axis.

6.2 Methods

For this research, cyclical patterns affecting growth variability were sought. Initially, a spectral study on the 150-650 year continuous sections of each of the four chronologies was performed in order to identify shorter trends in growth. This was done because Baker (1993b) criticizes previous spectral work on discontinuous sections by Shopov (1989) who had assumed a constant growth rate. Baker (1993b) suggests that a constant growth rate was unlikely to be accurate and that a smaller continuous sample would suffice to prove whether a cycle is present. The identification of oscillations from small, continuous sections of the chronologies was the main focus of this research.

Secondly, the entire chronologies were analyzed with the inclusion of the band-less sections in order to identify a range for long-term trends. This was done by modeling the band-less sections as fixed periods in time with a duration respective of average annual growth (Chapter 5).

An analysis of outlying data, or minimizing extraordinarily large peaks in the chronologies was performed to investigate spectral analysis results when large events (possibly errors) were removed. The outlying data points were divided in half on the

assumption that they possibly were double laminae that had been miscounted as singular. The outliers could also be real events such as singular climatic change events, for example, volcanic eruptions which are random events not related to climate cyclicity (Chapter 5).

The identification of longer (i.e. less reliable) trends and gap propagation analysis was done to identify long-term trends in the most reliable way. A spectral analysis of the chronologies was performed joining the end points of the banding-absent sections in order to construct continuous chronologies and to investigate the results of the spectral analysis. This procedure was used to investigate the properties of the spectral analysis with respect to inclusion and exclusion of gaps or band-less sections of the chronologies. By joining the end-points within each chronology and then propagating the length of the gap or band-less sections, based on a linear model, a range (upper and lower limit) is given in which the cyclicity is likely to occur. The analysis commenced with no gap and then the gap size was increased based on the linear model to $\frac{1}{4}$, $\frac{1}{2}$, $\frac{3}{4}$, and finally the linear model gap size value. Although no substantial quantitative results can be given regarding long-term trends due to the gaps in the chronologies, short-term trends should remain consistent. This exercise was performed to investigate possible ranges in trends or cyclicity.

6.3 Results:

Spectral analysis of the data can be graphically represented in a periodogram in which cyclicity appears as peaks in data organized in strength of occurrence and

frequency of occurrence. The continuous section periodograms showing frequency of significant peaks and ages of the periods were constructed and noted (Figure 6.1). The sinusoidal functions were programmed from the periodograms and superimposed on the original time series. The periodogram was smoothed using a Tukey weighted window of 5. “Smoothing” refers to a process in which each periodogram intensity is replaced by a weighted average that includes intensity estimates for a few neighboring frequencies. The smoothing was done in order to reduce the noise of the signal and to allow only strong trends to be identified. A study on continuous sections of the chronologies was performed in order to address smaller, significant trends as deemed by the spectral analysis. It is difficult to illustrate smaller trends on the order of 10-20 years when dealing with millennial scale chronologies, so smaller continuous sections were selected in order to facilitate visual representation (Figure 6.2).

The spectral analysis of 100-600 year sections of each chronology has yielded a consistent result of an 11-year trend in growth (Table 6.1). The results are illustrated by four of the resulting periodograms (Figure 6.1). In order to show graphically how these cycles coincide with the chronological data, the analyzed sections have been superimposed with an 11-year sinusoidal curve as resulting from the spectral analysis (Figure 6.2). The 11-year signal appears quite strong and coincides with peaks in growth in all samples except Glen Curran where the signal is present but weaker. Table 6.1 and Figure 6.1 show a ≈ 80 -year trend. This coincided with the Gleissberg Cycle of solar output variability influencing speleothem growth as proposed by Baker *et al.* (1998) (Figure 6.3). The aligned end-point chronology data set was used to provide a continuous

data set to illustrate the emergence of the ≈ 80 -year cycle. The ≈ 80 -year trend plotted on the time series coincides with peaks in growth of the speleothem (Figure 6.3).

The discontinuous data only permitted for the study of short-term cycles. The detection of long-term cycles requires that longer continuous data sets be analyzed. The second portion of the spectral analysis used the full chronologies with maximum gap size as indicated by the growth model. The results confirm the two smaller cycles of ≈ 11 years and ≈ 80 years and also show some longer cycles (Figure 6.4). Two tests were required before any inferences could be drawn about the longer cycles: it had to be determined that outliers have no significant impact on the resulting spectral analysis; it had to be shown that the gap propagation technique did not skew the resulting spectral analysis.

The next analysis tested the impact of outliers on the original chronology. Outliers are visible in Figure 6.5. The limit defining an outlying point is defined as a point lying further than three times the standard deviation from the mean (Weiss, 1993). Outlying points were eliminated in all four series by dividing any outlying peak greater than three times their respective deviations in half (Figure 6.5). This was done to test the dependence of the trends emerging from the spectral analysis on outlying singular events. The individual average mean bandwidths, standard deviations and numerical outlying point definition for each series appears below.

Time Series Name	Average Band Width (mm)	Standard Deviation (mm)	Outlying point (mm)
Aillwee	0.024	0.011	≥ 0.070
Cullaun	0.028	0.0083	≥ 0.050
Fergus River	0.032	0.0088	≥ 0.056
Glen Curran	0.034	0.0158	≥ 0.081

Spectral analysis of the new data sets (Figure 6.5) indicates that the trends originally identified by the initial spectral analysis (Figure 6.4) are not dependent on outlying events and are inherent in the chronologies.

The gap propagation technique used is important. If the ends of the smaller continuous data sets are simply joined together then there is likely to be a misfit of waveforms from each section. This part of the analysis tested several configurations of gap size (No gap, $\frac{1}{4}$, $\frac{1}{2}$, $\frac{3}{4}$, and complete) between continuous segments to find the optimum. Gap propagation (optimization) was investigated on all four time series and appears to have affected the two longest trends but not the Gleissberg cycle (≈ 80) and 11-year sunspot cycle. As the gap approaches the optimum, the values for the periodogram should increase. Low periodogram values for tables 6.2b and 6.2c indicate a weak signal in the chronology. In order of decreasing reliability, the most likely cycles occurring in the speleothem are: ≈ 11 year, ≈ 80 -90 year, ≈ 200 year (less reliable) and ≈ 700 -800 (least reliable). The occurrence of the two smallest cycles in all the gap propagation analyses confirms the results of the previous analysis section.

Although logically there may be little reason to presume that the gaps occurring in the chronologies are all correctly modelled, for all samples, the results of the gap propagation test showed no evidence that the linear growth model should be rejected. In addition, the comparisons with other proxies (Chapter 5) showed that the growth models used to propagate the gaps was reasonable. The entire chronologies (based on the growth

model), inclusive of band-less sections were plotted with their respective 633-833 year trends (Figure 6.6).

6.4 Discussion and Conclusion:

Spectral analysis reveals cycles in data, which may not be distinguishable to the naked eye. The results derived from this analysis show no obvious, substantial effect of the North Atlantic Oscillation, but rather a solar component similar to the solar-forced productivity cycles discussed in Chapter 3. The elimination of outlying points in the chronologies indicates that the results of the spectral analysis are not dependent on these outlying events and that the cyclicity can be accounted for by inherent trends in the chronologies. It is interesting to note that all samples demonstrate similar patterns in cyclicity over the course of their growth. This analysis has yielded the result that over the course of the Holocene there is a cycle of laminae growth of 11 years corresponding to the established 11-year sunspot cycle. This result is perhaps the most interesting piece of evidence, as the sunspot relationship with climate and speleothem laminae growth seems confirmed. During periods of decreased incoming solar radiation, as observed in periods such as the Maunder minimum (Chapter 5), global temperatures are thought to drop $<0.5^{\circ}\text{C}$ affecting precipitation and humidity (Baker, 1999).

The second spectral analysis used the entire chronologies, including portions of the samples where no banding existed. The spectral analysis has indicated trends of ≈ 11 and ≈ 80 years in growth as well as longer oscillations of 180-222, and 633-833 years that have affected the growth of speleothems in the Burren District. The gap propagation

analysis indicated that the long-term trends varied in length as the gap was propagated closer towards joining the end points yet the ≈ 11 and ≈ 80 year trends remained. The ≈ 11 and ≈ 80 year trends complement and support Baker *et al.* (1999) identification of sunspot activity and their multiple cumulative effect, and the Gleissberg Cycle, as influences on speleothem growth. It is believed, due to slight skewing of ages from errors in measurements, that the cycles correspond to the Gleissberg Cycle of solar activity, which has a periodicity of between 80-120 years. Baker (1999) similarly noted that speleothems from Northern Scotland demonstrated this cycle.

Schove (1955) has described a cycle of 280 years of solar activity which is simply two Gleissberg Cycles plus 78 years. There are indications that this cycle of 78 years is a cycle of humidity, when coupled with the Gleissberg cycle.

The longer 633-833 cycle is not strongly supported by these data and cannot be explained simply. Stuiver and Braziunas (1989) have indicated that the Sun's convective zone has an oscillary mode of ≈ 420 years. Cole (1973) derived a cycle of 560 years, which is simply a double of his previous value of 280 years derived from the Gleissberg sunspot cycle coupled with a cycle of humidity. Schove (1955) has estimated the interval between intense solar maxima is 554 years. These values presumably correspond to the underlying cycle of 633-833 years, which has been yielded by the spectral analysis of the Irish speleothem samples. Less confidence should be placed on the longer-term trend as gaps in data, as demonstrated in gap propagation analysis, can pose problems.

In summary, from the spectral analysis of the speleothem laminae it becomes apparent that the lamination sequences and their width are indicative of regional

paleoclimatic activity and influences and coincide with previous research and proxies of paleoclimate. The study of smaller continuous sections of each chronology indicates a strong periodicity of 11 years, which coincides with the well-regarded sunspot cycle. The appearance of a 80-90 Gleissberg Cycle and ≈ 11 -year sunspot cycle also affirms the role of sunspot activity, warming and cooling and biological activity on the growth of speleothem. Baker (1999) has noted the role of the NAO and its southward shift of northern hemisphere depression tracks, as being a control on precipitation. Baker's (1999) study attributes this southerly shift as possibly influenced by solar output, identical to the periods determined in this study. Gap propagation (Table 6.2 a-d) indicates that long-term trend range will vary according to how the gaps are modeled. This is consistent with Baker (1993b). The gap length chosen from the linear model has proven to be quite reasonable.

**Table of Results for Continuous Sections
Analysis**

Sample Name	Age of Section Analyzed (Ka)	Trend Wavelength	Periodogram value
Aillwee A	2.69- 3.32 (630 cases)	319 years	0.0086
		91 years	0.0047
		70.4 years	0.005
		11.7 years	0.003
Aillwee B	3.93- 4.64 (710 cases)	315 years	0.0081
		90.3 years	0.0043
		70.1 years	0.004
		11.5 years	0.003
Cullaun	0.412- 0.724 (312 cases)	78 years	0.0027
		22.3 years	0.001
		11.4 years	0.0016
Fergus River	5.93- 6.54 (610 cases)	203 years	0.0027
		87 years	0.0023
		11.3 years	0.0016
Glen Curran	2.46- 2.76 (274 cases)	131 years	0.091
		68.5 years	0.0112
		10.5 years	0.0015

Table 6.1: Spectral analysis results of continuous sections of chronologies used in this study. The consistent presence of the 11-year and ≈ 76 -year cycle becomes apparent.

Figure 6.1: Spectral analysis periodograms of four smaller continuous sections of chronologies used in this study (dates as seen in Table 6.1) Aillwee A periodogram appears. Series with an odd number of observations have been truncated (trunc) by one observation to become even. Similar periodicities of trends become apparent.

Figure 6.2: Continuous, smaller sections of each of the chronologies plotted with an ≈ 11 -year curve. Amplitudes vary slightly according to strength of signal in the chronology.

Figure 6.3: ≈ 80 year sinusoidal curves indicative of Gleissberg Cycle plotted with the four aligned end-point chronologies. Joined endpoint chronologies were used to help graphically represent ≈ 80 Gleissberg year cycle, as this would be difficult in a series of 200 case numbers. Wavelengths used vary slightly from Table 6.1 and Figure 6.1 due to use of spectral analysis on joined endpoint chronology.

Figure 6.4: Spectral analysis periodograms of the four entire chronologies used in this study series with an odd number of observations have been truncated (trunc) by one observation to become even. All laminae-absent sections have been included. Similar periodicities of trends become apparent.

Figure 6.5: Outlying halved time series with linear based gap propagation (same data as Figure 6.4). Spectral analysis yields that the signals remain inherent within the series even when outlying events are removed.

Description of gap propagation	Aillwee Series			
	Highest periodogram value trends			
	1st	2nd	3rd	4th
Aligned end-point (no gaps) propagation year value on periodogram	548 0.012719	137 0.003955	86 0.004739	11.6 0.0007
1/4 of original gap propagation from linear model year value on periodogram	606 0.14544	139 0.007474	90.9 0.004805	11.7 0.001655
1/2 of original gap propagation from linear model year value on periodogram	669 0.15004	143 0.007554	91 0.004338	11.3 0.000905
3/4 of original gap propagation from linear model year value on periodogram	726 0.014148	155 0.010493	87 0.003895	11.7 0.001246
Original gap propagation from linear model year value on periodogram	736 0.015184	236 0.009495	88 0.003895	11.7 0.002641

Table 6.2 a: Gap propagation analysis of Aillwee time series resulting from spectral analysis. Long-term trends vary during various gap propagations while the apparent Gleissberg Cycle and sunspot cycle remains consistent. Strongest and most reliable cycles appear in bold.

Description of gap propagation	Cullaun Series			
	Highest periodogram value trends			
	1st	2nd	3rd	4th
Aligned end-point (no gaps) propagation year value on periodogram	357 0.003849	179 0.00169	72 0.001174	10.9 0.000353
1/4 of original gap propagation from linear model year value on periodogram	357 0.003849	179 0.00169	82 0.001163	10.9 0.000353
1/2 of original gap propagation from linear model year value on periodogram	629 0.00603	209 0.001532	78 0.000689	11.8 0.000364
3/4 of original gap propagation from linear model year value on periodogram	815 0.008604	181 0.001064	67 0.000968	11.7 0.000208
Original gap propagation from linear model year value on periodogram	833 0.001563	180 0.001064	81 0.000968	11.6 0.000464

Table 6.2 b: Gap propagation analysis of Cullaun time series resulting from spectral analysis. Long-term trends vary during various gap propagations while the apparent Gleissberg Cycle and sunspot cycle remains consistent. Strongest and most reliable cycles appear in bold.

Description of gap propagation	Fergus River Series			
	Highest periodogram value trends			
	1st	2nd	3rd	4th
Aligned end-point (no gaps) propagation year value on periodogram	631 0.003059	210 0.001178	90 0.001896	11.8 0.000694
1/4 of original gap propagation from linear model year value on periodogram	725 0.004425	207 0.002226	91 0.001326	11.7 0.00065
1/2 of original gap propagation from linear model year value on periodogram	828 0.005842	331 0.004091	92 0.001533	11.8 0.00065
3/4 of original gap propagation from linear model year value on periodogram	930 0.007476	232 0.00185	84 0.001338	11.8 0.000658
Original gap propagation from linear model year value on periodogram	633 0.00321	211 0.00196	90 0.001740	11.8 0.00154

Table 6.2 c: Gap propagation analysis of Fergus River time series resulting from spectral analysis. Long-term trends vary during various gap propagations while the apparent Gleissberg Cycle and sunspot cycle remains consistent. Strongest and most reliable cycles appear in bold.

Description of gap propagation	Glen Curran Series			
	Highest periodogram value trends			
	1st	2nd	3rd	4th
Aligned end-point (no gaps) propagation year value on periodogram	631 0.001059	186 0.001228	90 0.001896	11.8 0.000692
1/4 of original gap propagation from linear model year value on periodogram	642 0.003425	191 0.002226	91 0.001326	11.7 0.00045
1/2 of original gap propagation from linear model year value on periodogram	686 0.005642	196 0.004091	92 0.001543	11.8 0.00065
3/4 of original gap propagation from linear model year value on periodogram	717 0.001476	217 0.00182	84 0.001338	11.8 0.000658
Original gap propagation from linear model year value on periodogram	742 0.00669	222 0.003562	76 0.00212	11.4 0.00132

Table 6.2 d: Gap propagation analysis of Glen Curran time series resulting from spectral analysis. Long-term trends vary during various gap propagations while the apparent Gleissberg Cycle and sunspot cycle remains consistent. Strongest and most reliable cycles appear in bold.

Figure 6.6: The chronologies with linear based modelled gap propagation used in this study, plotted with their longest trends as determined by spectral analysis.

7.0 Conclusions

7.1 Conclusion

Analysis of annual speleothem laminae in Ireland has yielded paleoclimatic results and illustrated the value of lamination studies. This study has yielded results which correspond to major known paleoclimatic events and proxies as well as coinciding with the well-documented solar cycles of Schöve (1955) and Gleissberg (1944). Although invaluable for paleoclimatic information, isotopic study of speleothem laminae is complicated and costly. Additionally, isotopic studies may not be possible for slow growing samples. Laminae analysis provides higher resolution, requires slightly less time and can be achieved at a lower cost than isotopic analysis. Speleothem laminae provide a high-resolution (annual) record of paleoclimate, which have the potential to give longer records than many other proxies such as tree-ring widths.

The major findings of this research were:

- 1) Speleothem laminae widths are high resolution proxies of soil-derived paleomoisture and paleoclimate as shown by analysis of laminae width chronologies which show climatic events and cycles;
- 2) Speleothem growth trends are consistent within different caves of the Burren District, County Clare, Ireland as demonstrated by similar patterns of growth and oscillation in overlapping-sections analysis of speleothem chronologies;
- 3) Growth trends of speleothem from the Burren District, County Clare, Ireland indicate similar climatic dependence and influence as those of peat bog

humification, Scottish speleothems (Baker 1993b), GISP2 ice core $\delta^{18}\text{O}$ and sunspot data.

- 4) Cycles of growth in speleothem from the Burren District, County Clare, Ireland have distinct periodicities, which are similar to solar cycles of sunspot variation.

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