1.1 Introduction: History and Archaeology

It is tempting to think that an historical period population, especially one so recent and from a period with a wealth of contemporary documentation, would have little to offer the archaeologist. In fact, the people who have left the best documentary evidence for their experiences and impact on the world are the great and the good, and those who had enough property to deem it necessary to keep records of how much money they have, where it came from, and where it went. The majority of what we know about individuals from the 19th century comes from their birth, marriage and death certificates, census returns, and the documents recording their monetary affairs such as the purchase of buildings, and their wills (Trickett 2006). A few have their names recorded for posterity by the newspapers of the time in terms of their achievements or crimes, and fewer still by their own publications.

This study addresses issues of diet and migration in London and Ireland during the period of the Great Irish Famine, defined by Kinealy as 1845-1852 (2006, xv). The subjects of this isotopic and historical study, the people buried in the cemetery of the Catholic Mission of St. Mary and St. Michael in Lukin Street, London, England and the Kilkenny Union Workhouse Famine cemetery in Kilkenny, Ireland (see figure 1.1) could be considered amongst the poorest socio-economic groups in mid-19th century Britain (White, 2007). In the first half of the 19th century the English and Irish poor could be almost invisible: they tended to move from place to place, over long distances to find employment, marriage or a better life, and locally as their accommodation needs changed at various stages in their lives (Hollen Lees 1979, 58f; White 2007, 35). Often illiterate, their names could be recorded with different spellings depending who wrote them down, and they rarely had enough property to bother with legal documentation for its acquisition or disposal.
Henry Mayhew may be the best known chronicler of mid-19\textsuperscript{th}-century London. He recorded his impressions of the working (and idle) men and women living in the city he knew, and noted down the replies they gave him to questions about their lives in “London Labour and the London Poor”, a series of articles written from 1849 and finally published as a collection in 1861. Charles Dickens began his writing career as a political journalist and published his first novel, “The Pickwick Papers” in 1836. His
most famous novel, “A Christmas Carol” (1843) was inspired by a visit to the mills of Manchester, England, and his desire to “strike a hammer blow” for the poor (Schlicke 1999, 98). The fiction Dickens produced is rich in the detail of the lives experienced by his characters, but the real individuals who peopled the streets of London at this time seldom appear in print. The written evidence alone, then, would not be sufficient to provide information about the lives of the invisible poor. Palmer (1990, 277), discussing the need for an archaeological approach to 19th- and 20th-century sites, wrote “written evidence about ordinary living and working conditions is rare....written evidence, then, is an asset rather than an alternative”. Archaeology in combination with the written record offers an objective way of examining the lives of these past people and their living environment.

1.1.1 The familiar past

The Industrial Revolution, a period of technological change which raised the average income of the masses (Lucas 2002, 109-110), began in Britain around 1760, and precipitated the movement of people to urban centres of industry. Against a background of social dislocations and emerging class structure, archaeology is one of the few ways we can challenge the stereotypes of the period (Lawrence 2006, 309f). Tarlow and West (1999) who entitled their book “The Familiar Past” encapsulate the problems associated with 19th- and 20th-century domestic archaeological sites: the study of the living conditions, culture, and customs of the post-Medieval period has been largely carried out by social historians (Lawrence 2006, 308). While industrial buildings and more recently institutions have been recorded (Tarlow and West 1999), until recently there was little attention paid by archaeologists to the recording and analysis of the material culture of the 19th and 20th centuries. The sheer quantity of material that remained was seen as is mere “overburden” which can be swept away when urban sites are redeveloped (Lawrence 2006, 308). However, the careful evaluation of the artefacts and detritus of the more recent past can allow us to make sense of the written record. Lawrence (2006, 314) suggests a “clear and explicit strategy” for the sampling of, and sensitive preservation of, artefacts and architecture of the period. If this opportunity is missed, there is a real danger of the loss of archaeological heritage for the post-medieval period.
The post-medieval burial record holds opportunities for students of the health and diseases of the 18th and 19th century. The large numbers of individuals in some cemeteries allows the collection of large amounts of information and because these are relatively recent burials, the preservation of the body tissues can be very good. Powers et al. (2011) and Wilson et al. (2012) discuss the need for strategies for sampling and preservation of human remains in order to preserve a small amount of what is to be reburied, and to apply modern techniques which have been developed to glean more detailed information about the lives of the individuals.

1.2 Using isotope measurements to investigate migration

Studies of migration have been transformed by the emergence of new scientific isotope techniques that allow patterns of mobility to be reconstructed. Those which examined the historic period combined scientific, artefactual and documentary evidence to great effect (Miles and Powers 2006; Montgomery and Evans 2006; Montgomery et al. 2009; Müldner et al. 2009). Such studies have the potential to improve our understanding of historical periods, and to test the validity of interpretations so that they might be applied to prehistoric periods with greater confidence. This project is a unique opportunity to use isotope analysis of teeth, bone and hair to reconstruct ‘lifeways’ for victims and survivors of an historical event: the Irish Potato Famine. Studies have shown that the diet of past populations can be reconstructed using measurement of carbon and nitrogen isotope ratios (e.g. O’Connell and Hedges 1999; Richards and Hedges 1999) from body tissues. Based on the documentary evidence which suggests differences between London and Ireland in food consumption, this thesis will investigate whether there is a difference in carbon and nitrogen isotope ratios between indigenous Londoners, first generation Irish migrants in Lukin Street, and those they left behind in the Kilkenny Union workhouse.

1.2.1 The Londoners

The cemetery at Lukin Street, Whitechapel, London, was only in use for eleven years from 1843-54. Contemporary documents suggest that the congregation contained first generation migrants: the coffin plates included Irish surnames with close links to Famine-affected areas of Ireland (Miles and Powers 2006). An important excavation in terms of size, non-conformist (Catholic) burials and the lack of disturbance by reburials, this site also falls within the last period in English history when the diet was truly local.
Londoners had access to a wide range of foodstuffs in the mid-19th century (Tames 2003), and the isotope ratios of their tissues should reflect this varied diet. Permission was granted by the Catholic Church to retain and analyse skeletal samples prior to reburial in 2009.

1.2.2 The Irish

The Irish people had a well-established tradition of migration. During the Great Irish Famine (1845-1852) many more left, arriving in Britain as a stepping stone to other destinations or settling in the major towns and cities: 108,000 settled in London during this period. Research by Hollen Lees (1979) shows that the Irish were dispersed across London and throughout the social classes, being a more varied group than early reports of Irish slums suggest. Contemporary documents suggest that the rural Irish existed on an extremely restricted potato-based diet (Clarkson and Crawford 2001). The cemetery of the Kilkenny Union workhouse (1847-1851) contained people who died during the Great Famine and who were most likely to have been reliant on the potato for their calories before the Famine (Geber 2012a). They would also have been reliant on the relief foods which were given to the inmates of the workhouses which included maize as the staple diet for a short period of about two years (Clarkson and Crawford 2001). The first Famine-period cemetery in southern Ireland to be excavated, assessed and analysed, Kilkenny Union workhouse provides a unique opportunity to establish the carbon and nitrogen isotope ratios of people whose diets were well-documented. Permission was given by the National Museum of Ireland to retain and analyse skeletal samples when the individuals were reburied in 2010.

Those who became workhouse inmates during the Great Famine would have had an extremely restricted potato-based pre-Famine diet, a short-term change in diet from a plant-based C₃ (potatoes) to a plant-based C₄ (maize), and were also subjected to the nutritional stress of the Famine. The Irish poor who survived the Famine and emigrated to London would carry the isotope ratios they have incorporated from their diet with them within their bones, teeth and hair. Should they die and be buried in a London cemetery, the measurement of these isotope ratios may be a method of distinguishing first generation Irish migrants from their London-born contemporaries.
1.3 Aims and objectives

Aim:

to characterize the bone collagen carbon and nitrogen isotope ratios of the dietary regimes consumed in mid-19th-century London and rural Ireland in order to identify Irish Famine survivors where no other evidence is available

Objectives:

an assessment of the likely dietary differences between London and Ireland will be carried out using contemporary historical documents and the work of historians of London in the 19th century or the Great Irish Famine.

bone collagen, dentine collagen and hair keratin from individuals from both cemeteries will be measured for carbon and nitrogen isotope ratios in order to compare the two populations and identify individuals who may have migrated to London.

Aim:

to improve temporal resolution for dietary changes using carbon and nitrogen isotope analysis of recovered skeletal tissues

Objectives:

the isotope ratios of adult bone collagen will be compared with juvenile bone collagen to establish the effect of bone turnover rates on dietary changes.

to carry out measurement of carbon and nitrogen isotope ratios in bone, dentine and hair which form at different times of life to establish “lifeways” for individuals.

to develop a technique to employ high-resolution isotope data from dentine to produce a dietary history during childhood.

Aim:

to investigate whether nitrogen isotopes in incremental dentine sections can identify physiological changes such as nutritional stress in children living through the Famine period
Objectives:

1. To produce profiles for changes in carbon and nitrogen isotope ratios for individuals who are known to have lived during the Famine and thus identify any changes in the nitrogen isotope ratios which are unrelated to dietary changes.

2. To compare dentine collagen nitrogen isotope profiles from individuals from both cemeteries and thus identify differences which can be attributed to nutritional stress.

3. To compare dentine collagen nitrogen isotope profiles from the teeth of children who have died with those of children who survived, at the same age, to identify differences between victims and survivors which could be attributed to health and/or nutritional status.

Resolving the stated aims will entail placing the Lukin Street and Kilkenny Union workhouse populations in their historical context. It is hypothesized that constructing individual “lifeways” using isotope data will give insights into the connection between health, deprivation and dental and skeletal manifestations of diet.

1.4 Structure of the Thesis

1) Chapter two, historical background, will give an overview of the lifestyles and customs of the rural poor of pre-Famine Ireland. This will establish which sections of the population were likely to emigrate, and which geographical and socio-economic groups came to settle in London as a result of the Great Famine. The evidence for their diets pre-Famine and during the period of Famine relief will be analysed. The same lifestyle and dietary analysis will be carried out for the urban Londoners and the expatriate Irish Catholics who lived around the Lukin Street area. Extracts from the Reports of the Registrar General, 1838-1856, will be used to show how different aspects of the living conditions of these populations were recorded at the time, and how these factors affected their life-expectancy. The historical background of both the site at Lukin Street and Kilkenny Union workhouse will be discussed.

2) Chapter three, the isotopic investigation of diet, introduces the theory and concepts behind the measurement of carbon and nitrogen stable light isotopes in
human tissues to reconstruct diet. The challenges associated with this and the potential to identify both migrants and victims of nutritional or physiological stress will be addressed.

3) Chapter four, bone, dentine and hair, gives a brief description of the development and structure of the three tissues, and of the proteins of collagen and keratin that are extracted and measured for isotopic studies.

4) Chapter five, materials and methods, will contain information about the excavations at the two sites in London and Kilkenny, and the individuals who were sampled for this study. The methods used to prepare the tissue samples and extract collagen from bone and dentine will be detailed. A description of the instrument used to measure the isotope ratios of the human tissues, the continuous-flow mass spectrometer, is included. The development of the methods used to sample dentine incrementally will be explored in detail. The method for cleaning and analyzing the hair samples will also be given.

5) Chapter six, results, will give the data from the analyses of bone, hair and dentine.

6) Chapter seven, discussion, will use the data from this study with data from contemporary British bone collagen studies and studies from prehistoric populations to evaluate whether the research questions can be answered.

7) Chapter eight, conclusions, will draw out any aspects to the methods and data which will add to the field of dietary reconstruction in relation to migration but also to the interpretation of stress, and including any novel or unexpected findings. The potential for further work will be discussed.
CHAPTER TWO
HISTORICAL BACKGROUND

2.1 Ireland
The Great Irish Potato Famine has been extensively reported and studied both at the
time and in the 150 years since its end. The Famine (1847–1848) was the culmination of
a long period of political and social upheaval that resulted in mass emigration. The scale
of the disaster, in which at least a quarter of the population died – the approximate
figure of two million being an underestimate (O’Grâda 1999, 87) – was due to a
combination of social, economic, demographic and ‘natural’ factors. A wealth of papers
and books has been written, and to a certain extent, the evidence they contain is biased
by the writer’s perspective. Orser (1997) carried out the first archaeological excavation
of 19th century Famine-period dwellings in Ireland in rural County Roscommon making
the point that in spite of all the contemporary documents we know very little about the
rural poor.

This study does not attempt to engage with “placing the blame” for the disaster. The
evidence available has been used to judge which groups in society were likely to be
amongst the workhouse population remaining in Ireland, which groups would have
succeeded in migrating to London, and what the dietary intake of those individuals
would have been before and during the Famine period.

Clarkson and Crawford (2001) carried out a comprehensive study of the diet of the
population of Ireland over the historical period. This was invaluable and, for example,
includes accounts of the food supplied to workhouse inmates and an evaluation of the
nutritional value of the extremely restricted potato-based diet. The work of Geber
(2012a) analysing the contemporary records for the inmates and staff of Kilkenny
Union workhouse has also been invaluable in placing the individuals in their context.

2.1.1 The Great Famine

Four Green Fields by Tommy Makem (1967)

What did I have, said the fine old woman

What did I have, this proud old woman did say
I had four green fields, each one was a jewel
But strangers came and tried to take them from me
I had fine strong sons, who fought to save my jewels
They fought and they died, and that was my grief said she

Long time ago, said the fine old woman
Long time ago, this proud old woman did say
There was war and death, plundering and pillage
My children starved, by mountain, valley and sea
And their wailing cries, they shook the very heavens
My four green fields ran red with their blood, said she

What have I now, said the fine old woman
What have I now, this proud old woman did say
I have four green fields, one of them's in bondage
In stranger's hands, that tried to take it from me
But my sons had sons, as brave as were their fathers
My fourth green field will bloom once again said she.

The Great Irish Famine is still alive in the memories of those who have Irish heritage both at home and around the world. The Irish folk song “The Four Green Fields” (above) was written over 50 years ago at the height of “the Troubles” in Northern Ireland and uses the Famine as a metaphor for oppression by the English. The “fine old woman” is Ireland.

2.1.2 A Malthusian disaster

Early interpretations of the scale of emigration from Ireland and the devastating effect on the population of the potato crop failures were that this was the consequence of overpopulation and insufficient resources, due to a backward agrarian economy. The
“Conacre” system of tenant farmers paid by access to land rather than cash, and the lack of investment in the estates by the landlords appeared to be compounded by the perceived fecklessness of the labourers. The writings of the Rev. Thomas Malthus proposed that when the population exceeded resources, “Malthusian checks” (war, famine and disease), would occur seeming to predict the disaster which followed (Mokyr 1980). This view has since been challenged: comparisons with other European countries show a similar or even higher density of population at the time, and the subsequent rise in the standard of living of the survivors was due to independent economic factors rather than the loss of population (Mokyr 1980).

Famine was a regular occurrence in post-medieval, pre-Industrial Revolution Europe (Mokyr 1980; Fogel 1992). Where the population was mainly rural, any factor which reduced the quantity of food crops, whether climate, military action, or pestilence, would have a devastating effect on the prices of food and the people who relied on the crops for their calories (Clarkson and Crawford 2001). Famine was not unknown in Ireland before the 1840s, and Fitzgerald produced a table showing 26 documented subsistence crises in Ireland between 1600 and 1845 (1997, 115-122). Documentary evidence (Clarkson and Crawford, 2001,136-139) shows that the population suffered when invading English armies destroyed the crops. In the 1580s, again in 1600-1601 combined with the severe weather conditions, and in 1640-1653, there are descriptions of the physical state and extreme behaviour of the starving people. Areas of Ireland were devoid of life, the survivors leaving behind corpses where they died.

The 1720s saw beggars on the streets of Dublin, and people “every day dying and rotting by cold and famine, filth and vermin” (Dublin Clergyman Dean Swift, quoted in Clarkson and Crawford, 2001, 137). Described as the worst period before the Great Famine, the winter of 1740-41 saw “universal distress...the Rich unable to relieve the Poor” and the dead buried in fields and ditches. Sir Richard Cox, writing in west Cork, one of the areas also most affected in the 1840s, describes the difficulties of transporting bodies for proper burial: “The common practice is to let the tree lie where it falls, and if some good natured body covers it with the next ditch, it is the most to be expected” (Clarkson and Crawford, 2001, 138).

Famine also stalked the land in 1799-1800, and again after the Napoleonic war in 1816-1818 when local authorities organized soup kitchens and people were driven to use their
seed potatoes to survive (Clarkson and Crawford, 2001, 139). It is possible that the older individuals in the Kilkenny or Lukin Street cemeteries had survived the periods of deprivation in the last half century.

2.1.3 Evidence for the pre-Famine diet

One important outcome from this episode of famine in 1816-1818 was that a large number of the rural poor opted to increase their reliance upon the potato as a crop which could be grown on marginal land, with a larger yield of calories than the oats that were previously the staple crop (Clarkson and Crawford 2001).

In spite of these periods of deprivation and the extremely limited potato-based diet of the rural poor, the population of Ireland appears to have been relatively healthy and fertile, as evidenced by its rise from five million to just over eight million between 1780 and 1841 (Swift 2002, 4). A part of this rise was due to the success of the potato as a food crop; a family of cottiers (labourers) could exist on a fifth of the land required for the cultivation of oats (Hollen Lees 1979, 24) and this allowed the cottiers to subdivide their plots for their children on marriage. Early marriage and a low rate of celibacy led to a high fertility rate. The Census of 1841 shows that 10% of families were living on less than one acre of land and that up to 50% of people in the south west were landless (Cousens 1960). Most people (66%) were dependant on agriculture but although a variety of food-crops was grown commercially, most of these were exported, leaving potatoes as the chief source of food for the indigenous population.

In 1839 a survey was carried out for the purpose of devising a dietary regime for the new workhouses, in order that the food should be less attractive than the diet outside. Information was gathered about the food served in public institutions and eaten by the labouring classes in their own homes (Clarkson and Crawford, 2001, 165-167). The evidence was used in order to ensure that the food provided in the workhouses would be less appealing than the diet outside, to discourage the local population from seeing the workhouse as an attractive alternative to their usual lives. A comparison was made with the contemporary prison diet, and found that convicts were better fed than the “feckless poor” in the workhouse (Clarkson and Crawford 2001, 184-221). Table 2.1 shows a comparison of diets for Irish male labourers, gaol inmates and able-bodied male workhouse inmates, adapted from Clarkson and Crawford (2001). Pre-Famine the potato-based diets were relatively high in protein content and had the highest calorie
<table>
<thead>
<tr>
<th>Diet</th>
<th>Protein (g)</th>
<th>Fat (g)</th>
<th>Carbohydrate (g)</th>
<th>Energy (kcal)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Labourer</td>
<td>153</td>
<td>2.4</td>
<td>1123</td>
<td>4868</td>
</tr>
<tr>
<td>Labourer</td>
<td>104</td>
<td>1.6</td>
<td>780</td>
<td>3368</td>
</tr>
<tr>
<td>Labourer</td>
<td>105</td>
<td>40</td>
<td>760</td>
<td>3680</td>
</tr>
<tr>
<td>Labourer</td>
<td>82</td>
<td>87</td>
<td>590</td>
<td>3372</td>
</tr>
<tr>
<td>Inmate</td>
<td>90</td>
<td>52</td>
<td>533</td>
<td>2834</td>
</tr>
<tr>
<td>Inmate</td>
<td>95</td>
<td>43</td>
<td>859</td>
<td>4010</td>
</tr>
<tr>
<td>Inmate</td>
<td>81</td>
<td>35</td>
<td>517</td>
<td>2584</td>
</tr>
<tr>
<td>Inmate</td>
<td>82</td>
<td>37</td>
<td>531</td>
<td>2683</td>
</tr>
<tr>
<td>Inmate</td>
<td>89</td>
<td>43</td>
<td>471</td>
<td>2547</td>
</tr>
<tr>
<td>Inmate</td>
<td>90</td>
<td>40</td>
<td>462</td>
<td>2490</td>
</tr>
<tr>
<td>Inmate</td>
<td>90</td>
<td>51</td>
<td>512</td>
<td>2724</td>
</tr>
<tr>
<td>Workhouse able-bodied male</td>
<td>93</td>
<td>30</td>
<td>534</td>
<td>2666</td>
</tr>
<tr>
<td>Workhouse able-bodied male</td>
<td>79</td>
<td>35</td>
<td>419</td>
<td>2238</td>
</tr>
<tr>
<td>Workhouse able-bodied male</td>
<td>63</td>
<td>23</td>
<td>424</td>
<td>2075</td>
</tr>
<tr>
<td>Workhouse able-bodied male</td>
<td>67</td>
<td>38</td>
<td>446</td>
<td>2307</td>
</tr>
<tr>
<td>Workhouse able-bodied male</td>
<td>77</td>
<td>37</td>
<td>420</td>
<td>2249</td>
</tr>
<tr>
<td>Workhouse able-bodied male</td>
<td>81</td>
<td>34</td>
<td>448</td>
<td>2342</td>
</tr>
<tr>
<td>Workhouse able-bodied male</td>
<td>86</td>
<td>38</td>
<td>493</td>
<td>2586</td>
</tr>
</tbody>
</table>

Table 2.1 Nutritional analysis of male daily diets 1839-1904 (adapted from Clarkson and Crawford, 2001)

content. The expected daily calorie requirement for an adult male engaged in very active physical activity in 1979 was 3350 kilocalories per day. Compared with this, other than the potato-based gaol diet of 1824, the institutional diets are insufficient in calories.

Two assistant poor-law commissioners, Hawley and Burke, assessed the diet of cottiers in their district. Their surveys (see table 2.1) showed that the food available in an average household was reduced if there was a need to share it with a pig.
The potato-dominated diet was very healthy: low in fat, but containing sufficient vitamin C and protein from the potato skin and vitamins A and D from the buttermilk, the only potential dietary deficiency was that of iron. It was easy to cook: potatoes were usually boiled whole in their skins, and the skin was scraped from the top of the potato to allow the buttermilk to sink in (Kinealy 2006, 45). Evidence shows that, although some livestock were kept, usually pigs and chickens, the eggs and meat were not consumed in the household but were the only source of cash to buy items that the family needed (Gray 2006). The average Irish male was eating 12–14lb (4.5-5kilos) of potatoes per day supplemented only by oatmeal, dairy products, eggs, and, in coastal populations, fish (Litton 1994,15; O’Neill 1976, 211). This was consumed in two meals, usually breakfast and an afternoon meal, with a later supper in the longer summer days. This appears to have been a healthy diet: in 1815, army recruits from Ireland and rural Scotland were taller than their colleagues from other areas of Britain (Floud et al. 1990, 201) The contemporary Scottish diet, although based on oats rather than potatoes, had a similar high carbohydrate, low fat content (Steven 1985). In 1845, the average height of the Irish was 70 inches, compared with 68.5 inches for the English and 68 inches for the Belgians (Davis 1991 13). The restricted nature of the diet meant that the population was vulnerable when this staple food crop failed, especially since the pattern of employment of the rural farm workers meant that they did not earn cash, and so could not afford to buy alternative sources of food during periods of need (Bourke 1976 ; O’Gráda 1999).

Potato blight appeared in Europe in 1845, and was the cause of much suffering elsewhere including other areas of the British Isles (Kinealy 2006, 31-2), although the impact on populations with a more varied selection of food crops was not as marked as in Ireland. When the potato blight reached Ireland in 1847, it coincided with a five-year period of cold winters and wet summers which allowed the fungus to remain in the soil. The most common potato, ‘the lumper’, grown by the cottiers for their own table, was particularly susceptible to the blight. At first, it was felt by the British and Irish Authorities that the potato crop failure was a single event, limited to certain areas (Kinealy 2006, 32). When crops failed again the following year a crisis developed, exacerbated by the Corn Laws (introduced as the Importation Act of 1815), which restricted the import of cheap food from abroad, and the prevailing political views on
Ireland which limited the Government’s response to the growing famine (O'Neill 1976, 209f).

2.1.4 Famine relief

Early attempts by the government to provide for the destitute relied on the unpopular local workhouses and the provision of work for aid: seemingly pointless projects such as breaking rocks and building “roads which went nowhere” (Kinealy 2006, 90-104). Often, one member of the household would work on the scheme to earn the cash to feed others, but this would increase the calories required by the worker. The money allocated for these projects was expected to be repaid by the Irish ratepayers, who were themselves often cash-poor (O’Gráda 1999, 50). Fraud was suspected, with landlords favouring their tenants, and food being sold rather than reaching those in need (Kinealy 2006, 92). During the period of the Famine, grain grown in Ireland was still being exported rather than providing food for the population (O’Gráda 1999, 124). However, the popular view that, had this remained in the country the disaster would have been averted, is not borne out by the documentary evidence (Bourke 1976). As a result of the Corn Laws any attempt to interfere with the market by reducing prices or importing cheap grain from abroad was politically unacceptable in England (Bourke 1976) and provoked outrage in the newspapers of the time.

There was an attempt made by Sir Robert Peel in 1845–46 to bypass the problem and relieve the widespread famine by the importation of maize (‘Indian meal’) from America. This unfamiliar food was unpopular, difficult to process and cook: its yellow colour and effects on the intestines of the starving Irish led to it being renamed ‘Peel’s Brimstone’ (O’Neill 1976, 216). When outdoor relief was eventually provided in the form of dry food, the bureaucratic administration meant that this was susceptible to fraud, with landlords favouring their tenants, and food being sold rather than reaching those in need (O’Gráda 1999, 70f). Provision of cooked food in order to avoid such abuse meant that families had to travel to the distribution centres, often long distances, at a time when they needed to conserve calories (O’Gráda 1999, 71). Those who were reliant on the relief foods would have been fed a diet which was almost exclusively maize-based for up to two years, and workhouse documents show the introduction of this food in 1846 (Geber, 2011). Contemporary sources describe a starving population who left their homes to go to areas where they hoped to receive food and medical help.
These nutrition-depleted individuals were particularly susceptible to infectious diseases such as the lice-borne typhus and yellow fever. The doctors and clergy who worked with the destitute also suffered high levels of disease and many died as a result (MacArthur 1976, 279). There are descriptions of starving and swollen individuals that are consistent with the protein deficiency disorder kwashiorkor described in the African famines of the 20th century, and with vitamin B deficiency, known as beriberi (Shetty 2006). Other descriptions match the wasting disease which results from a prolonged low calorie diet, marasmus: Dr Maginn, coadjutor bishop of Derry described Ireland as “a land of skulls, or of ghastly spectres” (MacDonagh 1947, 292). In some areas the death rate was so high that eye-witness accounts describe people buried at the roadside where they died, or in their dwellings as burial grounds were overwhelmed (MacHugh 1976, 419f ). Most of the deaths were not due directly to the nutritional deprivation, but from the lack of ability to fight off infection (MacArthur 1976).

2.1.5 Migration: the diaspora

The Irish diaspora was just a part of the movement of populations across Europe in search of work and a better life (Hollen Lees 1979, 15; Scally 1997). With the Industrial Revolution came the opportunity for paid employment within urban centres (Fitzgerald 1997, 104), and the Registrar’s report of 1851 (post census) demonstrates the movement of the English from rural parishes to those where manufacturing was taking place. The developing markets across the Atlantic (north America and Canada) were also drawing workers from Europe (Hollen Lees 1979, 24; Scally 1997, 22). Models of migration suggest that there are many factors which influence the decision to leave home (Anthony 1997; Chapman and Hamerow 1997, 5). Some are pulled towards a new destination by a particular event, for example the gold rushes of the 1840s in both America and Australia. Some are pushed from their homes (Anthony 1997, 22-24): the Scottish Highland clearances and the Great Irish Famine being two famous examples (Watson 2001, 223-4; Kinealy 2006, 216). Often there are pioneers who will migrate first, and are then followed by family or friends who rely on the money to travel and a home and job provided by the pioneer (Hollen Lees 1979, 63, 135; Anthony 1997, 25f). The establishment of a community at the new destination will allow the migrant to feel at home more rapidly (Hollen Lees 1979, 246-7). Stepwise migration will also occur.
when migrants will move on from their first new home in search of a further improvement in their conditions (Hollen Lees 1979).

2.1.6 A reason to leave

With the 100th and 150th anniversaries of the Famine, the history of 19th-century Ireland was subject to examination by modern historians. In the 1950s, the book edited by Edwards and Williams, and its subsequent revisions (1976) were written in the light of the prevailing social climate at the end of the Second World War in Britain and the politics of a divided Ireland. While it was seen as the classic description of the Famine and its effects, some of the interpretations made in light of the contemporary ideology and medical knowledge of the mid-20th-century have been revised in new works written at the end of the century. O’Gráda (1999) and Davis (2000) use the economic and documentary evidence to interpret the effect of the Great Famine on the population of Ireland in the wider context of a country with a rapidly growing population and a well-established pattern of emigration. For example, sources disagree on whether the Irish immigrants who settled in Britain were “emigrants of despair” and those who reached America “emigrants of hope”. O’Grada (1999, 113) and MacDonagh (1976, 340) agree with this view of “poor Paddy”, while Davis (2000, 23) feels that the evidence is far more complex, with many Irish people deliberately choosing their place of settlement based on their skills and previous occupations.

Irish migration in the early 19th century was driven largely by economics: Ireland was lagging behind the other countries trading with north America and Canada. Only the major cities of Dublin and Belfast had developing industrial centres and the population density meant that this was not sufficient for local requirements. The poor were not the first to leave Ireland. Those who migrated early, especially before the Famine, were those with the resources and skills that would allow them entry into the job market in their chosen destination. Hollen Lees (1979, 53) demonstrates that those migrants to London with professional skills, often Protestant and culturally similar to the English, were moving to the districts where other professionals lived and were integrating well with their English counterparts. Craftsmen and artisans would join the social world of the London trade unions (and indeed became a very vibrant part of that movement). The rural poor, illiterate, often with Gaelic as a first language, were the least likely to find that the streets of London were paved with gold, and relied heavily on the Irish
community network (Hollen Lees 1979, 84-86) choosing to leave Ireland only when the situation at home was intolerable. The steady stream of migrants before the Famine was mostly single men and women moving for economic reasons: single men joined the unskilled workforce in the capital, while single women found a ready source of employment in domestic service. Families were much more likely to travel together during the Famine, when the situation at home was worse than the perceived risks to the children of long distance travel (Hollen Lees 1979, 51).

2.1.7 Patterns of migration

There was already a well-established pattern of seasonal Irish migrant workers to Britain: many would settle permanently and London had a well-established Irish community before the Famine. At the end of the Napoleonic war in 1815 the settlement of Irish-born soldiers in England was just a part of the estimated 50,000 emigrants per year (Swift, 2002, 3). The population of Ireland peaked at over 8 million in 1841 (Swift, 2002, 54), in spite of the considerable number of people who chose to leave Ireland to live abroad in search of a better life. The recording of the actual number leaving Ireland is probably inaccurate and complex. The prevailing culture of “exile” (Swift, 2002, 7) from their homeland meant that some migrants eventually returned home when their economic circumstances permitted. Some were forcibly repatriated from other areas of Britain when they were deemed to be destitute (Swift, 2002, 74). What is clear is that the Famine caused a huge rise in the number of people leaving Ireland: approximately one million people left between 1815 and 1845. A peak of at least one and a half million was reached between 1845 and 1851: from 1851 to 1914, a further four million emigrated (Swift, 2002, 3).

At least one quarter of all Irish emigrants settled in Britain: records for 1851 show that over a quarter of a million people left Ireland with approximately 108,000 finally settling in London, some via other cities such as Bristol. Their eventual destination was often determined by their ports of departure and arrival, by family connections in the town or city and by the availability of suitable work, whether skilled or unskilled.

Many joined the already-established Irish community in London where, by 1851, 4.6% of the population were Irish-born (Swift, 2002, 35). By 1897, 24% of the population of Whitechapel were immigrants (Powers, 2008).
2.1.8 The effect of the Famine

The severity of the famine varied across Ireland. Some districts, particularly in the north and east, were less reliant on the rural economy, with a thriving textile industry based on linen, and could afford to buy alternative foods: the population of Munster and Connaught were twice as likely to die as those of Ulster and Leinster (O’Grada 1999). In the south and west, the Catholic, Gaelic-speaking cottiers left their homes to avoid destitution, death or eviction, and clearances were common (Swift 2002, 6) (see figure 2.1).

![Figure 2.1 Record of evictions from the Mahon estate, County Roscommon for the village of Gorttoose (Gurthuse). From the Freemans Journal, April 29th 1848.](image)

Those landlords with resources often assisted their tenants in leaving the district. Some paid for their tenants’ passage from Ireland (MacDonagh 1976, 332f). The emigrants tended to follow particular routes when leaving Ireland (Cousens 1960); whilst those with the resources would travel via English ports to the Americas or Australasia, the poorest would remain in England or Scotland (Cousens 1960). Pathways were often dictated by the shipping patterns and the relative costs of travel: fares on the steam ships between Ireland and England after 1825 were low enough to encourage agricultural labourers to undertake seasonal travel (Hollen Lees 1979, 46). The establishment of the
railways in the 1840s allowed cheap fares to west coast ports such as Bristol and Liverpool. Those travelling to London are most likely to have come from the south and west of Ireland, via Cork and Bristol (Swift 2002, 27) and may be from the areas (Connaught and Munster) which experienced the worst deprivation during the Famine. There is evidence that Irish surnames found in the epigraphic records of cemetery populations (Miles and Powers 2006), some of which can be traced to particular districts, may also be a guide to the origins of the individual or their parents (Smith and MacRaild 2009) (figure 2.2).

![Figure 2.2 Map of Ireland showing distribution of Irish surnames from Lukin Street (visitireland.com, origin markers added by author)](image-url)
2.1.9 The workhouse

In England and Wales a series of Acts of Parliament since the Black Death had established a parish-based system of relief for the Poor (Fraser 2009, 39) aimed more at preventing vagrants from moving from area to area than as a means of aid for the destitute. The Elizabethan Poor Law of 1601 proposed that three classes of poor were to be treated differently. The “able-bodied” would be given work in a “house of correction” and punishment given to the “persistent idler”. The “old and infirm” should be provided with housing, but the majority of aid was given in the form of “outdoor relief”, helping those in their own homes by giving money, food and items such as clothing and blankets. This was to be funded by the wealthy of the parish. In 1723, “indoor relief” was defined as the right of a parish to make an applicant enter a workhouse and carry out tasks for no pay. Following the Napoleonic wars and a period of unrest and uprisings by agricultural labourers in England caused by poor harvests (and see section 2.6), the Amendment of the Poor Law Act in 1834 ended outdoor relief, and led to the establishment of Poor Law Unions to provide all relief via the workhouse system (Fraser 2009, 63-64).

Prior to the Act of Union in 1800, Ireland had no system of relief comparable to the Elizabethan Poor Law. The Irish Poor Law Act of 1838 was modelled on the English Poor Law Act of 1834. One hundred and thirty workhouses formed the basis of the relief system, each administered by a Board of Guardians either elected, or appointed from local magistrates. Overall the system was planned to accept up to 80,000 people for indoor relief only, and in the early years, was little used (Kinealy 2006, 28-9). By 1851, the Famine had driven four times this number into the institutions (National Archives of Ireland 2012). Guinnane and O’Gràda (2002) assessed the risk of mortality to inmates in the North Dublin Union workhouse and found that it was correlated to the state of health of the individual on entry, the distance from place of origin and the economic situation in Dublin. Those who were entering for purely economic reasons were likely to survive and leave the workhouse, which implies that as a short-term measure for the local poor, the workhouse was a successful method of relief, and healthy individuals did not catch infectious diseases while inmates. The extreme Famine conditions which drove migrants to Dublin, the sickness resulting from nutritional
deprivation and the lack of economic resources with which to feed the inmates were the true cause of the high death rate within the workhouse (Guinnane and O’Grâda 2002).

2.1.10 Kilkenny Union workhouse

Opened in April 1842, the workhouse at Kilkenny was the fifth largest in Ireland. Although the south east of Ireland was more prosperous than the southwest and west, Kilkenny was the poorest county in Leinster with the decline of the local textile industry and high long-term unemployment (Geber 2012a). Built to house 1,300 inmates, during the Famine the numbers ranged from 2,340 in July 1847 to a maximum of 4,857 in 1851. These included migrants from Cork and Limerick, who, according to the local press, were subjected to prejudice which has echoes in the treatment suffered by Irish migrants to Britain at the time (Geber 2011). Temporary camps were set up around the city, local buildings rented, and wooden sheds erected at the workhouse to accommodate the extra inmates. The living conditions were notoriously poor and resulted in the spread of infectious disease and mass deaths. Often the destitute had to make a choice: starve outside or risk infection in the workhouse. There are contemporary descriptions of people dying on the streets as the death rate within the workhouse rose from 80 per month to a peak of 200 per month in early 1847 (Geber 2012a). In April of that year, the schoolmistress, assistant master and workhouse chaplain all died in the overwhelming typhus fever epidemic.

The regime within the workhouse remained strict throughout the Famine period. In 1848 there is a newspaper account of four men being sent to gaol for refusing to work (Geber 2011). Able-bodied adults were only permitted entry as a whole family, although orphans and the aged and infirm were permitted entry. Earl Grey’s Famine Orphan Scheme offered orphan girls from workhouses in each of the 22 counties the opportunity to emigrate to Australia (irishfaminememorial.org Anonymous 2011). From 1848-1850, 4,112 girls and young women travelled on ships with new clothes and essential items provided for a new life, and were given the opportunity to work as domestic servants on their arrival. They included 89 girls from the Kilkenny workhouse: their leaving is recorded in the workhouse minute books and the local press noted that “the most beautiful” were selected to give the best impression of Kilkenny girls to the Australians (Geber 2012 pers. comment). Most passed through the Sydney Barracks, and the website for the Famine memorial there has a database of all the ships and
women who took up the offer (irishfaminememorial.org)(2011). Some of the entries include biographies for the girls by their descendants: a poignant reminder that other workhouse inhabitants did not survive to tell their story.

2.1.11 Burials

The traditional Irish burial was seen as an essential ritual, with even the poor saving their pennies in Friendly societies to allow them a dignified funeral (Gorsky 1998). Even the poorest would want to be buried in a decent manner with a Wake held in their memory (Keneally 1998, 21). The effect of the large numbers dying and the lack of resources was the distressing departure from the usual burial practices. There were stories of undertakers using a “sliding coffin” with a removable base, so that the body could be dropped into the grave and the coffin re-used (McHugh 1976). The local Irish press report corpses being targeted by abandoned dogs (Kinealy 2006, 106), and coffins being opened by relatives to find the inhabitant not dressed or shrouded, but naked (Litton 1994, 112).

In Kilkenny the local cemeteries of St Maul’s and St Patrick’s reached capacity: a few early intramural burials had earned a reprimand for the Guardians from the Poor law Commission (Geber 2012a). However, during the typhus outbreak in 1847, there was no choice but to use the most distant corner of the workhouse grounds. To bury here was unethical and insanitary and when the Guardians purchased a plot at Hebron Road in Kilkenny their first action was to build an enclosing wall with a gate to allow consecration: when burials started here in 1851, intramural burials ceased. The minute books record the purchase of pine coffins and the archaeological evidence shows the presence of shrouds (see site report section 5.2). Dignity was maintained as far as possible (Geber 2012a). There is no direct evidence to link records from the “Minute Books” of the workhouse to individual burials, although some of the individuals were subject to post-mortem examination, and may be identifiable from the skeletal remains (Geber 2012b).

After the Famine period the presence of these burials appeared to be forgotten. This could be due to the lack of descendants of the individuals or a symptom of repression of the Famine memory (Geber 2012a). The Sisters of Mercy took over the workhouse in 1875, and in 1921 when workhouses were abolished, in common with many others it
became the local hospital. The buildings were used as a depot for the County Council from 1942, and when the re-development took place that brought the burials to light, they were incorporated into the MacDonagh shopping centre to preserve them. The individuals were re-interred with full burial rites in a purpose-built memorial garden on the site in 2010.

2.2 London

"The Mountains of Mourne" by Percy French (1896)

Oh, Mary, this London's a wonderful sight,
With people all working by day and by night.
Sure they don't sow potatoes, nor barley, nor wheat,
But there's gangs of them digging for gold in the street.
At least when I asked them that's what I was told,
So I just took a hand at this digging for gold,
But for all that I found there I might as well be
Where the Mountains of Mourne sweep down to the sea

2.2.1 Migration to London

The streets may not have been paved with gold, but an industrial city with unskilled jobs was a magnet for those whose traditional agricultural roles would no longer supply their basic needs. The London of 1900 was two and a half times larger than the London of 1800 (White 2007 3). Migrants came from local counties, remoter areas of Britain, and also from abroad. However, an urban life was not without its dangers: it was recognised at an early stage by the comparison of the Registrar’s reports for districts across England that the morbidity and mortality within towns and cities was much greater than in rural districts (Various 1838-1856) (see section 2.4.5). If the Famine was a watershed in Ireland, advancements in technology and town planning had the same effect on London in the 1850s. The development of the railway system would change the diet of Londoners once fresh food could be imported over longer distances, and the keeping of livestock and the cultivation of food was virtually eliminated from the city centre.
By as early as 1851, milk was imported to London by rail, and fish was imported to Billingsgate market from the east coast ports from the 1850s onwards (Tames 2003, 79). At the same time social reform began to change the living conditions and health of the population, with regulation and the introduction of a water and sewerage system reducing the contamination of food and water and improving sanitary conditions (White 2007).

2.2.2 Arriving in London – the local diet

Contemporary accounts of the food eaten by the poor in London suggest that this was dramatically different to that of rural south-west Ireland. London in the mid-nineteenth century had access to a range of foods – both local and imported via the Thames, by road and later by rail – limited only by ability to pay (Tames 2003, 31). Until the new railway system was established and could carry perishable food into the capital quickly enough to arrive at the markets in a fresh state, most of the residents ate locally-produced vegetables. Market gardens, established in the early 18th century by Dutch immigrants, made use of the small area available for cultivation by the use of manure and intensive cultivation (Strype 1720, 41; Hope 1990). Fruits and vegetables sold in the many markets in the capital were generally grown in these market gardens, initially within the city, and from 1796 until the 1880s in Barking to the east, as far as Ealing in the west by 1800, and along the south bank of the Thames (Tames 2003, 81f). The wealthy could and did indulge in imported treats (Hope 1990, 40; Tames 2003, 100f; Picard 2005, 192) but the most exotic imports enjoyed regularly by the lower classes were tea and sugar (Tames 2003, 79). However, it is important to remember that wheat for bread, the staple of the labourer, may have been grown in Ireland or elsewhere in the Union, although not imported from further afield because of the Corn Laws prior to 1846 (O'Neill 1976, 210). Because the overwintering of herds had been introduced at the end of the 17th century, beef was available all year round. The cattle would be driven into Smithfield market, then to city slaughterhouses and processed there (Dickson 1822-1824). It appears that livestock was kept throughout the city, with cows providing milk from back yards and even cellars (Atkins 1977 ; Picard 2005, 30). The Irish immigrant population was known to have brought with them the tradition of the “cottage pig” and indeed, Shepherd’s Bush was known as the “the pigsty of the metropolis” (Rixson 2000, 289).
W.B. Tegetmeier’s “Manual of Domestic Economy” (1858) contains suggestions for his middle-class female readers, who might be visiting the poor with an eye to improving or supplementing their diet, that have some bearing on the situation in earlier decades (Picard 2005, 180). A labourer’s daily intake should include 2lb of bread and two pints of milk. He suggests keeping a pig if possible, and lists the cheapest cuts of meat with cooking instructions (boiling rather than roasting and using bones for broth). However, cooking facilities were not always available in the homes of the very poor, and they would eat cooked food at “cookshops”, take advantage of soup kitchens provided for them, and rely on “white meats” (milk, butter and cheese) and salted fish for their protein (Hope 1990, 18, 42, 126).

Fish could be had cheaply at close of day at Billingsgate and those visiting the poor describe their dwellings as smelling overwhelmingly of fish. It was said of the East Enders of London that their babies grew up on jellied eels, often bought ready cooked and eaten with mashed potato (Hope 1990, 133) Oysters were also a cheap delicacy (Drummond and Wilbraham 1939, 309; Hope 1990, 22). Mayhew (1985, 16, 66) describes onions, ‘sparrow grass’ (asparagus) and watercress as common additions to the diet. Those in domestic service were often given part of their wages as ‘beer and tea money’ (Picard 2005, 149). Often people would drink weak ale as an alternative to the unpleasant local water (Picard 2005, 149), and tea was a small luxury which many could afford (Hope 1990, 88). Small and larger breweries were plentiful in the city (White 2007, 173). The work of Dr John Snow and others in the case of the Broad Street Pump cholera outbreak served to confirm suspicions about the unhealthy water in some areas of London (Brody et al. 2000). In this case it was due to contamination with infective organisms, but the contamination of drinking water in 19th century London via lead-lined piping, from nearby industrial processes, and of food and drink consumed from lead-glazed vessels, is well-documented (Wohl 1983; Warren 2000, 56). With their sweet taste and bright or white coloration, the use of lead compounds to improve the taste and appearance of food was widespread (Cox 1996, 291; Needleman 2004). The poor quality of fresh food being sold in London was a cause for concern. Bread flour was often also supplemented with potato flour (Hardy 1988; Hope 1990, 101). Contamination of bread with crushed bone was common in London (Cox 1996, 41) and alum in the daily loaf was blamed for chronic dyspepsia (indigestion) (Drummond and
Wilbraham 1939, 295; Hope 1990, 101). Within both Irish and English households, when food was scarce it was the custom for men, who would have had higher calorific demands, to receive meat and larger portions of food with women and children forced to live on bread, weak tea and leftovers (Wohl 1983, 12).

The development of the railway system in Britain brought about a major change to the potential source of food for Londoners. As early as 1851, milk was imported by rail to the centre of London: the majority of the capital’s milk was brought in from rural sources by the late 1860s (Atkins 1992), and the speed of transport by rail opened up new markets for fresh foods. Fish could be imported from the English east coast town of Grimsby and rhubarb from west Yorkshire (Tames 2003, 88). This importation of foods has expanded over the years, and it is possible now in London shops to buy food imported long distances by air freight, and bottled waters from many countries in the world.

2.3. The Irish in London

As discussed in section 2.2.7, the Irish migrants were a varied group including people of all profession and classes. For the purposes of this thesis, the discussion here will focus on the rural poor who were the most likely group represented in the Lukin street cemetery. Handicapped by a lack of money and skills, and immersed in a foreign language and culture in London, the Irish rural poor found urban life challenging (Hollen Lees 1979, 84-86).

2.3.1. History of Irish migrants in London

Evidence that travelling Irish were present in London comes from statutes in 1243 and again in 1413 ordering their expulsion. The first recording of Irish residents of the parish of St Giles in the Fields was in 1640 (Hollen Lees 1979, 48-49). In 1814 a group of English philanthropists counted the Irish persons in need of charity in London: they found 14,000, but estimated that this was only half, and did not account for the able-bodied.

The number of Irish-born resident in the capital in the census of 1841 was 75,000. This is three times the number of Scottish-born, and a third of the total from elsewhere in England. In the Famine period this figure rises to a peak of 109,000 in 1851, dropping slightly to 107,000 in 1861. By then 4-5% of all residents in London were Irish-born,
and this does not account for the second and third generation Irish, who are invisible to the census. Hollen Lees calculates that this would increase the numbers to approximately 156,000 in 1851, and 178,000 in 1861. In 1853, John Garwood made the point that only two English towns had a population bigger than the number of Irish Londoners. The total number of people of Irish origin in London was greater than the population of Dublin, or of Belfast, Cork and Limerick combined (Garwood 1853, 246). This influx of Irish migrants was repeated in other cities and industrial areas of Britain wherever unskilled labour was required and cheap housing available (Davis 2000).

2.3.2. Recorded origins of the migrants

The London Irish, as recorded in the more detailed census of 1861 and from London workhouse records of 1871, appear to have been mainly from western Munster (Cork) (two thirds) and eastern Leinster (one quarter). Garwood certainly thought that most of the Irish came from Munster, especially Cork and Kerry (1853, 304). Mayhew (1985, 109) also states that “the great immigration in to London is from Cork”. Mayhew held the opinion that most Irish street sellers and construction workers had worked on the land before migrating and supported this by recording the histories of some of his informants:

“I had a bit o’ land yer honor, in County Limerick. Well it wasn’t just a farrum, nor what ye would call a garden here, but my father lived and died on it-glory be to God! - and brought up me and my sister on it. It was about an acre and the taties was well known to be good. But the sore times came and the taties was afflicted and the wife and me- I have no childer- hadn’t a bite nor a sup, but wather to live on, and an igg or two. I filt the Famine a-comin’. I saw people a-feedin’ on the wild green things, and as I had not such a bad take, I got Mr--- (he was the head master’s agent) to give me 28s for possession in quietness and I could some poultry I had…the wife and me walked to Dublin, though we had better gone by the “long say”, but I didn’t understand it thin, and we got to Liverpool. Then sorrow’s the taste of the worruk I could git, beyant ontce 3s for two days of harrud porthering, that broke my back half in two, I was tould, I’d do betther in London, and so Glory be to God! I have-perhaps I have!” (Mayhew 1985, 105-106)
The contrast between a turfed house on the land and the crowded tenements of the courts of London must have been stark. The health risks of moving from a rural to urban lifestyle will also have been marked (see section 2.7.4).

Families migrated in stages pre-Famine, working to send back part of their wages to pay for passage (Hollen Lees 1979, 145). During the Famine more travelled as whole families (Mayhew 1985, 155, 121). Their destinations were determined by economic costs and distance, but also by the influence of kinship and community (Garwood 1853, 258). Chains of migrants chose to go to destinations where family and friends had already established themselves. For many, the well-established community in London outweighed the financial advantages of a life independent from England in the USA (Hollen Lees 1979, 55).

2.3.3. Prejudice

Arriving in London would mean facing challenges: the first would be prejudice, not only from the English who thought the newcomers were good only for the lowest of menial jobs (Hollen Lees 1979, 94), but also from the established Irish (who called themselves “Irish cockneys”). They dubbed the new arrivals “Grecians” and complained that they were taking “the bread out of our mouths” and undercutting their wages (Garwood 1853, 303). Even County boundaries from the Old Country were re-instated in London. The area around Golden Lane (served by City Bunhill cemetery, see comparative sites chapter seven) was described as a Connaught colony, with those from Munster living elsewhere (Garwood 1853, 304).

English prejudice also saw the Irish as a group who chose to live in appalling dirty conditions, when in fact they had no economic alternative. Garwood describes the Irish community in both favourable and unfavourable terms: he found them to have high moral standards, the rate of illegitimacy to be low, and that they tried in the meanest of accommodation to make it decent (Garwood 1853, 260). However, he also describes a culture of drinking alcohol, and dependency on the support of others, the Church or the State (Garwood 1853, 310). However, this chapter of Garwood’s book is aimed at encouraging a London mission for the active conversion of Catholics to Protestantism, so may well be biased by the stereotypes of the time.
2.3.4. A place to call home

The poor in London were a mobile group, often relocating from one rented house to another while staying within a local area (Hollen Lees 1979, 59). Sometimes this was following eviction, but more likely to cope with a change in family circumstances (Hollen Lees 1979, 63). Due to the cost of rents, multiple occupancy of houses, and even of rooms, subletting from each other was the norm: such overcrowding, especially when unrelated male and female adults shared accommodation, was considered unacceptable behaviour by the English reformers (Garwood 1853, 260). Most Irish households were based on a nuclear family, parents and children; when the children were small and the mother unable to work, lodgers were also taken into the home to add to the income (Hollen Lees 1979, 64). The costs of the household budget were usually afforded by the efforts of all, with children carrying out some paid work from an early age, and women taking in home work, often sewing (Hollen Lees 1979, 88). Outside the home, the Irish males dominated the professions of costermonger (street seller), dock worker, and bricklayers’ assistants (hod carriers) (Garwood 1853, 315).

The attempts by the London authorities to clear the slum districts and improve the streets by demolition were not matched with re-housing the occupants, often exacerbating the local overcrowding as everyone tried to stay within the reduced housing stock (White 2007, 48). The Booth poverty map of 1898-99 shows that the areas around Lukin Street (then Lucas Street) still have some of the lowest rated housing, interspersed with better streets, more than four decades later (figures 2.3, 2.4).
Figure 2.3 Section from Booth Poverty map 1898-99 [http://booth.lse.ac.uk/]

- **BLACK**: Lowest class. Vicious, semi-criminal.
- **DARK BLUE**: Very poor, casual. Chronic want.
- **LIGHT BLUE**: Poor. 18s. to 21s. a week for a moderate family
- **PURPLE**: Mixed. Some comfortable others poor
- **PINK**: Fairly comfortable. Good ordinary earnings.
- **RED**: Middle class. Well-to-do.
- **YELLOW**: Upper-middle and Upper classes. Wealthy.

A combination of colours - as dark blue or black, or pink and red - indicates that the street contains a fair proportion of each of the classes represented by the respective colours.

Figure 2.4 Key for the Booth Poverty map (figure 2.3)
For a more detailed description of the seven classes of residents on the Booth Poverty map see Appendix 2.

Booth wrote a description of the Lukin Street area and its population in 1889:

“The church of St Mary and St Michael in Commercial Road...is supported by its people, who are mostly poor Irish labourers...The priests all refer to the difficulties experienced in retaining the young men...The poor Irish, who form the bulk of the Catholic population, are careless, but are naturally devout. They are rough – people are greatly helped by their connection with the police at times, and they drink a good deal.....But from day to day, these poor people are greatly helped by their connection with the Church; restrained, controlled and blessed in their rough lives by its care” (in: Miles 2013).

Settling in cheap housing in the tenements and courts in unpopular districts around the docks, the congregation for whom the mission of St Mary and St Michael was established did not live in a ghetto (White 2007, 10-11). They were distributed among the other working class communities in the area, but maintained their distinct culture by the networks they made (Hollen Lees 1979, 45). Working for Irish masters, they patronised Irish pubs, Irish businesses and political groups. They maintained close links with the Catholic Church, which often vied with the local illegal drinking clubs to entertain and retain the men (Garwood 1853, 313). Friendly societies allowed them to make savings towards important occasions such as marriages and deaths (Gorsky 1998). The records of marriages at this time show that they even chose to marry partners who had been born in the same areas of Ireland as themselves (Hollen Lees 1979, 154) to maintain the cultural links.

2.4.5. Dietary preferences

19th century migrants across the world often chose to eat familiar imported foods rather than rely on what was available locally. Evidence from faunal remains shows that Tasmanian whalers (Lawrence and Tucker 2002) and Newfoundland French fishermen (Guiry et al. 2012) still relied on imported meat rather than locally sourced food. Irish migrants to London maintained their preference for the potato as their main source of calories. The established Irish communities around Whitechapel still retained some of
their traditional potato-based diet as noted in the Registrar’s report (Various 1838-1856) (see section 2.7.2).

The Irish in London were also well known for keeping pigs. White (2007, 132) describes the living conditions of the Irish population in Whitechapel during the pre-Famine era: 14,000 Irish Catholics lived in six riverside parishes near the docks in 1816. In that year, for example, “700 Irish and 100 pigs” were living in a narrow court of twenty-four small houses (White 2007, 132). In common with the other poor Londoners, the Irish would have eaten large quantities of bread, and the cheap and readily available fish and shellfish (Drummond and Wilbraham 1939, 309).

2.4. The cemetery of the Catholic mission of St Mary and St Michael

The cemetery of the Catholic mission of St Mary and St Michael was an unusual burial ground. Before the early 19th century, most people were buried in their parish churchyard. By the middle of the 19th century, the overcrowding was so severe that bodies were frequently buried under the floorboards of churches, chapels and even school buildings, or at a shallow depth, causing a health risk to those living or working nearby. Non-conformist (i.e. not Anglican) burial grounds, away from parish churchyards, including Lukin Street and Bunhill Fields, City Road (see comparative sites, chapter seven) were relatively rare in London. Garwood makes the point in 1853 that there is “scarce a Romish burial ground” in the East End (Garwood, 309). People travelled out of the district in which they lived to be buried in the cemetery of their choice rather than the local Church of England parish churchyard. Used by the Catholic community, and for only 11 years, there were at Lukin Street none of the problems associated with many contemporary longer-established graveyards where the re-use of the land meant disturbance of earlier burials and intercutting (Miles and Powers 2006).

The problem of overcrowding in burial grounds was not confined to London. In 1845 a pressure group, the National Society for the Abolition of Burial in Towns, was formed. Although from the 1820s onwards, commercial burial grounds outside town centres attracted those able to afford to be buried in more attractive, landscaped surroundings, the Cemeteries Clauses Act of 1847 (Anonymous) enabled the construction of municipal burial grounds in an attempt to relieve the pressure on inner city cemeteries.
However, the Burial Act of 1853 (Anonymous) stated that “after a time mentioned in the Order burials in such city or town, or within such limits, or in such burial grounds or places of burial, shall be discontinued wholly” and so, in 1854, all burials in London ceased, and were moved to the newly-established municipal cemeteries on the outskirts. The proud boast of these was that the remains of a loved one could lie “undisturbed for eternity” (Murray 2007, 22), unlike the old city and town churchyards which were at the time disturbed for new burials and, in more recent years, disturbed by the re-development of inner city areas.

Restrictions on the building of Catholic churches in England were removed in 1791, but lack of resources meant that the area of south London was only served by two Catholic churches: many professed Catholics would not participate in Catholic services because of the lack of facilities and the distances involved. The building of “missions” within Catholic residential areas was the method used by Cardinal Wiseman, himself an Irish migrant, to allow the church to revive interest in the local community (Hollen Lees 1979, 174-176). The Catholic Mission of St Mary and St Michael bought land along Commercial Road in the East End in 1842. Costing £3,000, part of the plot was set aside for burials, and by the 24th July, 1843, surrounded by a substantial brick wall, the ground was consecrated (Miles and Powers 2006). Combined with the building of the large Gothic-style church in 1844, this represented a major achievement for the community of impoverished migrants. Father Kelly, in The Tablet, January 6th 1844, said of St Mary and St Michael:

“This splendid new church has doubled my congregation;...it beats hollow in beauty the finest of the [gin] palaces...and has, in the eyes of our protestant neighbours, raised this poor congregation at least fifty years in social position and consideration”(Hollen Lees 1979, 175-176).

Cardinal Wiseman continued to increase the mission work by introducing nuns to London primarily as teachers, and male orders who also ran schools for the poor (Hollen Lees 1979, 175).

The burial ground at Lukin Street was closed for new burials in 1854, and in 1856, plans of the church describe the area as a “garden”. By 2004, the area was the children’s playground at the Bishop Challoner Primary School. The area was due to be redeveloped for a building extension and test pits revealed human remains. Further
details about the site and excavation can be found in the site report in section 5.2, and in the “He Being dead yet speaketh” MOLA monograph (Miles 2013). The epigraphic evidence is discussed in conjunction with the results of the isotope analyses in chapter six.

2.5 Nutrition and undernutrition in Britain 1800-1850

If adequate nutrition is defined as the availability of all the essential dietary components required for growth, development, maintenance, repair and function of an individual, then this is subject to the factors which control those requirements. These include the individual’s activity levels, energy expenditure to maintain body temperature, diseases such as infections and parasitic disease and the frequency and duration of these, and periods of physiological stress such as growth and pregnancy (Gopalan 1992).

“Undernutrition” therefore, is a situation when the intake of nutrients is insufficient for the requirements of the individual (Shetty 2006).

The nutritional status of an individual is the result of a complex interaction between the intake of nutrients and the disease environment to which they are exposed (Payne 1992). The actual intake of food by an individual is subject to a number of factors: the prevailing local economic situation, the socio-economic status of the individual, any disease affecting appetite and absorption, and the distribution of food within the individual household (Osmani 1992b). Amartya Sen (1981) demonstrated that famine is not necessarily directly related to the lack of food precipitated by crop failure, but to the lack of “entitlement” of certain sections of society to a portion of the available food supply. Fraser (2003) argues that the combination of the social aspects of “entitlement” combined with the environmental fragility of the single-crop culture in pre-Famine Ireland were responsible for the extent and impact of the Great Famine on certain sections of the population. The “entitlement” of the poor of 19th century Britain and Ireland to the available resources is a factor in their access to adequate nutrition.

2.5.1 The effect of undernutrition on the human body

The human body will react to minimise the effects of a period of undernutrition (Osmani 1992a). In the short-term, the individual body can make changes to improve metabolic efficiency, recycle and release stored nutrients. These parameters can be returned to normal when adequate nutrition is restored. This homeostasis means that,
when viewed over a longer period, the effect on the body of this short period of
undernutrition would not be apparent (Srinavasan 1992).

In the long-term, adaptation to chronic undernutrition will result in permanent changes
in metabolic efficiency, in physical dimensions, and in behaviour. Barker (1998) shows
how nutritional deprivation \textit{in utero} can result in babies of low birth weight, with two
possible adaptations: small in length but proportional, or normal length but thin. He
further demonstrates a correlation between low birth weight and impaired glucose
tolerance in adulthood (Barker 1998) an adaptation that is favourable to the
undernourished fetus maximising glycogen stores, but damaging in a well-nourished
adult. Fogel (1986, 271f) states that “\textit{mean final height reflects the accumulated past
nutritional experience of individuals over all of their growing years including the foetal
period}”. The Darwinian model of “genetic potential”, i.e. that all groups of people in
the world, free from nutritional restraints, are capable of achieving the same physical
dimensions, has been borne out by research showing that in modern times the
differences in height between countries in the developed world have almost disappeared
(Osmani 1992b, 11). The concept of a “\textit{small but healthy}” individual, who has adapted
to survive during a chronic lack of food, assumes that the stuntin of growth has not
resulted in the impairment of function of the individual (Osmani 1992a). However,
increased adult height in modern society is a powerful predictor of upward social
mobility, reduced morbidity and increased life expectancy (Floud \textit{et al.} 1990) implying
that there is some level of impairment present in those whose genetic potential has not
been reached. A recent study of the population in the Black Death cemetery at the Royal
Mint site, London (1348-1350) has shown that low stature was associated with
increased mortality risk (DeWitte and Hughes-Morey 2012). However, no correlation
was found between low stature and those in the population who lived through the Great
Famine of 1315-1322 in England, demonstrating that the observed stunting must have
had another cause.

Undernutrition in terms of overall calorie intake is often accompanied by the lack of
essential nutrients: for example, insufficient vitamin D in the diet (or lack of sunlight)
will result in a disturbance in the mineralization of bone leading to the softened bone
and deformation which characterises rickets in children and osteomalacia in adults. In
Gaskell’s “The manufacturing population of England”(1833, 161f) a medical observer
describes the physical deterioration of the textile workers as follows: “their stature low...average height of men being five feet six inches. A very general bowing of the legs....raised chests and spinal flexures...” The description suggests a diagnosis of rickets and stunting among this group.

2.5.2 Height as a measure of undernutrition in the past

Floud at al. (1990) in their book “Health, height and history” show how the nutrition of an individual during childhood and adolescence will affect the final height of the adult. Using data from modern studies of children with adequate nutrition who are exposed to frequent infections (Floud et al. 1990, 250f), they demonstrate that not only do infections cause a loss of weight in infants, but that frequency of infections is related to stunting. Nutritional status is important in the host-response to infectious diseases, especially viral and intra-cellular bacterial diseases where the cell-mediated immunity of the host is impaired by poor nutrition. Infections are more severe where this immunity is impaired. Where nutrition is adequate, the effect on nitrogen balance in the individual is not affected (Powanda and Beisel 2003), but fever, sweating and vomiting, and especially diarrhoea will adversely affect the nutritional status of an individual. It is of note that the wealthy British children of the mid-19th century are still shorter than their modern counterparts: while unlikely to be deprived of food, they would still have been exposed to the other stresses including infections endemic in the population (Floud 1992, 236).

The recorded heights of adolescents in the last 250 years on entry to the Marine Society, The Royal Military Academy at Sandhurst and adult males on recruitment to the Armed forces are used by Floud et al. (1990) to demonstrate temporal changes in the mean height of these groups during the first half of the 19th century, but also to show that height is correlated with socio-economic status. The Marine Society of London recruited boys aged 12-17 years to serve on navy and merchant ships. Founded in 1756, its remit was to recruit boys for the Navy from the London slums, who would not have the financial ability to purchase the sea clothing they would require. Entry to their training ship on the Thames, irrespective of age, was subject to a minimum height requirement of 4ft 3ins or 129.5cm. Recruited from the very poorest sections of society, their mean height for 13-year-old recruits born in 1753-1780 was 130cm, 25.4cm less than London children measured in 1960 (Floud et al. 1990, 182). There is a marked
contrast in mean height between the Marine Society recruits and the upper class adolescents who attended the Royal Military Academy at Sandhurst (established in 1806 for boys 12-16). The Academy cadets, although short compared to modern upper class boys, were taller than the same age cohort at the Marine Society, by about 20cm (Floud et al. 1990, 178f, 225).

The temporal profile of heights for these adolescents mirrors the changes seen in the adult military recruits to the British Army in the first half on the 19th century (Floud et al. 1990, 288). The changes brought about by the mechanisation of labour affected not only the urban factory workers, but also the rural poor. During the Napoleonic wars, the wages of rural workers were elevated because of the shortage of labour: in 1815 the return of the armies from the war, compounded by the introduction of agricultural machinery such as threshing machines, which reduced the need for labour, caused a drop in rural wages. A series of acts of Parliament, culminating in the Inclosure (consolidation) Act of 1801, saw landowners removing the rights of the landless rural poor to use common land for grazing, fire-wood gathering and food production (Hindle 2003, 50-55). The now landless poor provided a ready source of labourers for the developing urban industrial economy, and in the countryside around these urban centres, the wages of farm workers remained high as landowners competed with the factory owners for workers. Some areas of England, particularly East Anglia and south-east England, were distant from such urban centres resulting in the fall of rural wages. Without the opportunity to use common land, more families relied on parish relief which was only available for local residents, effectively imprisoning families in the rural area of their birth (Hindle 2003, 62f). The “Swing” riots, which began in Kent in 1830 a month after the start of the French Revolution, followed a period of poor harvests, rising Church tithes and low demand for labour (Tomkins and King 2003, 5). Named after the fictitious leader “Captain Swing” whose name was often appended to the threatening letters sent to authority figures, the riots saw the destruction of workhouses, agricultural machinery and tithe barns when wages did not rise. The riots directly affected the landowning classes who held the right to vote for members of Parliament, and the Government imposed harsh punishment on the arrested rioters: 644 were imprisoned, 505 sent to penal colonies in Australia, and 252 sentenced to death (although only 19 were eventually hung)(www.national archives.gov.uk). While the
rioters failed to achieve much improvement in their conditions, concerns to avoid a revolution similar to that in France hastened the introduction of the Great Reform Act of 1832 which allowed any man with sufficient property to vote (www.parliament.co.uk). There is a marked rise in the mean heights of military recruits from Britain for those born around 1800, suggesting that they benefited from a post-1815 fall in food prices in England (Floud et al. 1990, 290f). The change is more marked in the adolescents, probably due to the increased rate of growth during this period of life. There is also a marked fall in the mean heights in those recruits to the British army born 1830-1850, interpreted by Floud et al.(1990) as a marker of the multi-factorial changes at this point in history in the living conditions of the poor. Compared with the Londoners, rural recruits, particularly of Scottish and Irish origins in the first half of the 19th century, were taller. The increase in working-class wages which prompted the movement of people from rural communities into urban centres such as London was accompanied by a fall in their living conditions (see Registrar’s reports 2.6.5). The high cost of rent in relation to wages meant living in overcrowded rooms which were poorly heated, damp and without sanitation. This was accompanied by a rise in infections associated with poverty, such as the lice-borne typhus, and air and water-borne infections such as tuberculosis and cholera (Chadwick 1842, 369-372). The poverty “lifecycle” discussed by Hanly (2003, 77) showed that families tended to move in and out of poverty: single adults of working age, couples during the early years of marriage, and families with working-age children were relatively prosperous. In comparison, the single elderly and families with children under working age were the most disadvantaged groups in society (Hanly 2003, 77). Poor living conditions led to a consistently high infant mortality rate as recorded pre-1837 by the Bills of Mortality (Roberts and Cox 2003). Undernourished children failed to grow and succumbed to infections. Poor nutrition in pregnancy and lack of early medical intervention in the peri-natal period was followed by inadequate and contaminated weaning foods (Thompson 1984, 128f). Children under the age of 3 years have the highest protein and energy requirements per kg of body weight (Gopalan 1992, 27-29). Infants aged 0-3 years were the most frequently affected by infections, and the most severely ill (section 2.6.6). The effects on the body of surviving this period of infancy and early childhood in working-class London would
result in the sort of growth retardation seen in the adolescent recruits of the Marine Society.

2.6 Reports of the Registrar General 1838-1856

From 1838, the Bills of Mortality, which had been used in the past to collect information about the public health status of London, were replaced by registration of all births, marriages and deaths in England and Wales. These were then collated and included as tables in the Report each year of the Registrar General. The tables record the deaths by age groups, male and female, by causes of death, and by geographical district. The London statistics are recorded separately.

Some reports contain a “Letter” from William Farr, the compiler of statistics for the General Register office of England and Wales from 1838 until 1880. A qualified medical doctor despite humble beginnings, William Farr is regarded as one of the founders of medical statistics. His use of epidemiology, discussing the registered deaths in more detail, forms part of the movement from the theory that infectious disease is caused by miasma or contaminated air, to the now universally accepted germ theory of disease. Although he originally rejected Snow’s hypothesis that cholera was a waterborne infection (Brody et al. 2000) and was an adherent to the miasma theory, by the time of the publication of Farr’s "Report on the cholera epidemic in England" in 1866, he had changed his mind, and this document was seen as conclusive proof of the germ theory of disease. Extracts from the data and additional material in the Registrar’s Reports are used in the following sections to show how they record details of the lifestyles, mortality and health of the population and in particular the Londoners.

2.6.1 Causes of death

One interesting detail is that starvation as a cause of death only appears in the first annual Register: it was deemed politically unacceptable to acknowledge that people could die from lack of nourishment, and so “privation” was the term employed in subsequent reports (figures 2.5 and 2.6). This included neglect and cold as well as lack of nutrition.
### Figure 2.5 Pages 306-7 of Registrars’ report 1838 showing starvation as a cause of death.

| CAUSE OF DEATH | 0 | 5 | 10 | 15 | 20 | 25 | 30 | 35 | 40 | 45 | 50 | 55 | 60 | 65 | 70 | 75 | 80 | 85 | 90 |
| Living         | 239,985 | 235,298 | 229,355 | 221,053 | 211,144 | 200,724 | 190,005 | 180,977 | 171,448 | 161,607 | 151,460 | 141,120 | 131,598 | 122,197 | 112,000 | 102,200 | 92,860 | 83,100 | 73,970 |
| Dying          | 1,271 | 1,271 | 1,271 | 1,271 | 1,271 | 1,271 | 1,271 | 1,271 | 1,271 | 1,271 | 1,271 | 1,271 | 1,271 | 1,271 | 1,271 | 1,271 | 1,271 | 1,271 | 1,271 |

### Figure 2.6 Description of deaths by “privation”, Registrars’ report 1841.

From excessive drinking, a female 46 years; excessive drinking of spirits, a male 27 years; apoplexy from ardent spirits, a male 50 years; excessive eating at dinner which produced a fit, and in struggling ruptured a blood-vessel in the abdomen (inquest) a male 2 years; and 2 cases of opium eating, a female 48 years and a female 53 years.

**Op Deaths Accounted to Privation, the following are selected as examples:**

- Natural death accelerated by destitution, a male 17 years; natural causes accelerated by want of proper nourishment, a female 45 years; natural causes accelerated by want and cold, 3 cases, 47, 49 and 50 years; cold and hunger, a female 74 years; natural death accelerated by great privations and inclemency of the weather, a female 46 years and a male 78 years; natural death by visitation of God, but may have been accelerated by want, a female 15 years; exposure to cold, and want of food, a male 76 years; natural death brought on by cold and exposure to the atmosphere, a male 38 years; exhaustion from exposure to cold, a male 75 years; exposure to cold, and exhaustion, a male 45 years; want of food and other necessaries, a male 34 years; scantiness of nourishment, 61 years; destitution and disease, a female 61 years; want of common necessaries of life, 2 males, aged 35 and 73 years; inflammation of the brain induced by starvation (Union Poor House), a male 20 years; starvation from not having applied to the parish for relief, a female 33 years; diarrhoea and insufficiency of food, a male 55 years; exposure to cold and wet, a female 22 years; fatigue and inclemency of the weather, a male 40 years; starvation through insanity, a female 38 years; starvation by refusing food in a state of insanity, a female 43 years; exposure to cold and wet, having under derangement of mind strayed from her home, a female 56 years; cold and exposure to the atmosphere, having fallen down in the public road, being in a state of bodily infirmity, 51 years; starvation from a spasmodic affection of the throat, a female 29 years; natural death accelerated by want of nourishment and ordinary comforts, from neglect of her husband, a female 74 years; absence of natural nutrition owing to disease of the mother, a female 8 months; defective nutrition (a nurse-child), a female 2 months; also, cases of inanition, want of breast milk, &c.
2.6.2 Dietary evidence from the Reports

In the first report, each registrar in the London districts is named and their responses recorded to such questions about the living conditions of the population in their district. The map from the 1838 report shows that the site on which St Mary and St Michael will be built is just on the edge of St George in the East (figure 2.7). The congregation was drawn from the Catholic communities in the surrounding districts. The answers from the district registrars are varied in their detail, but give an insight into the populations whose living conditions are represented in the registers (see figures 2.8 and 2.9). Unfortunately the registrar for St George in the East was unwilling to answer the questions, so we are reliant on the detail in the surrounding districts.

Figure 2.7 Detail from map in Registrar’s report of 1841 showing registration districts. The Catholic mission of St Mary and St Michael is in the district of St George in the east.
In the response to part f, “does their principal food consist of Potatoes, Bread or Butchers’ Meat?” the registrar for the Aldgate district answered “fish and potatoes” (see figure 2.9). The area is adjacent to Lukin Street, and this response is echoed by other registrars in the Whitechapel area, confirming that the diet amongst the poor was low in meat, but high in potatoes, bread and fish. An exception was the area around Whitechapel Church and the London Hospital, where the district is described as “Living well- not a very poor one.”
2.6.3 Irish migration in the Reports

The problems arising from the Irish migration are addressed within several of the reports. In the report of 1851, the mortality rate for the preceding 5 years, including the worst years of the Famine, shows that the death rate is at its highest in 1847, with over 5,000 more deaths than in any of the following years.
Figure 2.10 Table of deaths in London for the Famine years 1847-1851.

(figure 2.10). These are accounted for by a large rise in diseases of the respiratory system, and of influenza and typhus. This would correlate with the typhus epidemic seen in 1847 in Ireland. In the report for 1847, William Farr’s “Letter” to the Registrar
carries out an assessment of the political and economic factors which affected the figures that year. He noted that:

“potato disease appeared in 1845…the produce of wheat was below that of the previous 3 years”. “Ireland was thrown into a state of panic: and in England as the year advanced, the pressure on people must have been more severe than the price…of wheat implies; for the obvious reason that the lower classes who fed on potatoes, could not purchase wheat in any quantity”.

He goes on to discuss the political process that led to the repeal of the Corn Laws in 1846. He states that:

“in October large sums of money were voted by the Baronies of Ireland for Public Works…in December nearly half a million labourers were employed on the works. Great numbers of the poor famished population sought the shores of England at the close of the year and…aggravated the dysenteries, diarrhoeas and fevers...” clearly relating the situation in Ireland to the recorded rise in illness in England.

The high mortality in the towns which received the most migrants was traced to:

“crowded lodgings – dirty dwellings – personal uncleanliness” and “emanations from narrow streets without fresh air, water or sewers”.

In fact most of the typhus deaths in the Irish-occupied areas were amongst migrants who had only been in the country 2 to 3 months. Liverpool, a major port which received a large number of Irish migrants by ship, is singled out as “the hospital and cemetery of Ireland”.

The effect on the English population of the Famine may not have been as devastating as the Irish experience but in 1851 Farr pointed out the resurgence of scurvy. He demonstrated that:

“scurvy, which was formerly common, has almost disappeared since the potato entered largely into the food of the population” by showing that it disappeared when potatoes became part of the staple food in prison populations. Giving the example of Cook’s measures with anti-scorbutics on long sea voyages, he says
“the groundless prejudice against fruit were dwelt upon before scurvy made its appearance. It is true that fruit when taken to excess produces symptoms which may be mistaken for…common cholera” but “without these aliments the blood…escapes from the vessels in purple spots under the skin or…into the structure of the internal organs”.

Given the high rate of diagnosis of scurvy by Geber and Murphy in the Famine period Kilkenny Union workhouse individuals (2012), it is unsurprising that it should reappear in the populations who were reliant on potatoes in England when they became unavailable as a result of the potato blight. This highlights the fact that the potato was seen as a cheap and nutritious food in both England and Ireland and that populations other than the Irish were adversely affected by the loss of the potato crop (Hollen Lees 1979, 31f).

Other annual reports include “Letters” from Farr on the reduction of mortality in childbirth, and a paper in 1851 by the Registrar himself, George Graham, dealing with issues of occupational health. Occupational health effects such as poisoning with substances like lead were common, well-known and recorded as causes of death in the register. Two more “Letters” are discussed in sections 2.6.4 and 2.6.5.

**2.6.4. Urban and rural populations**

In the report for 1844, the text includes a long and detailed analysis by Farr of the “excess” mortality in urban districts when compared with rural districts of England (1844, 396-495). He shows that the annual mortality of boys under the age of 5 years in town districts of Manchester is 148 per 1000, while in extra-metropolitan Surrey, it is 48 per 1000. The total excess mortality for the seven years 1838-1844 was 16,145. A similar comparison is made of life expectancy in Whitechapel (a poor district of London) and St George, Hanover Square (one of the most wealthy) with a similar contrast: the average life expectancy for a female born in Whitechapel was 34 years, for St George, Hanover Square, it was 56 years. It is probable that the rural to urban movement of the Irish migrants would see them subjected to a new set of risks to their health.

Using the evidence available from the death Register, he assesses the likely causes of this difference and considers overcrowding, pollution (especially the effect on the lungs
of particles in the air) and the need for clean water sources and sewerage. He also compares two urban districts with different population densities with the conclusion that the excess mortality can be addressed with a few simple health measures. In fact the same subject was addressed in each of the preceding four annual reports. It is interesting that, at the time miasma theory held sway, but the suggested improvements were actually successful because of the elimination of waterborne germs.

2.6.5. **Premature death of infants**

The reports are also critical of a society where mothers are forced to go out to work soon after infants are born, with the attendant high death rate in infancy. The Registrar in 1847 said

> “Here in the most advanced nation of Europe – in one of the largest towns in England” (in this case Manchester) “children were…left alone long days by their mothers – soothed by opium”.

In a seven year period 13,362 children in Manchester had died “over and above the mortality natural to mankind”. The pattern was repeated across urban Britain where women were employed in the mills and factories.

2.6.6 **Summary of the Registrar’s reports**

What emerges from the documentary evidence contained in the Registrar’s reports is a picture of the working-class Londoners living in crowded and unsanitary conditions, poorly nourished, and likely to suffer premature death. The influx of Irish migrants had a marked and measurable effect on the death rate for 1847. The deprived childhood in poor urban areas leads to a group of adults who have chronic health problems, leading to problems with childbearing and high infant mortality, and a low life expectancy. Such a group are also much more likely to contract infectious diseases, and to recover badly from them. Wohl (1983) discusses the public health measures which were taken in Victorian London with regard to some of these factors, and the reports of the Registrar proved to be a big influence on the government in funding such initiatives.

2.7. **A last chance for a local London diet**

The Cemetery of St Mary and St Michael, Whitechapel, is of significance not only for the potential Irish immigrants buried there but also in the study of the diet of the mid-19th-century London population. Current legislation regarding the re-burial of human
remains may result in the loss to the archaeological researcher of recent and future specimens for studies such as this: as the towns and cities of Britain are re-developed and the previous generations are moved and re-buried, there is the potential for the information contained in these cemeteries across certain periods in our history to vanish. Thus any information about the burials at Lukin Street forms an important part of the archaeological record of this period.

There were enormous changes in the burial practices in mid-19th-century London resulting in larger peripheral cemeteries which are unlikely to be disturbed, combined with changes in the sources of food and drink (see section 2.2.2). Individuals dying before 1854 and buried in town and city cemeteries which are excavated as a result of urban development may provide the last chance of using skeletal human remains to study truly local diets. Chapter three discusses the use of the stable light isotope ratios of carbon and nitrogen measured in human remains for dietary studies, and introduces their potential as a tool for investigating migration between populations with different diets. An historical period cemetery, such as those in Lukin Street and Kilkenny Union workhouse, with documentary evidence for the lifestyles and diet of the incumbents, provides an ideal opportunity to test the methods currently used to reconstruct diet in past populations.
CHAPTER THREE
THE ISOTOPIC INVESTIGATION OF DIET

3.1 Introduction

This thesis does not address the use of the isotope ratios of oxygen or heavier elements such as lead and strontium as markers within human tissues for geographical origin. The value of these in the identification of migrants in a cemetery population has been well-established (e.g. Dupras and Schwarcz 2001; Montgomery et al. 2005; Bell et al. 2009; Chenery et al. 2010; Wright et al. 2010; Kendall et al. 2013). With unlimited resources, the ideal study would employ a suite of isotopic and elemental analyses to improve the chance of identifying those whose origins in life do not match their burial site.

The interpretation of variation in the ratios of stable light isotopes of carbon (δ\(^{13}\)C) and nitrogen (δ\(^{15}\)N) in skeletal tissues has been well-established as a robust method of reconstructing the dietary habits of individuals, and has parallels in modern clinical studies. This chapter introduces the concepts behind the use of the stable light isotopes of carbon and nitrogen to reconstruct diet. Case studies are used to illustrate how the investigation of such challenges can result in advances in understanding and interpretation of the isotope ratios in human and animal diet.

3.2 The principles of dietary reconstruction by stable isotope analysis

3.2.1 Basic concepts

Most elements have more than one naturally occurring isotope: the atoms of each isotope contain nuclei of the same atomic number, but the mass differs because of different numbers of neutrons in the nucleus. For example, carbon occurs as 3 isotopes: the radioactive carbon-14 (\(^{14}\)C) and the stable isotopes carbon-13 (\(^{13}\)C) and carbon-12 (\(^{12}\)C). In the case of the stable isotopes of lighter elements, the difference in mass between the isotopes is sufficient to affect how these behave in chemical and biological reactions (Pollard and Wilson 2001, 194-195; Gross 2004, 50-51; Sharp 2007). This is known as a primary kinetic isotope effect because the isotope itself is involved in the reaction (Gross 2004, 51).

A simple example is that of water evaporation. The isotopes of both hydrogen (\(^{2}\)H and \(^{1}\)H) and oxygen (\(^{18}\)O and \(^{16}\)O) are involved: energy is required for evaporation to take place and more energy is required to move the heavier isotope from one state to another. The
water vapour thus contains more of the lighter isotopes and any remaining water more of the heavier isotopes. This process is called fractionation. The effect is dependent on the mass difference between the isotopes, and is larger for hydrogen than oxygen. However, the difference between the naturally-occurring ratio of the two isotopes and the ratio after evaporation can be measured (Pollard and Wilson 2001, 194).

3.2.2 Fractionation in dietary studies

Fractionation is the key to understanding the dietary pathway of carbon and nitrogen within the biosphere through the food chain, and allows the reconstruction of the diets of fauna and humans. When an element is incorporated in the tissues of a plant or animal, fractionation occurs and the newly-formed tissue will contain more of the lighter isotope. This means that ratio of the heavier isotope of nitrogen to the lighter ($\delta^{15}\text{N}$) increases as a result of metabolic fractionation by 2-5 ‰ and the ratio of the heavier isotope of carbon ($\delta^{13}\text{C}$) by about 1-2‰ at each trophic level of a food chain and can therefore provide information about the relative consumption of plant, animal and marine protein (Schoeninger and DeNiro 1984).

Calculations are based on the ratio of the natural abundance of the isotopes: in the case of carbon this is 98.89% $^{12}$C and 1.11% $^{13}$C. Changes to this ratio are expressed in delta notation ($\delta$) in parts per thousand (per mil or ‰) relative to an internationally agreed sample material.

$$\delta^{13}\text{C} = \frac{R_{\text{sample}}}{R_{\text{standard}}} - 1$$

where $R$ is the isotope ratio $^{12}$C/$^{13}$C in this case (Coplen 2011). The international standard for carbon was PDB, a carbon belemnite fossil from the Pee Dee formation in South Carolina, USA which has been completely used up. Vienna PDB (V-PDB), calibrated from the original PDB, is now used as a replacement (Pollard and Heron 2008, 353). For nitrogen the international standard is atmospheric nitrogen (AIR)(Pollard and Heron 2008, 355).

3.2.3 Carbon and nitrogen isotope ratios in dietary studies

Traditional archaeology relies on the detritus left behind by humans to estimate their dietary behaviour, e.g. discarded food waste, faunal bones and the artefacts used in the preparation and eating of food. In a review paper Lee-Thorp (2008) summarised the pathway research has taken over the preceding 30 years leading to the established methods.
and interpretations of δ^{13}C and δ^{15}N in studies of human nutrition in the past. The advantage of analysing the skeletal and dental remains of humans is that “it reflects the foods actually eaten by and individual, or group of individuals” (Lee-Thorp 2008). After the early studies which established the relationship between diet and stable isotope ratios in body tissues, the volume of published δ^{13}C and δ^{15}N data in dietary research has grown exponentially, and it would be impossible to critique all the different papers which have used the technique across different periods and geographical areas. The following section briefly summarises the studies which have laid the foundations for the interpretation of δ^{13}C and δ^{15}N in human tissues.

3.2.4 Carbon and nitrogen stable isotope ratios in body tissues.

When food is ingested, it is metabolised by the human body and will be incorporated into the tissues: modern studies of living individuals have used blood and urine (Kalhan and Parimi 2000; Kraft et al. 2008; Kuhnle et al. 2012), hair (O'Connell et al. 2001; Petzke 2005; Mekota et al. 2006; Huelsemann et al. 2009) and fingernail (Fogel et al. 1989; O'Connell et al. 2001; Fuller et al. 2006a; Nardoto et al. 2006) to investigate the δ^{13}C and δ^{15}N of living subjects over short time periods. Hair and nail keratin survives in some archaeological conditions, and can provide information about the diet and physiology of an individual in the period leading to death (O'Connell and Hedges 1999; O'Connell et al. 2001; Wilson et al. 2007). Bone and teeth survive in some burial conditions when the shorter-turnover tissues do not. Analysis of the different tissue types in any animal will result in different δ^{13}C and δ^{15}N (e.g. Kraft et al. 2008; Orr et al. 2009) and this will reflect the composition of the tissue (O'Connell and Hedges 1999; O'Connell et al. 2001; Wilson and Gilbert 2007; Williams et al. 2011) because of the different proportions of the individual amino acids present in the proteins which make up the tissue (Smith et al. 2009; Raghavan et al. 2010). Studies have also shown that different portions of the diet are routed to different body tissues. For example, the inorganic portions of bone, dentine and tooth enamel have also been used for isotopic studies of diet. All three tissues contain carbonate, which has been shown to have a different dietary to tissue offset for δ^{13}C to that of collagen. Ambrose and Norr (1993) and Tieszen and Fagre (1993) demonstrated in feeding studies that the δ^{13}C from the protein element of diet was preferentially routed to collagen, while the carbonate reflected the δ^{13}C of the whole diet. This is borne out by the findings by Lee-Thorp et al. (1989) using isotope values from a range of free-grazing animals. For this
study it is part of the organic fraction (specifically, collagen) of bone and dentine, and hair keratin, which have been analysed. Collagen has been found to be a protein which survives remarkably well for long periods in the burial environment (Collins and Galley 1998). From both bone and tooth dentine, subject to quality indicators (Ambrose 1993; van Klinken 1999) (and see chapter six, results) even where the yield of collagen from bone is low, the isotopic values remain reliable.

3.3 Carbon

This section discusses how carbon is incorporated into the foodweb, and how carbon isotope ratios allow us to explore diet in human skeletal tissues.

3.3.1 C₃ and C₄ plants

The early researchers 35 years ago carefully selected sites and populations where there appeared from the archaeological record to be a major change in the behaviour of the human population, and a likelihood of a measurable difference in the stable isotope ratios as a result. Smith and Epstein (1971) showed that the photosynthetic pathways of C₃ and C₄ plants (the numbers relate to the number of carbon atoms in the product of the first step of photosynthesis) produced very different carbon isotope ratios in the tissues of terrestrial plants. Although the δ¹³C of C₃ plants can vary depending on the conditions in which the plant grows (e.g. humidity, moisture, light intensity) fractionation while fixing CO₂ within the photosynthetic process produces a lower δ¹³C in the plant tissue. C₄ plants convert carbon from all the CO₂ they collect and thus fractionation does not take place, resulting in a higher δ¹³C than the C₃ plants. The geographical distribution of C₃ and C₄ plants vary: most C₄ plants are adapted to environmental conditions of high solar radiation and lower pCO₂ (Ehleringer et al. 1997) while C₃ plants are widely distributed. A third group of plants use CAM photosynthesis (Crassulacean acid metabolism) and are able to alter their photosynthetic pathway to respond to changing, especially arid, climatic conditions. These were not grown or imported in any quantity in 19th-century Britain, and there is no evidence for their consumption by the populations in the study in this thesis, so they will not be considered in the interpretation of the results.

The observed difference in δ¹³C in plants was employed in the studies by Vogel and van der Merwe (1977) and van der Merwe and Vogel (1978), who demonstrated that when the consumption of maize (a C₄ plant) is introduced into a population who had only been
eating C\textsubscript{3} plants, changes were identified in $\delta^{13}\text{C}$ of human bone collagen. Dietary changes were also linked to changes in the health of the population which are visible in dental and bony pathology as noted in this case by Larsen (1995). This group of prehistoric North American Woodland natives were chosen because of the evidence for changes in subsistence and social practices. The $\delta^{13}\text{C}$ offset between diet and collagen was found to be about $+5\%$ for humans (van der Merwe and Vogel 1978) and confirmed in studies of free-ranging herbivores (Lee-Thorp \textit{et al.} 1989), although the trophic shift at subsequent levels of the foodweb are smaller, $+1$-$2\%$ (Lee-Thorp 2008).

\textbf{3.3.2 Terrestrial and aquatic ecosystems}

$\delta^{13}\text{C}$ values in marine fauna have been found to be higher than in terrestrial fauna. Plankton use photosynthesis to fix dissolved CO\textsubscript{2} from seawater, which results in less fractionation (Richards and Hedges 1999) and this lower value is carried through the marine foodweb. Freshwater ecosystems vary and can be complicated. Algae from lakes have been shown to have higher $\delta^{13}\text{C}$ values then those from fast-flowing water (France 1995). Very large and/or carbonate-rich lakes may also give rise to higher $\delta^{13}\text{C}$ values (Katzenberg and Weber 1999; Katzenberg \textit{et al.} 2009). Some fauna can move between saltwater and freshwater environments, but generally $\delta^{13}\text{C}$ from freshwater fauna are within the terrestrial range (Grupe \textit{et al.} 2009; Szpak \textit{et al.} 2009; Fuller \textit{et al.} 2012). Tauber (1981) and Chisholm \textit{et al.} (1982) were the first to report differences in the exploitation of marine resources between human populations on the basis of the $\delta^{13}\text{C}$ in their bone collagen. Tauber (1981) demonstrated a diachronic shift between Danish Mesolithic exploitation of marine resources and Neolithic dependence on a terrestrial diet, while Chisholm \textit{et al.} (1982) found marine consumption among the prehistoric population on the Pacific coast of Canada. The observation that the consumption of marine and freshwater resources also result in higher values for $\delta^{15}\text{N}$ in the tissues of consumers than terrestrial foods (Schoeninger and DeNiro 1984) opened the way for the comparison of marine and terrestrial C\textsubscript{3} based diets across other periods and geographical areas.

\textbf{3.4 Nitrogen}

This section discusses how nitrogen is incorporated into the foodweb, and how nitrogen isotope ratios allow us to explore diet in human skeletal tissues.
3.4.1 Nitrogen in the foodweb

$\delta^{15}\text{N}$ values in the lowest order of the food chain (terrestrial plants and marine plankton) are determined by the biological fixing of nitrogen. In most plants this is from inorganic compounds in water and soil produced by bacteria (Robinson 2001) with leguminous plants utilising nitrogen from both soil and the atmosphere (Lodwig et al. 2003).

Atmospheric nitrogen, as the standard, has a $\delta^{15}\text{N}$ of 0‰, but other sources can vary depending on recycling of the nitrogen. For example, soil which has been treated with manure will contain recycled nitrogen and $\delta^{15}\text{N}$ values will rise in the plants growing there (Bogaard et al. 2007; Fraser et al. 2011). $\delta^{15}\text{N}$ will also rise in plants grown in conditions of aridity, anoxia and salinity (Heaton 1987; Britton et al. 2008), and leaching where rainfall is exceptionally high (Ambrose 1991).

Fractionation (see above, section 3.2.2) produces trophic level shifts of approximately +2-6‰ from plants to herbivores and herbivores to carnivores in both terrestrial and marine foodwebs (DeNiro and Epstein 1981; Schoeninger and DeNiro 1984; Sealy et al. 1987).

In a recent paper, Szpak et al. (2012) reviewed the published literature and found that the mean values for diet-bone collagen offset to be $3.7 \pm 1.6$‰ for $\delta^{13}\text{C}$ and $3.6 \pm 1.3$‰ for $\delta^{15}\text{N}$. The number of trophic level shifts in the lengthy aquatic foodwebs results in distinctive high $\delta^{15}\text{N}$ for top carnivores (Richards and Hedges 1999) compared with terrestrial carnivores (Schoeninger and DeNiro 1984). Freshwater fauna also will have high $\delta^{15}\text{N}$ but without the higher values for $\delta^{13}\text{C}$ seen in marine fauna (Fuller et al. 2012). Thus the combination of both $\delta^{15}\text{N}$ and $\delta^{13}\text{C}$ from the bone collagen of humans should give detailed dietary information about the individual and the population.

3.4.2 Physiological effects on nitrogen isotope ratios

It has been established in plant and faunal studies that environmental conditions which can cause physiological stresses, such as aridity, will cause a rise in the nitrogen isotope ratio of their tissues (see section 3.4.1). The $\delta^{15}\text{N}$ will respond to changes in body physiology in humans. When there is no shortage of nutrients the body aims to achieve homeostasis, balancing the incoming nutrition with the requirements for energy and growth/repair and nitrogen balance will be affected by anabolic and catabolic changes (see table 3.1). When the body nutritional requirements are greater, for example during growth, an anabolic state is reached when there is a positive nitrogen balance: less nitrogen is excreted and $\delta^{15}\text{N}$ in the body tissues will fall (Waters-Rist and Katzenberg 2010). However, during nutritional


stress, if there is insufficient intake of protein and calories a *catabolic* state is reached, nitrogen within the body is recycled, a trophic level effect occurs and the $\delta^{15}$N in the body tissues will rise.

<table>
<thead>
<tr>
<th></th>
<th>caused by</th>
<th>mechanism</th>
<th>effect on nitrogen balance</th>
<th>effect on $\delta^{15}$N body tissues</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Catabolism</strong></td>
<td>periods of fasting, wasting diseases, fevers, burns, malnutrition</td>
<td>polymers in body broken down to provide 1) energy 2) new polymers(recycling)</td>
<td>negative nitrogen balance (output greater than input)</td>
<td>$\delta^{15}$N rises</td>
</tr>
<tr>
<td><strong>Anabolism</strong></td>
<td>periods of growth, tissue repair, pregnancy</td>
<td>new polymers created, dietary protein utilised</td>
<td>positive nitrogen balance (input greater than output)</td>
<td>$\delta^{15}$N falls</td>
</tr>
</tbody>
</table>

Table 3.1 Causes of catabolism and anabolism in the body and the effect on $\delta^{15}$N

Changes during pregnancy can demonstrate both these states of nitrogen balance. During the anabolic state of rapid fetal growth a fall in $\delta^{15}$N can be seen in a pregnant mother (Fuller *et al.* 2004) but a catabolic state is seen in mothers experiencing severe morning sickness (Fuller *et al.* 2004). Raised $\delta^{15}$N values of body tissues may be the result of extreme nutritional stress (Hobson *et al.* 1993; Guthrie and Picciano 1995). Mekota *et al.* (2006) showed how body mass index (BMI) was related to changes in the $\delta^{15}$N values of individuals deliberately depriving themselves of food, while Duška *et al.* (2007) demonstrated a negative nitrogen balance (catabolism) in acute starvation in a clinical setting. Hatch (2006) advised the use of isotopic values from hair as a diagnostic tool for anorexia and bulimia. Powanda and Beisel (2003) noted that the metabolic effects of infection on nitrogen balance were masked or reduced when protein and calorie intake was increased, suggesting that the effects of any illness on nitrogen balance would be greater when nutrition was also insufficient. It has also been suggested that chronic illness may cause changes in the $\delta^{15}$N values of pathological bone (Katzenberg and Lovell 1999).

The effect on nitrogen balance of long-term starvation was shown in a study by Owen *et al.* (1998). Obese patients deprived of nutrition for 21 days demonstrated an initial rise in the rate of excretion of urea which gradually falls until 18-21 days, and then remained stable. As the period of starvation extends into months, the depletion of lean body mass organs, including the heart, is dangerous for the individual. The body requires protein for the production of energy: the energy demands of the citric acid cycle in mitochondria have precedence over all other body requirements and even patients who have a reservoir
of fat which could be used to produce energy will die once the available body protein stores are exhausted (Owen et al. 1998). Neuberger et al. (in press) report the segmental analysis of hair for forensic investigation of 15 adults and 1 child who were thought to have died as the result of food deprivation. They found a trend for the \( \delta^{15}N \) values of the hair segments to rise as body mass index (B.M.I. a measure of the height to weight ratio of the individual) reduced. This is consistent with earlier isotopic studies of the \( \delta^{15}N \) values hair of individuals who are deprived of food (Hatch et al. 2006; Mekota et al. 2006). Neuberger et al. (in press) also noticed a trend in some adults for \( \delta^{13}C \) to be in phase with B.M.I. This change in the \( \delta^{13}C \) was thought to be the result of the breakdown of body fat deposits for energy and synthesis of new body tissues in the absence of carbohydrate in the diet to replenish the body stores of carbon. Body fat \( \delta^{13}C \) is lower by approximately 3‰ relative to other body tissues such as muscle (Tieszen and Fagre 1993). This drop in \( \delta^{13}C \) in nutritionally stressed adults is consistent with the findings of Mekota et al. (2006) who record a rise in \( \delta^{13}C \) and a fall in \( \delta^{15}N \) in the hair values of recovering anorexia nervosa patients once re-feeding started. In the hair of the 10 month-old child, Neuberger et al. (in press) found the \( \delta^{15}N \) and \( \delta^{13}C \) covaried, suggesting a different metabolic pathway for the infant during food deprivation.

Rigaud et al. (2000) report a paradoxical rise in the protein catabolism and resting energy expenditure (R.E.E.) of near-death patients with low B.M.I. This was recorded as a high R.E.E. and raised urinary nitrogen output at the beginning of re-feeding treatment compared with anorexia nervosa patients with similar initial B.M.I. Both parameters fell to match the anorexia nervosa patients within days of re-feeding. They interpret this rise in both R.E.E. and urinary nitrogen output as related to the consumption of the last useable muscle mass by oxidation (Rigaud et al. 2000). The introduction of even small quantities of carbohydrate to the starving patients in the studies by both Rigaud et al. (2000) and Owen et al. (1998) resulted in an immediate reduction in urea nitrogen. Bandsma et al. (2011) found that children with severe malnutrition, particularly when protein-deprived, reached a state where their ability to absorb glucose was impaired, and they failed to recover. The effect on \( \delta^{15}N \) (and \( \delta^{13}C \)) of prolonged nutritional stress appears to be complex and depends on the duration and nature of the dietary deprivation i.e. calorific or protein deficiency. It is also possible that the effect of starvation on the body \( \delta^{15}N \) and
δ^{13}C values may not persist long enough to affect the values in bulk bone collagen (see section 3.8.1)

3.5 Addressing the challenges in dietary studies

It is tempting to think that the early researchers had found universal values for foodstuffs of different types, and that all the values which were found in bone collagen of fauna and humans would follow a simple relationship: thus their diet could be identified by simply looking at their relative position on a graph (Richards and Hedges 1999)(figure 3.4). However, it is obvious that the actual relationship between diet and bone collagen δ^{15}N and δ^{13}C is more complex: the results do not always reflect the archaeological evidence, and there is a huge amount of variation between individuals within a population who appear to have consumed the same diet. Human bone collagen datasets from a given population will produce a “cloud” of data from the subjects, which suggests that individuals will choose to consume a different diet, or that, because of biological variation the food they eat is processed in a different way by each person, or a combination of both.

![Diagram showing the relative positions within a carbon and nitrogen plot for trophic levels for a terrestrial C_3 plant-based food chain and marine food chain, and the relative position of C_4 plants. The axes have no values as these vary depending on archaeological period, geographical location and climate.](image)

The following sections 3.6 to 3.9 highlight well-documented discussions in the archaeological and isotopic literature which centre on the inconsistency between the archaeological evidence and the bone collagen isotope ratios. These demonstrate how
well-designed research can investigate issues such as these to advance the understanding of complex human behaviour and the effect on $\delta^{15}$N and $\delta^{13}$C in bone collagen.

### 3.6 Dietary routing of amino acids

As discussed above in section 3.3.1 the early research by Vogel and van der Merwe (1977) and van der Merwe and Vogel (1978) established that $\delta^{13}$C in bone collagen changes with a shift from a C$_3$ to a C$_4$ plant-based diet. However, the archaeological and osteological evidence for the change in behaviour in this case appeared to pre-date the changes seen in the bone collagen isotope ratios of the human remains (Larsen 1990). Subsequent animal feeding studies which demonstrate the selective routing of protein to bone collagen (Ambrose and Norr 1993; Tieszen and Fagre 1993) can be used to explain this apparent temporal offset. The value of this to human studies was shown by Harrison and Katzenberg (2003), who used the values for diet-to-collagen and diet-to-carbonate spacing from the feeding studies to compare bone collagen and carbonate from burials in south Ontario from 2300 BC to 1636 AD, spanning hunter-gatherer and early maize cultivation through to the historic period. The diet- to-carbon spacing for bone carbonate is quoted as 9.4‰ and for bone collagen, 5‰. The offset between $\delta^{13}$C carbonate and $\delta^{13}$C of collagen should therefore be 4.4‰, but this will vary if the $\delta^{13}$C from the whole diet is not the same as for the protein element of the diet. The data from the Ontario sites demonstrates, from the changes in $\delta^{13}$C carbonate to collagen spacing, the consumption of C$_4$ plants (maize) had begun at an earlier period than suggested by the $\delta^{13}$C of bone collagen alone. Low-protein maize was not a large enough influence on the bone collagen $\delta^{13}$C values at first, although present in whole diet as measured by $\delta^{13}$C carbonate, thus the $\delta^{13}$C did not change until maize became the major source of protein in the diet, suggesting a threshold above which the maize was the main influence on the collagen. Other studies have suggested models which can be used to interpret the $\delta^{13}$C values in bone apatite of both humans and animals to examine the proportions of C$_3$/C$_4$ and marine/terrestrial input to the diet (Lee-Thorp et al. 1989; Kellner and Schoeninger 2007; Froehle et al. 2012).

The proportion of protein in the diet appears to be an important influence on how it is utilised by the body. Collagen and keratin are proteins which are complex molecules made up of a series of amino acids. It is the proportion and arrangement of the amino acids which provides the proteins with their characteristic shape, and allows them to act as structural units within the body tissues or hair. There are differences between the range of amino acids in the two proteins, and the proportion present of each is characteristic, or even diagnostic for that protein (Robbins and Kelly 1970; Smith et al.
Humans can synthesise some of the amino acids (non-essential) and are obliged to recover some from their diet (essential). Some are deemed conditionally essential as they may be required from the diet at some periods of life.

Jim et al. (2004), in a study of rats fed with isotopically-controlled diets, demonstrated differences in the effect of protein and whole diet on the $\delta^{15}N$ and $\delta^{13}C$ of bone collagen. Where a high-protein and high-calorie diet is consumed, non-essential amino acids will be incorporated into collagen without fractionation: when a low-protein diet is consumed, non-essential (and some conditionally essential) amino acids may require synthesis, and the recycling of the carbon and nitrogen as a result will cause a trophic level effect and a change in the $\delta^{15}N$ and $\delta^{13}C$ (Jim et al. 2004). It has been suggested that a threshold effect exists in populations where there is archaeological evidence without corresponding isotopic evidence for significant consumption of marine resources. Prowse et al. (2004) found that higher $\delta^{15}N$ values in bone collagen of humans from Roman Isola Sacra did not result in the corresponding rise in $\delta^{13}C$ values expected in consumers of marine protein. She suggests that the routing of carbon atoms used for amino acid synthesis is influenced by the relative proportion of protein and carbohydrate in the total diet (Prowse et al. 2004). Craig et al. (2009) suggest that, although there is ample artefactual and historical evidence that the Roman inhabitants of Velia were using marine resources, because the major source of calories is carbohydrate (in this case, bread) this could be sufficient to affect the $\delta^{13}C$ values and mask the marine effect on the isotope ratios of bone collagen.

New techniques are allowing researchers to examine the isotope ratios of individual amino acids in biological proteins such as keratin and collagen. These analyses have the potential to tease apart the effect of dietary changes and physiological stress on the bulk values of isotope ratios in these proteins (Fogel and Tuross 2003; Corr et al. 2005; Smith et al. 2009).

### 3.7 North European Mesolithic-Neolithic dietary changes

A well-documented example of the evidence for diet from bone collagen isotope ratios appearing to differ from the archaeological evidence is that of the apparent sharp shift from the use of marine resources to a wholly terrestrial diet at the time of the Mesolithic/Neolithic transition in northern Europe (Tauber 1981; Richards et al. 2003). As discussed above (section 3.4.2) marine foods in the diet may be identified by an increase in both the $\delta^{15}N$ and $\delta^{13}C$ of bone collagen. In northern Europe at this time there
is no exploitation of C₄ plants, so it can be assumed that changes in δ¹³C are due to the effect of marine foods. It would seem counter-intuitive that a population would completely ignore a source of protein which had previously formed a large part of the diet, and archaeological evidence still appeared to show some exploitation of marine foodstuffs in northern Europe even after the δ¹⁵N and δ¹³C values in bone collagen had changed (Milner et al. 2004). The discussion amongst the research community centred on the potential for a “threshold” for marine protein as a component of diet before it became evident in the isotope ratios in bone collagen (Richards and Mellars 1998; Richards and Hedges 1999; Hedges 2004; Milner et al. 2004; Richards and Schulting 2006). In fact, some of the bone collagen studies from Neolithic sites in Europe do suggest an element of marine input to δ¹⁵N and δ¹³C, for example in Denmark (Fischer et al. 2007), Sweden (Eriksson et al. 2008) and the Netherlands (Smits et al. 2010). It was also possible that if fish consumption was an occasional supplement to an otherwise terrestrial diet, this may not greatly influence the overall bone collagen isotope ratios because of slow bone turnover rates in adults (Hedges et al. 2007). Analysis of juvenile bone collagen and bulk dentine collagen from incomplete roots of teeth from the Neolithic site of Sumburgh in Shetland did suggest that a higher element of marine input was present in the diet of juveniles compared to adult bone collagen and dentine collagen from complete tooth roots at the site (Montgomery et al. in press). Two possible explanations were posed: either juveniles had a different diet to adults in the population, and that this changed by the age that teeth were completely formed and was masked by the long-term bone remodelling in adults; or marine foods were a resource which was only eaten for short periods of time by the whole population but the effect is blurred or lost in adult bone due to slow bone turnover and lifetime averaging. In order to resolve the problem, δ¹⁵N and δ¹³C of collagen were obtained from incremental dentine sections of eight teeth from the site with varying formation times (Montgomery et al. in press). The results demonstrate that, over the period of use of this site, the Neolithic terrestrial diet was adhered to as far as possible, with a short (possibly seasonal) return to a marine diet at times of stress.

3.8 Temporal resolution in human tissues

This section explores the potential problems, opportunities and practical issues involved in the incremental analysis of human tissues. Improving temporal resolution of isotopic data
would have the potential to resolve challenges such as the occasional or seasonal use of resources (see section 3.7 above), environmental change, or migration (Lee-Thorp 2008).

For a more detailed description of the structure and formation of collagen, bone, dentine and hair see chapter four.

3.8.1 Bone

The study of diet in the past through the analysis of bone collagen from adults in a population has had some major disadvantages. Bone collagen $\delta^{15}N$ and $\delta^{13}C$ reflects the protein portion of the diet, can represent an average of many years dietary consumption, and is best used in context with analysis of faunal remains from the same site or area. The isotope ratios within a population can then be interpreted: there may be individual food choices or the application of a social convention of entitlement to certain foods. In a burial population with a large variation in isotope ratios, this may reflect a wide range of available foodstuffs, or the influence of individuals present in the cemetery from another place or culture with a different diet. There may be a variation in the diet with age or sex. $\delta^{13}C$ and $\delta^{15}N$ in bone collagen reflect the main sources of protein consumed at the time that new bone is forming (van der Merwe and Vogel 1978; Ambrose and DeNiro 1986; Sealy et al. 1995; Hedges and Reynard 2007). Sealy et al. analysed collagen from five African individuals from different periods, using two teeth forming at different times of life, along with collagen from bones which have different rates of turnover, long bone and rib (Sealy et al. 1995). In combination with enamel strontium isotope ratios, these were used these to produce “lifeways” for the individuals, giving insight into their possible migratory and dietary histories. Sealy et al. suggest carrying out analyses such as these using individuals with known provenance to test the techniques (Sealy et al. 1995). Other studies have also used parts of the skeleton which have differing turnover rates to achieve temporal resolution (Bell et al. 2001; Hedges et al. 2007). Waters-Rist and Katzenberg (2010) discussed the potential effects of growth, pregnancy and nutritional/physiological stress on nitrogen balance. They compared the $\delta^{13}C$ and $\delta^{15}N$ of bone collagen taken from the epiphyses (areas of bone which were actively growing) with areas of compact bone from the diaphyses (where turnover would be slower) of juvenile long bones, and found that the effects of growth on $\delta^{15}N$ could not be identified using bone collagen (Waters-Rist and Katzenberg 2010). Nitsch et al. (2010) investigated the effect of pregnancy on nitrogen balance. A study on modern individuals by Fuller et al. (2004) demonstrated that
during normal pregnancies a reduction in $\delta^{15}$N in hair of mothers could be detected. Nitsch et al. (2010) found that they could not identify changes in $\delta^{15}$N of bone collagen from mothers who were known from the burial records to have had multiple pregnancies. Both studies conclude that the bone turnover rate is too slow to record the transitory, short-term changes in the isotope values which have been identified in hair studies (Nitsch et al. 2010; Waters-Rist and Katzenberg 2010). Studies of the effect of the “bomb peak” in $^{14}$C caused by nuclear weapon testing in the late 1950s and early 1960s have allowed an estimate of the time taken for carbon to be assimilated and to turnover in modern human bone collagen (Stenhouse and Baxter 1977; Wild et al. 2000; Geyh 2001). Bone turnover rates in juveniles are much greater and thus isotope values will reflect a much shorter period of life (Valentin 2003). For some studies, bone collagen from juveniles has been avoided as it was considered likely to be affected by breastfeeding, or may represent a juvenile rather than adult diet. The assumption of an effect from breastfeeding has, however, allowed researchers to estimate breastfeeding and weaning practices in past populations using the bone of neonates and infants (e.g. Mays et al. 2002; Jay et al. 2008; Nitsch et al. 2011) (and see section 3.9).

3.8.2. Dental Enamel

The age at which individual human teeth develop has been well-established (Hillson 2005; AlQahtani 2009) and do not change significantly with sex, geographical origin or nutritional status (Reid and Dean 2000; Reid and Dean 2006; Feeney et al. 2010) thus proving to be a robust method of assessing the age of juvenile remains. This has meant that researchers could use bulk analysis of tissues from teeth which develop at different ages to achieve a degree of temporal resolution. For example, this was particularly well demonstrated by the use of strontium isotopes in dental enamel from teeth with different formation times (Montgomery et al. 2000) to show migration in a Neolithic case study from southern England. Some studies have attempted to use the incremental structures present in human enamel as a way of achieving temporal resolution for isotope analysis. This requires the use of much smaller samples of tissue with the practical problems which that will entail. Sponheimer et al. (2006) used laser ablation to sample incremental structures down the surface of a Neanderthal tooth. Simonetti et al. (2008) highlighted the analytical problems associated with laser ablation compared with conventional methods. Humphrey (2008) measured isotopic ratios across a section of molar enamel following
incremental structures either side of the neo-natal line in an attempt to establish pre- and post-natal variation. However, the formation of the enamel matrix which is recorded by the incremental structures is not the only period in which mineralization of the developing enamel takes place (Suga 1989; Nanci 2003a). The process of enamel mineralization, when the elements will be incorporated into the inorganic bioapatite and carbonate of the enamel is a complex process. There are three major waves of mineralization which are mediated by the ameloblasts during tooth formation (Suga 1989), and a further mineralization event at the surface of the enamel post-eruption which is controlled by the action of saliva in the oral cavity (Nanci 2003a). During these waves, mineralization will reach the surface of the tooth faster in areas of the enamel which are thinner, such as the cervical margin, although the matrix in thicker areas, such as the buccal surface, will have been completed first. The crown morphology of different teeth varies, and features such as fissures will result in differences in enamel thickness, especially in premolar and molar teeth. Thus, it is difficult to utilise enamel to achieve more than a basic “early, middle and late” mineralization sequence moving from the enamel dentine junction (EDJ) to the enamel surface. The exception is the EDJ itself which mineralizes almost immediately after formation. Zazzo et al. (2005) used micro milling to test the δ^{13}C variation in bovine tooth enamel from surface to EDJ. This confirmed that there was damping of the signal produced by the complex mineralization during maturation and that the innermost enamel could provide the best information (Zazzo et al. 2005). Wright (2012) utilized the EDJ to produce a three stage temporal series of values from human enamel because of the swift and simple mineralization at this position in the enamel, and with a similar conclusion. The EDJ is only microns wide (Nanci 2003a). Designing a study which can achieve a true temporal sequence with high resolution using this area of the enamel will require the use of microsamples such as micro milling or laser ablation, with instruments capable of analysing tiny samples and overcoming issues of contamination and precision.

### 3.8.3 Dentine

Because dentine is mineralized within days of the matrix formation and does not remodel, it offers the chance of true time resolution (see section 4.4). Bulk dentine collagen δ^{13}C and δ^{15}N will give a measure of the average diet during the period of formation of a tooth, which is useful when a tooth is the only sample available. Bulk dentine collagen analysis has been employed as a measure of childhood diet in comparison with adult bone collagen.
(Sealy et al. 1995; Wright et al. 2010; Chenery et al. 2011; Müldner et al. 2011) or in consecutively forming teeth to investigate changes during childhood and adolescence (Wright and Schwarcz 1999). Fuller et al. (2003) sampled permanent human dentine collagen, dividing the roots into up to five increments, and showed variations in the diet of individuals in Wharram Percy during the period of tooth formation. This technique was limited by the size of collagen sample required for analysis. However, much higher resolution sampling of dentine is possible, as shown in the study by Eerkens et al. (2011), where 5-10 increments were obtained for the M1’s of individuals in order to examine weaning patterns amongst Californian hunter-gatherer-foragers.

3.8.4 Hair and Nail

Hair and nail samples have been employed to assess the diet of both modern and ancient individuals (O’Connell and Hedges 1999; O’Connell et al. 2001; Fuller et al. 2006a; Hatch et al. 2006; Shetty 2006; Wilson 2008). These tissues are both rich in keratin, and have the advantage of forming incrementally over a short period of time. Hair will record dietary changes which will become measurable after about 4 weeks (Petzke and Lemke 2009) although a human feeding study has shown that changes in $\delta^{13}$C will take longer than $\delta^{15}$N to appear because of the large body pool of carbon (Huelsemann et al. 2009). Williams et al. (2011) pointed out that caution should be taken when analysing increments from human hair as some of the hair follicles may be dormant at any given time. Where bulk samples will reduce the effect of this, incremental analysis from a single hair will have a high chance of representing a time other than that expected, and analysis of multiple hairs may be necessary, with some matching of any profiles achieved. The serial analysis of hair can allow a high degree of time resolution and has been employed for dietary reconstruction within archaeological individuals, for example in the comparison of two Chiribaya sites in Peru (Knudson et al. 2007) and the comparison of two historic period groups of North American Plains Indians (Roy et al. 2005). Modern incremental hair analyses have been used for both clinical studies of nutrition (Petzke 2005; Mekota et al. 2006; Shetty 2006) and anthropological research in regard to weaning and breastfeeding (Fuller et al. 2006a). Fogel et al. employed the analysis of increments of fingernail to investigate weaning and breastfeeding in modern mothers and infants (Fogel et al. 1989). Fingernails and toenails form more slowly than hair: in a healthy adult fingernail grows at a rate of approximately 3.5mm per month, and toenail approximately
1.5mm, except the great toenail which grows slightly faster, approximately 2mm per month (Yaemsiri et al. 2010). This means that a whole great toenail would contain about 10 month’s growth for analysis.

The growth of both hair and nails will be affected by factors such as pregnancy, malnutrition and disease, and these should be taken into account when estimating the time for each increment to form (Bradfield 1972 ; Wilson and Gilbert 2007). Once cleaned to remove any adherent contamination, hair and fingernail, because of the high proportion of keratin, can be measured directly by mass spectrometry without further extraction, allowing the use of small samples.

3.8.5. Combining body tissues

The analysis of more than one body tissue from the human remains of an adult, if present, can give a potential dietary history (see figure 3.5). Teeth develop between birth and the age of approximately 23 years (Moorrees et al. 1963 ; Brown 1985 ; Hillson 2005 ; AlQahtani 2009), adult bone will represent tissue laid down over approximately the last 10 years of life (Valentin 2003 ; Hedges et al. 2007) and hair and fingernail will still be forming around the time of death (Wilson and Gilbert 2007). If tissues which develop at different times of life are analysed in bulk and compared (allowing for any offset because of the difference in the tissue) it may be possible to produce a “lifeway” for an individual. For example, bulk analyses of tooth and bone have revealed differences in isotope ratios which may be linked to migration after the teeth were formed e.g. (Sealy et al. 1995 ; Chenery et al. 2010) (and see section 3.8.3). O’Connell et al. (1999 ; 2001) compared bone and hair from modern and archaeological individuals and established a likely offset for $\delta^{13}$C and $\delta^{15}$N, which enables comparison of the hair keratin with bone collagen when seeking short-term dietary changes.
3.9 Weaning studies

It has been established from modern studies that a trophic level shift of 2-4‰ in $\delta^{15}$N is seen between the hair and fingernail keratin of mothers and their infants during breastfeeding (Fogel et al. 1989; Fuller et al. 2006a). Once other foods are introduced to the diet, this offset should reduce until breastfeeding ceases completely (Fogel et al. 1989; Millard 2000; Fuller et al. 2006a; Jay et al. 2008). The model currently used in archaeological studies of weaning behaviour is based on the assumptions that the mean value (plus or minus 1 standard deviation) of the $\delta^{15}$N values of collagen from the adult females defines the maternal range, and that infants have the same isotope ratio as their mother at birth because the mother is the source of all nutrition for the infant via the placenta during pregnancy. If the infant is subsequently breastfed, it is assumed that there will be a trophic level rise (see section 3.1.2) in the infant bone collagen and measuring the $\delta^{15}$N values of infants who died at different ages can give an approximation of when and whether breastfeeding and weaning occurred in an archaeological population (Richards et al. 2002; Fuller et al. 2003; Jay et al. 2008). The age at which weaning is deemed to take place using this method can vary both geographically and over time; for example, in British studies it appears to vary between time periods. There appears to be a trend towards earlier weaning over time, commencing at about the age of two years in the late Romano-British site in Oxfordshire (Fuller et al. 2006b) falling to one year in medieval Wharram Percy (Mays et al. 2002) and less than a year in post-medieval Spitalfields, London (Nitsch et al. 2011). Because of the importance of breastfeeding and weaning behaviour to the health of infants, and to the control of fertility and birth spacing, many studies of bone collagen from burial populations where juveniles are present have used the model above to
estimate weaning age as part of their discussion of the wider dietary information from the site e.g. (Privat et al. 2002 ; Lightfoot et al. 2009).

There is evidence from published studies that may cast doubt on the accepted model and enable a different interpretation to be proposed: δ¹⁵N values which are higher than 1 standard deviation (SD) above the female mean (and therefore interpreted as representing the consumption of breastmilk) have been recorded in foetal and neonatal individuals at British sites including medieval Wharram Percy, Yorkshire (Richards et al. 2002), 18th/19th-century Spitalfields, London (Nitsch et al. 2011), and the sub/late-Romano British site of Queenford Farm, Oxfordshire (Fuller et al. 2006b). Explanations for the high foetus/neonate δ¹⁵N values included premature birth, inaccurate age estimation, or an atypical individual maternal value not matching the putative maternal mean. Infants with lower than expected bone collagen δ¹⁵N values have been suggested to have had little or no access to breastmilk (Nitsch et al. 2011). However the bone collagen δ¹⁵N values of rapidly growing foetuses and neonates represent the physiological status of the mother only during pregnancy and this may not be the same as the long-term, life-time averaged bone collagen values obtained from the actual or putative mothers.

Bone collagen takes time to turnover (Valentin 2003 ; Hedges et al. 2007), and even neonates, whose tissue growth is much faster than in adults, will take time to record changes in the isotope values of the food consumed. Thus, the recording of unexpectedly high or low δ¹⁵N in peri-natal bone collagen could be interpreted as an in-utero value. Kinaston et al. (2009), in a study of a 3000 year-old site in Vanuatu, noted high δ¹⁵N values in foetal and peri-natal individuals who were too young to have been breastfed and suggested that these values may be reflecting maternal stress during pregnancy. Pearson et al. (2010) compared weaning ages at two Neolithic sites in Anatolia, and interpreted high neonatal δ¹⁵N as inaccurate age estimation or the result of nutritional stress in the adult females.

The neonates with low δ¹⁵N bone collagen values in the published studies could be recording a low maternal in-utero value. In pregnancy, it has been shown that δ¹⁵N values can be raised during a period of nutritional stress such as morning sickness because of catabolism (the recycling of proteins which causes a negative nitrogen balance) (Fuller et al. 2004). The opposite can also be true, during periods of rapid fetal growth δ¹⁵N values of the mother can be reduced by anabolism (a reduction in the excretion of nitrogen from
the diet which causes a positive nitrogen balance) (Fuller et al. 2006a). The study by Nitsch et al. (2010) using 19th century individuals from Spitalfields compared the $\delta^{15}$N bone collagen values of females for whom there was documentary evidence of frequent and multiple childbearing, with the adult female mean, and found no evidence for a lower value. This was interpreted as being because of the slow bone turnover rate in adults.

The studies above suggest that $\delta^{15}$N values of infants at birth may not be the same as the bone collagen values of their mother if she is experiencing a short-term change in $\delta^{15}$N, and the high or low values seen in neonates could be a way of estimating the nitrogen balance of the mothers. Fall et al. (2003) pointed out that the link between maternal nutrition and fetal nutrition is indirect. Because there is maternal partitioning of nutrients between storage, use and circulation, and the action of the placenta will further alter the rate at which nutrients will reach the fetus, the nutrition of the mother and the fetus is not the same. It has been shown that $\delta^{15}$N will rise in response to nutritional stress, or as a result of high demand on the body through illness and growth (Hobson et al. 1993 ; Guthrie and Picciano 1995 ; Mekota et al. 2006)(and see section 3.3.2). Barker (1998) in his discussion of the effects of in utero nutritional deprivation on adult health, states that rapid growth in the third trimester of pregnancy results in the catabolism of fetal amino acids for energy production. This has been borne out by studies showing that fetal urea concentrations are significantly higher than maternal urea concentrations (Kalhan and Parimi 2000). Alanine (and other amino acids) is transported from mother to fetus against an upward gradient, showing that the fetus is able to synthesise alanine (Kalhan and Parimi 2000). Perinatal isotope tracer studies of $[^{13}$C] leucine using umbilical and maternal blood samples show that the fetus is dependent on maternal glucose until birth. When the maternal supply of glucose is insufficient for the energy required for growth, the consequent increase in fetal catabolism could cause a rise in $^{15}$N in fetal tissues. In the hours after birth, liver glycogen stores provide a short-term source of glucose, and until a source of carbohydrate-based nutrition is provided the neonate produces further glucose from amino acids such as leucine and alanine (Kalhan and Parimi 2006) with a consequent rise in urea production and catabolism. Once adequate nutrition is established the neonate directs nitrogen towards protein synthesis with a consequent drop in urea production and a fall in the $\delta^{15}$N in tissues of the neonate (Kalhan and Parimi 2006). The mechanisms which
maintain the normal plasma glucose concentrations in the last trimester of pregnancy and the perinatal period, while short-term, could affect the perinatal bone collagen $\delta^{15}\text{N}$. It is also possible that the $\delta^{15}\text{N}$ values of the infants at any age may be the result of influences other than breastfeeding and weaning. Given the high turnover rate of juvenile bone (Valentin 2003), it is possible that the infants who are dying during early childhood are recording short term raised $\delta^{15}\text{N}$ values as a result of perinatal stress, or disease or malnutrition if that has contributed to their early death, as well as any fractionation of their mother’s breastmilk. Time resolution using incremental tissues forming in the perinatal and childhood periods of life would be helpful to help explain the role of each factor in the changes in $\delta^{15}\text{N}$ values. The paper by Eerkens et al. (2011) is an attempt to analyse incremental dentine of first permanent molars (which form between 30 weeks in utero and the age of $9.5 \pm 0.5$ years (AlQahtani 2009)) from six individuals to investigate this important milestone. The paper demonstrates that the $\delta^{15}\text{N}$ profiles produced vary over time in a similar pattern in all six teeth, and discusses differences between individuals with high and low-status burials. Further work on tissues forming over the perinatal period, especially from healthy, well-fed modern individuals with a known breastfeeding history, would enable a better interpretation of the $\delta^{15}\text{N}$ profiles from ancient individuals.

3.10 Migration

The differences in $\delta^{15}\text{N}$ and $\delta^{13}\text{C}$ bone and dentine collagen values within a population have been exploited by archaeological scientists to investigate not only changes in subsistence and farming practices over time, but also as a means of identifying human migrants who have consumed a diet which is not consistent with the population in which they are buried e.g. (Trickett 2006; Chenery et al. 2010; Smits et al. 2010). Bone collagen from domestic animals which have been imported may also be able to add to the information available. Guiry et al. (2012) used $\delta^{15}\text{N}$ and $\delta^{13}\text{C}$ values from pig bone collagen to argue that the pork being consumed at 19th-century English and French fishing stations in Newfoundland came from different sources. One group chose to eat imported European pigs or salt-pork meat, while the other were keeping pigs locally and feeding them a marine-based diet. However, $\delta^{15}\text{N}$ and $\delta^{13}\text{C}$ values will not give a direct link to any particular geographical location, and it is only in combination with the context, archaeological or historical, that any likely origin of a migrant can be inferred. The amount of time that has elapsed between migration and death may also have an effect on the $\delta^{15}\text{N}$
and $\delta^{13}C$, depending on the age of the individual, the body tissue analysed and the turnover rate of that tissue.

### 3.10.1 Modelling dietary regimes

Chapter two has discussed the historical evidence and likely diet for the populations who are likely to be found in the two sites studied for this thesis, the Famine cemetery at the Kilkenny Union workhouse, Ireland, and the burial ground at the Catholic mission of St Mary and St Michael, Lukin Street, London. From this it was hypothesized that four main dietary regimes would be identifiable in the Lukin Street and Kilkenny populations using carbon and nitrogen isotope analysis. These regimes are characterized as follows:

1) A diet containing meat, fish and mainly C$_3$ plants consumed by those living in London (based on the mean values for a contemporaneous population in Chelsea, London) (Trickett 2006).

2) The restricted pre-1847 (C$_3$) potato diet eaten by the rural Irish poor, which may resemble a Neolithic C$_3$ plant-based diet, but with higher $\delta^{15}N$ caused by buttermilk consumption.

3) A diet based on regime 2 but where potatoes are replaced by (C$_4$) maize eaten by those receiving imported Indian meal as famine relief.

4) The nutritionally-stressed famine diet, based on regime 2, but demonstrating a rise in $\delta^{15}N$ as a result of the recycling of body tissues when few or no calories are consumed.

The identification of regimes 2, 3 or 4 in the London population would suggest that these individuals may be recent migrants. Figure 3.6 is a $\delta^{13}C$ and $\delta^{15}N$ biplot showing the possible relative values for the four dietary regimes.
Chapter four, materials and methods, will expand on the site information and the samples chosen for this study. The methods employed to investigate the diet through the $\delta^{15}N$ and $\delta^{13}C$ of the bone and hair of the individuals buried in these cemeteries will be discussed. The rationale for the development of methods for incremental dentine collagen analysis and how this was achieved will be explored.
CHAPTER FOUR
BONE, DENTINE AND HAIR

4.1. Introduction
The three human tissues of bone, dentine and hair which have been sampled in this study contain proteins which the body constructs from food and drink consumed, and thus the isotopic ratios of these proteins will be directly related to the diet.

4.2 Collagen
Collagen is a structural protein present in most tissues of the human body (Shoulders and Raines 2009). Collagen fibrils can combine to produce sheets of soft tissue, or an organic matrix which is mineralized to form bone and dentine. Collagen derives its strength from its structure, three chains of amino acids combining to form a tight triple helix (Nanci 2003b, 65; Shoulders and Raines 2009)(see figure 4.1). This means that collagen is an extremely robust structure and resistant to damage in the burial environment. Three amino acids, glycine, proline and hydroxyproline are particularly important in the maintenance of the structure, and a change in the abundance of these will result in a morphological alteration of the protein molecule. For example, the formation of hydroxyproline, by oxidation of proline, requires the presence of vitamin C. Scurvy occurs when there is insufficient vitamin C and new collagen cannot be formed properly leading to symptoms when damaged collagen in the tissues cannot be replaced (Peterkofsky 1991).

Figure 4.1 Helical structure of collagen (source P.Montgomery and author)
In order to analyse collagen for nitrogen and carbon isotope ratios, bone and dentine are
demineralised, and the collagen is then denatured to produce a gelatin, which can then
be analysed using isotope ratio mass spectrometry (see Chapter 5, section 5.5).

4.3 Bone structure and growth

The human skeleton forms the hard framework of the body, protecting softer structures
such as the brain, and acting as the attachment for muscles and tendons (Weiner and
Wagner 1998). A complex structure with organic and inorganic components, it acts as a
metabolic reservoir for minerals and some hormones and has a role in buffering the
blood (Confavreux 2011). Bone will grow rapidly in infants and children and again at
puberty, and is constantly remodelling throughout life although the rate of turnover
slows once adulthood is reached (Valentin 2003). In an adult the structure of bone can
vary depending on its function. Compact bone provides the structural shape and strength
to the bones of the skeleton, is dense and hard, and will remodel slowly. Trabecular
bone (also known as cancellous bone) has more open structure with a larger surface area
allowing the metabolic exchange required by the body and a faster turnover of bone
(Weiner and Wagner 1998; Nanci 2003b, 141) (see figure 4.2).

![Figure 4.2 Section of mandible showing compact and trabecular bone (Nanci et al. 2003)](image)

At the microscopic level, bone consists of a framework of long protein chains to which
are attached inorganic molecules (Weiner and Wagner, 1998). By weight, bone is 67%
inorganic and 33% organic. The majority of the protein is type I collagen (28% of bone
by weight) and the inorganic component is mostly bioapatite, a crystalline form of
calcium phosphate. Other minor proteins and inorganic molecules are present, but in
much smaller quantities (Weiner and Wagner, 1998). The cells which form bone are
osteoblasts. These secrete a protein matrix (osteoid) containing mostly collagen fibrils
which are then mineralised by deposition of the calcium phosphate. Primary bone, laid down during the initial growth and modelling of the bones of an individual, has a lamellar structure. The osteoblasts surround themselves with bone and remain within lacunae, maturing to become osteocytes (Weiner and Wagner, 1998). These bone cells (osteocytes) respond to the metabolic requirements of the body, maintaining calcium homeostasis and responding to strain and stress in the bone (Martinez-Maza et al. 2006). When repair or remodelling of the bone is required, osteoclasts are recruited and begin to demineralize an area of bone. This produces pits or depressions on the bone surface, Howship’s lacunae. Once this is formed the osteoclastic function ceases and osteoblasts begin to lay down new bone from the outside edges of the lacuna. The lacunae become surrounded by a concentric lamellar structure as bone is laid down in layers, and form the basic unit of bone, the secondary osteon (Weiner and Wagner, 1998). At the centre of each is a Haversian canal which contains blood vessels and is lined with a single layer of bone cells (figure 4.3).

![Figure 4.3 Structure of a secondary osteon (author)](image)

The balance between the action of osteoblasts secreting bone and osteoclasts remodelling allows bone to respond to growth, changes in functional shape and to facilitate the release of minerals required by the body (Weiner and Wagner, 1998). This balance will vary over the life of an individual during periods of growth, changing metabolic requirements and with age (Confavreau 2011). Histologically, as bone remodels over time, the number of secondary osteons will increase. The pattern of
secondary osteons will change as the bone responds to the body requirements, and the number of osteons within an area of bone, known as the Osteon Population Density (OPD) has been used as a histological method of aging individuals (Stout and Paine 1992). As an individual gets older, the density of secondary osteons in the bone will generally rise. This rise in density can vary from one individual to another and the rate of bone turnover has been shown to be reduced by metabolic diseases such as pellagra (Paine and Brenton 2006). Sampling of bone for isotopic analysis should take into account the different types of bone and their relative turnover rates. This has been discussed in section 3.7.

4.4 Dentine structure and growth

Human dentine is secreted and mineralized in a two-phase process similar to bone formation. The odontoblasts secrete an initial dentine matrix, or predentine, which is then mineralized by the deposition of short (20-100 nm) crystals of carbonate hydroxyapatite within the collagen fibre matrix. The rate of dentine secretion in a permanent tooth is relatively consistent at 4-6 µm per day throughout the cuspal areas of permanent teeth (Dean and Scandrett 1995). The retreating odontoblasts move away from the enamel dentine junction (EDJ) producing a layer of newly secreted predentine (Hillson 1996). The mineralizing front follows the same path 10-20 µm behind, suggesting that the dentine is secreted and fully mineralized in approximately 3-8 days.

The formation of root dentine begins from the cement-dentine junction (CDJ) and proceeds at a rate of 1.3 to 1.5 µm per day. The rate changes, rising to the same rate as the cuspal dentine within the bulk of the root, and then reducing again to 1.3 µm per day as the odontoblasts approach the pulp chamber (Dean and Scandrett 1995). As the odontoblasts move towards the pulp chamber, they leave tissue within the dentinal tubules throughout the thickness of the dentine, maintaining a network for nutrients. The tubules follow the path of dentine formation and are s-shaped rather than linear (Dean and Scandrett 1995 ; Nanci 2003b)(figure 4.4). The Andresen bands (represented by dashed lines in figure 4.4) record diurnal changes in the position of the secreting front (and therefore the mineralization front) of the odontoblasts. It can be seen from Figure 4.4 that points A and B are within the same Andresen band, and mineralized at the same time, although separated by a number of dentinal tubules. Tissues which are laid down after the primary dentine has formed should also be considered. Cementum is
a mineralized tissue which is part of the periodontium. From the middle third of the root to the apex, it has the potential to remodel over time, becoming thicker around the root apex (Bosshardt and Selvig 1997; Nanci 2003b). The thickness of cementum increases with age and age estimation has been attempted using a count of the annulations seen (e.g. Roksandic et al. 2009).

Secondary dentine is laid down very slowly throughout life by the odontoblasts on the wall of the pulp chamber in permanent teeth after the tooth is fully developed. Tertiary dentine is produced in specific sites on the pulpal wall, in response to damage on the dentine surface such as wear, or caries (van Rensburg 1987; Nanci 2003b).

The dentinal tubules of older individuals become occluded over time by the deposition of intratubular dentine, causing dead tracts seen as root translucency in the apical area.

Figure 4.4 Diagram showing the direction of dentine development in a human molar tooth, the relationship between Andresen bands and the mineralizing front, and points A and B within the same Andresen band (Beaumont et al. 2013b)
The area of dentine affected increases with age and has been used in age estimation studies (e.g. (Gustafson 1950; Lamendin et al. 1992).

The incremental sampling strategies used in this study were designed with regard to dentine development. These strategies are described in Chapter 5, section 5.5.

4.5 Keratin

65-95% of human hair (depending on the moisture content) is made up of proteins (Robbins 2012) most of it α-keratin. Keratin has a characteristic amino acid composition which is different to the composition of collagen (O'Connell et al. 2001; Smith et al. 2009) which means that the $\delta^{13}$C and $\delta^{15}$N values of keratin will differ from those of collagen for the same individual producing an offset in values, and this is taken into account when estimating diet.

α-keratin is fibrous and provides hair with strength and elasticity. Made up of amino acids arranged into tightly linked peptide chains, the stability of the fibre is enhanced by the alpha helical structure of keratin intermediate filaments and the disulphide bridges which form due to the high proportion of cysteine (Robbins 2012).

4.6 Hair structure and growth

Human hairs form within separate follicles (see figure 4.5), organs formed from part of the dermal layer of the scalp, and from which cells emerge and are differentiated to form the different parts of the hair fibre, and harden, or ‘keratinise’ (Wilson and Gilbert 2007).

Consisting of medulla, cortex and cuticle (see Figure 4.6), the hair does not change once keratinised and so records any isotopic information from the diet at the time of formation. Caucasoid-type hair will grow at a rate of approximately 1cm a month which allows temporal resolution for the isotopic information (Wilson and Gilbert 2007).
Human hair follicles have a cyclic growth, which can be summarised into 4 phases. The majority of scalp follicles will be in the active anagen phase, which can last for up to 10 years. The second, resting phase lasts about 3 weeks (catagen phase) and is followed by approximately 3 months resorption (telogen phase) before the hair fibre is finally shed (exogen phase), before the follicle repeats the hair growth cycle. For the human scalp, hair follicles normally follow a “mosaic” pattern of hair growth, which should be taken into account when examining time sequences in hair: bulk analysis will reduce the effect of hairs out of phase, but from single hairs, the results could be as much as 3 months out of phase with each other (Williams et al. 2011).
4.7 Taphonomy and diagenesis.

*Taphonomy* is the term used to describe the processes which affect body tissues from the death of the individual until the recovery of that tissue, while *diagenesis* describes the biochemical changes which the tissue undergoes in the depositional environment (Nicholson 2001). From death onwards, the body tissues will begin to alter through intrinsic and extrinsic processes. Treatment of the dead by the living can affect the survival of the body tissues. The range of pre-burial behaviours includes cremation, excarnation or exposure, all of which may influence the survival of bone, dentine and hair (Millard 2001; Nicholson 2001).

Because of the porous nature of bone, dentine, and hair, these are tissues which once in the burial environment can be affected by:

1. ingress of contaminants
2. damage by microbial action
3. the leaching out of components.

Many studies have assessed the effects on bone of different burial conditions (e.g. (Hedges and Millard 1995; Janaway 1996; Millard 2001; Collins *et al.* 2002). Moisture levels, temperature and pH of the soil will all have effects on the tissue, as will the cause of death and length of time since death.

Hair can be subject to taphonomic alteration, most prominently from the action of specialised ‘keratinolytic’ fungi (Wilson *et al.* 2010; Thompson *et al.* 2013) and rarely survives in the depositional environment unless preservation conditions are exceptional (Wilson and Gilbert 2007). Thompson *et al.* (2013) state that where hair survives it is considered to be suitable for isotopic analysis, as the bulk amino acids in the keratin will be largely unaltered. The outward morphological condition of the hair should be considered, and quality parameters considered (see 4.7.1 below and chapter five materials and methods).

4.7.1 Assessing diagenesis

This study has only analysed the organic fraction, mainly collagen, extracted from bone and dentine. Because of the structural similarities between dentine and bone, diagenetic
alteration of both tissues are expected to follow similar pathways, although most studies only address diagenetic alteration of bone.

Bone is a composite material made up of organic (mainly collagen) and inorganic (bioapatite) components (Weiner and Wagner 1998). The effects of the burial environment on bone reflect the intimate relationship between the two components. Both bone and dentine have been shown to be subject to diagenetic alteration by leaching of and replacement of the elements deposited throughout life in the inorganic portion of bone, leading to a gradual shift to the values of the geology of the burial site (Montgomery 2002). The collagen fibrils are protected from chemical deterioration by hydrolysis, and from microbial attack by the presence of the apatite (Collins et al. 2002). Collagen appears to be one of the most stable proteins in bone (Collins et al. 2002), partly due to the strong chemical bonds within the protein, and because of the close relationship between the fibrils and the hydroxyapatite within the bone and dentine structure (Weiner and Wagner 1998).

In order to assess the level of alteration to bone, a number of screening methods have been developed. Nielsen-Marsh and Hedges (2000) suggested a suite of “diagenetic parameters” for assessing the state of preservation of bone. Table 4.1 shows the diagenetic parameters used to assess the state of the bone, how changes to these parameters reveal the effects of diagenetic alteration of the organic and inorganic portions of the bone.

<table>
<thead>
<tr>
<th>diagenetic parameter</th>
<th>screening method</th>
<th>alteration measured</th>
</tr>
</thead>
<tbody>
<tr>
<td>1  histogram index</td>
<td>ground section microscopy</td>
<td>alteration of bone microstructure</td>
</tr>
<tr>
<td>2  protein content (%N)</td>
<td>CHN analyzer</td>
<td>quantity of collagen in the bone</td>
</tr>
<tr>
<td>3  &quot;s&quot; porosity (small or sub-fibril)</td>
<td>mercury intrusion porosimetry</td>
<td>increase = loss of collagen fibrils, decrease = deposition in spaces</td>
</tr>
<tr>
<td>4  &quot;m&quot; porosity (medium or microbial)</td>
<td>mercury intrusion porosimetry</td>
<td>microbial alteration of bone microstructure</td>
</tr>
<tr>
<td>5  &quot;l&quot; porosity (large)</td>
<td>mercury intrusion porosimetry</td>
<td>catastrophic mineral dissolution</td>
</tr>
<tr>
<td>6  bulk bone density</td>
<td>mercury intrusion porosimetry</td>
<td>whole bone including pore volume</td>
</tr>
<tr>
<td>7  skeletal density</td>
<td>mercury intrusion porosimetry</td>
<td>density of the material between pores</td>
</tr>
<tr>
<td>8  crystallinity (&quot;splitting factor&quot;)</td>
<td>X-ray diffraction (XRD) or Fourier transform infrared spectrometry (FTIR)</td>
<td>recrystallization of diagenetically altered bone</td>
</tr>
<tr>
<td>9  carbon/phosphate ratio relative to fresh bone</td>
<td>FTIR</td>
<td>elevated = deposition of inorganic, depleted = loss of organic</td>
</tr>
<tr>
<td>10 % calcite</td>
<td>FTIR</td>
<td>deposition of new inorganic material</td>
</tr>
</tbody>
</table>

Table 4.1 Ten diagenetic parameters, methods used to assess them, and the alteration to bone they represent, modified from Nielsen-Marsh and Hedges (2000) and Smith et al. (2007)
Smith et al. (2007) analysed bone from a range of sites from the European Holocene, and suggested that archaeological bone would reach one of four diagenetic states. The first, well-preserved (WP) was bone which had little or no changes to the structural or chemical parameters compared with fresh bone. The second, accelerated collagen hydrolysis (ACH) is characterised by an increase in “s” porosity and a lower %N resulting from the destruction of the collagen fibrils leaving a larger number of small pores in the bone. The third, microbially attacked (MA) bone results from post-mortem colonization by bacteria and fungi and is characterised by an increase in “m” porosity and an alteration in the bone structure as measured by the histological index. The fourth, catastrophic mineral dissolution (CMD) is the result, as the name suggests, of the bone dissolving. The overall picture revealed by the screening processes shows that assessing the state of diagenetic alteration results from complex interplay of variables. The histology of the bone may appear to be preserved when there is an increase in the inorganic content of the bone but a loss of organic content. The “s” porosity may decrease once the collagen fibrils have been lost because of ingress of new crystals into the structure. Porosity and microporosity measurements were found to be a useful indicator of diagenetic change in studies of archaeological bone (Hedges and Millard 1995; Nielsen-March and Hedges 2000) however an increase in porosity could demonstrate either a loss of collagen, or of apatite and collagen.

Brock et al. (2010) tested techniques for screening bone to assess whether it was suitable for the extraction of collagen with a yield of 1% or more by weight for radiocarbon dating purposes. In the Brock et al. study (2010) only one of these parameters (%N) predicted the yield of collagen from the bone and was recommended for use. It has to be suspected, then, that any form of diagenetic alteration can affect the collagen yield. Where the collagen itself has degraded, the strong bonds are lost between the individual amino acids in the protein, and the smaller molecules which leach out of the bone. This collagen degradation may be the result of microbial action, which can be slowed down by the protective hydroxyapatite crystals, but once started will continue until all the collagen is lost (Nielsen-March and Hedges 2000; Collins et al. 2002). In the presence of water, especially where there is movement of water through the depositional environment, the result will be dissolution of the
hydroxyapatite and hydrolysis of the collagen (Hedges and Millard 1995; Nielsen-Marsh and Hedges 2000).

Once collagen has been extracted from archaeological bone and dentine, there are recommended parameters which can be used for assessing quality as compared to collagen extracted from fresh bone. These are the % yield by weight (Ambrose 1993; van Klinken 1999), the elemental mass percentages of carbon and nitrogen (Ambrose 1993; van Klinken 1999), and the C:N ratios (DeNiro 1987; van Klinken 1999).

The parameters for assessing the quality of the collagen and keratin will be further discussed in chapter five, materials and methods.
CHAPTER FIVE
MATERIALS AND METHODS

5.1 Materials and methods.
This chapter contains information relating to the archaeological sites, Lukin Street and Kilkenny Union Workhouse, included in this study. A summary is given of the individuals who were sampled from these sites and the tissue samples from each that were analysed.

5.2 The sites
(see map, figure 1.1)

5.2.1 Lukin Street
The Lukin Street cemetery, Tower Hamlets, London (figure 5.1) was consecrated as the cemetery of the Catholic Mission of St. Mary and St. Michael, and was in use for just 11 years (1843–1854)(Miles and Powers, 2006). It contains the remains of individuals who died before, during and after the Famine of 1845–52. In 2005, the cemetery was partially excavated by Museum of London Archaeology (MOLA), as part of renovations at the site, which was in use as a school playground. Documentary evidence suggested that the site had been undeveloped prior to use as a graveyard. No evidence was found for any earlier human activity.

The following descriptions are from the original post-excavation report by Miles and Powers (2006) and the forthcoming MOLA monograph (Miles).

The burial ground had disturbed much of the naturally-formed deposits, a yellow/orange sand and gravel: the deepest burials were 3.9 m and the shallowest 0.6m below the modern ground surface. The deep graves penetrated the natural gravel surface into the softer sand beneath. Six separate areas were excavated, a total of approximately 175m² (see figure 5.2). The burials were all supine and extended, probably all in wooden coffins although of the total of 747 individuals who were retained for osteological analysis, only 742 coffins were fully recorded. Although the majority were buried in stacks with a number of individuals in each grave cut, burials were not truncated by other interments.
Figure 5.1 Location of the Lukin Street site (A:LUK04) in the London Borough of Tower Hamlets and within Greater London (re-drawn from Miles, forthcoming)

Figure 5.2 Location of excavated burials at St Mary and St Michael’s burial ground (Miles 2013)
On the main part of the site, the burials were in reasonably well-defined rows in an east-west orientation, with the individuals laid out with the head at the west end of the grave. The most westerly grave cuts within the excavated area held eight adults located in three grave cuts oriented east-west which appeared to be separated from the other burials. Three child burials within the main rows were also orientated east-west.

Most of the surviving coffins appeared to be kite-shaped. Small children and neonates were found in the few rectangular coffins. Coffin design and decoration follow the pattern of other contemporary burial grounds. Where the stacks of coffins had collapsed, it was difficult to establish to which of the burials the iron coffin furniture and fitments were related. Although badly decayed by the soil conditions, it appears that almost all had decorative grips and grip plates, and approximately 38% had stud decoration.

Epigraphic information was retrieved from a total of 203 breast plates (depositums), 34 of which contained full names, 87 the year of death, and the others revealed partial names or titles. Only one of these breast plates was lead, and no lead coffins were present, which could be interpreted as either a cultural or economic choice. It appears from the information on coffin plates, that each grave represents the burials on a single day rather than family plots.

Preservation of other materials included 29 coffins with resin beds, evidence for textiles in the interior of 26 and two pillows.

5.2.2 Lukin Street: demography

The demographic data and figures are adapted from “He being dead yet speaketh” a monograph reporting three post-medieval sites in London, including Lukin Street (Miles 2013).

The total number of individuals fully analysed and recorded from the site is 705, of which 62% (437) were subadults, and 38% adults (268). The adult male/female ratio was 1.4:1, and the proportion of males in the adult sample (143/268: 53.4%) is significantly higher than females (105/268: 39.2%) (p ≤ 0.001). The comment is made in the report that the M/F ratio is much higher than that expected ratio of births in a population (Miles 2013). Of the adults, only 12/268 were considered too incomplete for accurate sexing, which demonstrates that the skeletal remains were very complete and well-preserved.
The age at death profile for the population is similar to most post-medieval assemblages with a peak in the 1-5 year age group (figure 5.3)(Chamberlain 2006, 90). There was no significant difference in the male/female adult age at death (figure 5.4).
Within the subadults the highest mortality is seen in the 0-3 year olds, with a peak at 1 year (figure 5.5). When the groups assigned a gestational age are assessed, there is a peak at 38 weeks (full-term) compared with 37 and 40 weeks (figure 5.6).

One adult female (LUK 1312) was found with foetal remains (LUK 1345) of approximately 30 weeks gestation within the pelvic cavity.
5.2.3 Kilkenny Union workhouse Famine cemetery

The description of the site is adapted from the excavation report by O’Meara (2006) and the doctoral thesis by Geber (2012b). During the building work for the “McDonagh Junction” shopping complex development, at the junction of John Street and Dublin road, an unmarked and unrecorded burial ground was found at the north-eastern corner of the former Union workhouse grounds, Kilkenny (figure 5.7).
After monitoring and test assessment by Kilkenny Archaeology in 2005 it transpired that the site at the Kilkenny Union workhouse was a mid-19th-century burial ground. Excavations were carried out by Margaret Gowen & Co. Ltd. from January to June 2006. An isolated cremation deposit with associated pottery, probably Bronze Age, was uncovered, truncated by the next phase of activity in the mid-19th century. The burial ground was located to the north-east of the Workhouse infirmary building, and occupied approximately 500m². The 62 complete or partial subrectangular pits revealed had been dug through the natural silt subsoil to an underlying layer of free-draining gravel. The complete pits measured 1.5-2.5m by 1.5m, with a maximum depth of 1.2m. Human
remains were found in 61, of which 19 were truncated by modern activity and three contaminated with diesel. The pits were roughly arranged in rows aligned south-west/north-east (figure 5.8). The remains of 970 individuals were recovered, all but four positioned with the head to the south-west. Each pit contained multiple burials laid out in rows of three or four and buried four to six deep, varying from nine to 25 interments in each.

All the individuals had been buried in wooden coffins with some fragments of pine surviving. Iron coffin nails, found in the surrounding soil, were heavily corroded. A mixture of topsoil, silty subsoil and gravel had been used as backfill for the pits and inclusions of lime and sulphur were recorded. A number of textile pouches containing rosaries were found, although no clothing or shroud material survived. The material items found included personal items such as copper finger rings and religious medals, pottery, glass and clay pipes confirming the broadly mid-19th century date for the site. The minute books for the workhouse indicate a date between August 1847 and March 1851 for the interments (and see chapter two, section 2.1.10).

5.2.4 Kilkenny Union workhouse: demography

The information in this section is taken from the osteological report by Geber (2011). The burial ground at Kilkenny Union workhouse contained the remains of 970 individuals. Subadults represented 56% (545/970) and adults 44% (425/970), with an adult male/female ratio of 1.04:1, not statistically significant. Of the adults, 32/970 (3%) were considered too incomplete for accurate age assessment, demonstrating that the skeletal remains were well-preserved.

The age at death profile for the population is different to most post-medieval assemblages (see section 5.3.1 and figure 5.3, Lukin Street) with two peaks, one in the 1-5 year/6-12 year age groups, and one at 36-45 years (figure 5.9). There was no significant difference in the male/female adult age at death (figure 5.10). In historical famines, the demographic data has shown that the highest levels of mortality occur in the very young and elderly, and that females have an advantage in survival over males (Speakman 2013). The demographic profile in figure 5.9 is consistent with this pattern: however, there are a higher proportion of females than males within the 26-35 year age group at Kilkenny (figure 5.10). This could reflect the demography of the workhouse itself, as it was the policy of the Guardians to admit orphaned children, whole families
or the aged and infirm (Geber 2011), meaning that able-bodied men made up a smaller proportion of the inmates than in the population outside.

Figure 5.9 Distribution of aged individuals from Kilkenny Union workhouse (data from Geber (2011))

Figure 5.10 Adult age distribution from Kilkenny Union workhouse (data from Geber (2011))
5.3 Samples

This section provides details of the samples from each site. For a full list of skeletal numbers, their age and sex and which samples were taken from each individual, please see tables A.1, A.2, A.3 and A.4, Appendix 1.

5.3.1 Bone samples

From Lukin Street, bone samples were analysed from 119 individuals. Age and sex were assessed by combining epigraphic data with the results of osteological analysis provided by MOLA. All were cortical rib apart from two neonates, where the only large enough sample of bone available was parietal. The samples in this study were from well-preserved bones with no evidence of new or pathological bone formation. Sample numbers were limited by MOLA who allowed a maximum of 10% from each age group.

Bone was analysed from twenty individuals selected from the Kilkenny Union workhouse, reflecting a range of ages and both sexes, and where possible, pathology, as determined by osteological analysis (Geber 2012b). Bone preservation was good with no evidence of pathology or new bone formation on the samples. All were samples of cortical rib.

5.3.2 Hair samples

Six of the 119 individuals sampled for bone from Lukin Street site had sufficient hair retained for a bulk sample to be taken and analysed. It is unusual for any hair to remain in open cemeteries rather than crypt burials and suggests favourable preservation conditions for these remains (Wilson and Cadwallader, 2010). The hair samples in this study were all short (less than 2cm in length) and securely attached to surviving scalp tissue. Teeth were also collected from these six individuals.

5.3.3 Incremental dentine sections

Incremental dentine sections were taken from a total of 36 teeth. Ten were from individuals recovered from Kilkenny Union workhouse (KUW), 26 from Lukin Street (LUK). Of the KUW teeth, five were permanent first molars (M1) and five were permanent second molars (M2). The LUK teeth were as follows: seven M2s, eight M1s, one permanent second premolar (PM2), one permanent canine (C), three deciduous first molars (DM1) and six deciduous second molars (DM2).
5.4 Bone collagen extraction.

The aim of this procedure was to remove surface contamination and, as far as possible, any mineral content of the bone leaving the organic portion undamaged. During filtration, any remnants which are larger or smaller than collagen fibrils are excluded, and the resulting organic material is freeze-dried to obtain a dry product which can measured by mass spectrometry.

5.4.1 Cleaning and sample preparation

All samples of bone were cleaned to remove surface debris. Air abrasion equipment, using aluminium oxide powder (53μ), was used to gently abrade the surface of the bone and the cut ends. A section of approximately 200-300mg was cut from the bone, weighed and placed into a glass tube. Because collagen fibrils follow the “grain” of the bone as far as possible, the bone was kept in its original shape to maximise the collagen yield (Collins and Galley 1998).

5.4.2 Demineralization

The samples were demineralized in a 0.5M aqueous solution of hydrochloric acid (HCl) in a refrigerator at 4⁰C. Slow demineralization under low temperature reduces the risk of hydrolysis of the protein molecules within the collagen (Collins and Galley 1998; Cleland et al. 2012). The tubes were covered with a loose layer of aluminium foil to protect the samples from contamination and to allow the CO₂ gas produced to escape. The samples were monitored daily and the acid changed periodically until no bubbles were evident and the bone had become soft and gelatinous. For most bone samples in this study this took approximately 14 days. The bone samples were then rinsed 3 times in deionised water.

5.4.3 Gelatinization and filtration

In order to produce soluble collagen, the triple helix structure of the protein was denatured by heating the samples in a weak acid solution of HCl (pH 3). The temperature and duration of heating was carefully controlled to maximise the yield but avoid degrading the protein (Brown et al. 1988). The samples were heated at 70⁰C for 48 hours and the solution then filtered to remove residues using 8μ Eeze© filters (Elkay Laboratory Products (UK) Ltd). The smaller contaminants were removed using ultrafiltration (Brown et al. 1988; O'Connell and Hedges 1999) to remove any
molecules below 30,000 Dalton. Amicon® (Millipore corporation, Billerica, MA, USA) filters were rinsed once with 0.1M NaOH and 3 times with deionised water following the manufacturer’s recommendation to remove any contamination from the protective glycerine coating. The samples were then passed through the ultrafilters using a centrifuge at 2000 rpm and the fraction remaining in the filters collected. It must be noted that, although the filtration process will improve the quality of the collagen collected (Bronk-Ramsay et al. 2004), other researchers noted that there was a loss of yield reported as 40-60% (Jay 2005; Müldner 2005) and as much as 86% (Jorkov et al. 2007) depending on the condition of the bone samples.

5.4.4 Freezing and lyophilisation

The collected collagen fractions were placed into test tubes sealed with Parafilm® (Bemis Company, Inc., Neenah, Wisconsin, USA), and frozen at -35°C laid at an acute angle to produce a thin solid layer of frozen substrate with a larger surface area. The Parafilm® was pierced to allow removal of water vapour, and the tubes placed in a freeze-dryer for 48 hours. The lyophilised collagen was then reacclimatised to laboratory conditions, weighed and transferred to microtubes for storage prior to measurement by mass spectrometry.

5.5 Incremental dentine collagen analysis

The following two methods are detailed in Beaumont et al. (2013b). This section describes the laboratory process that led to the development of the two methods.

5.5.1 Seeking greater time resolution

Following analysis of the results obtained from the bone collagen analysis, it became clear that the individuals whose remains held the most interesting carbon and nitrogen isotope ratios were mainly the juveniles from both populations (Beaumont et al. 2013a). For most individuals, a tooth had been collected, and in some cases the root of this tooth was still developing at the time of death. Where hair was not available, the root dentine would then represent the last tissues to form prior to death. Dentine collagen has been used in the archaeological literature as a way to reconstruct diet during childhood, and compared to the bone collagen values to establish dietary changes throughout life and possible migration (Chenery et al. 2011). The intention was always to carry out bulk dentine collagen analysis of some of the population from each cemetery. Fuller et al. (2003) had
demonstrated that differences in the values from different parts of the tooth could give
greater time resolution, although the maximum number of sections achieved was 5, and
there appeared to be some confusion in the paper whether dentine could remodel, which
could change the timing of dentine mineralization.

Human dentine forms at a regular rate and does not remodel (Dean and Scandrett 1995;
Nanci 2003b) (see section 4.4), and the age at which teeth develop has been well-
established in clinical, forensic and archaeological research (Brown 1985; Hillson 2005;
AlQahtani 2009). Studies have shown that the rate of growth of teeth during childhood is
extremely robust regardless of genetic origin or socioeconomic status (Reid and Dean
2006; Cardoso 2007; Conceição and Cardoso 2011): the developmental stage of teeth is
used as a preferred method for the age estimation of juveniles, both modern and in past
populations. Thus it is possible not only to measure the carbon and nitrogen isotope ratios
in the latest forming part of the root, but also to section the tooth root and obtain values for
earlier periods in life and to estimate the age at which each section was formed. Using
the dentine collagen from any individual gives the $\delta^{15}\text{N}$ and $\delta^{13}\text{C}$ values during the period of
formation of the tooth, and thus the childhood diet of any individual regardless of their age
at death. The importance of this is that direct comparison can be made between a juvenile
who died and an adult who survived, at the same age, and avoids any bias normally seen
with the “osteological paradox” (Wood et al. 1992).

Developing a method for sectioning and analysing any tooth root relies on two factors:
the ability to produce a reliable and reproducible section size; and the section size being
large enough to produce sufficient collagen to measure using the available instruments
for mass spectrometry. However, sampling which follows the curve of the visible
dentinal tubules may not greatly improve the resolution of the signal because
mineralization proceeds from the EDJ or CDJ towards the pulp chamber. Consequently,
even if a single layer of dentine between dentinal tubules is sampled, it will contain
dentine secreted by each odontoblast in the layer over a period of time, which still
produces an average value. At a rate of 3-5µm per day, this could be 100-150 days
depending on the thickness of the dentine between EDJ/CDJ and the pulp chamber.
Sampling along the Andresen bands (see figure 4.3) would represent the ideal but is
technically difficult because these are only visible with microscopy and a longitudinal
ground section, and resulting samples would be too small for isotope analysis. When
designing a sampling strategy the effect of cementum and secondary/tertiary dentine should also be taken into account. The impact of these tissues on dentine collagen isotope results is expected to be minor relative to the bulk of the tissue and may be avoided altogether by appropriate sample selection and preparation. For instance, the thin cementum layer can be removed during mechanical cleaning of the tooth root surface and secondary dentine may be avoided through selecting, where possible, caries-free and unworn teeth where such deposits should be minimal, or by reaming out the pulp cavity before sampling. As the root develops, it will grow in thickness towards the pulp chamber as well as in length (figure 4.3). Comparison of the most recently mineralised edge of a developing tooth with the same section of a fully developed tooth may run the risk of ignoring this thickening, but because each increment represents an average over a period of time, should not affect the general trends seen.

The first teeth to be sectioned were modern, donated teeth, and initially sectioning was carried out freehand, using a diamond saw in a straight motor-driven handpiece (following a similar method to Fuller et al., 2003). The main problems with this approach were: difficulty in producing sections of regular width, manually holding the tooth still, and collecting the very small increments which could be easily displaced by the rotating saw. Using a fixed Isomet saw allowed better control over the size of section, but gripping the sample was still a challenge. Method 1, (figure 5.13) embedding the teeth in plaster allowed much better positioning of the tooth for the section to be cut, and collecting the embedded sample was much easier. However, roots with a large degree of curvature or with very fine developing root tips caused problems with the accuracy of the section sizes. Kirsanow et al (2008) had produced small samples from ovicaprid dentine which had been demineralised before sectioning. For method 2, (figure 5.14) a longitudinal section of a single root, or a whole root of a multi-rooted tooth, was removed and demineralized whole prior to sectioning. This allowed the freedom to follow any curvature, and manage the sectioning of thinner areas of root, or to cut an accurate final section of a developing apex.

The sample sizes were a potential problem: they could be too small to produce duplicate measurements from the instrument available. The modern tooth samples produced for the pilot study were demineralized, gelatinised, filtered and ultrafiltered following the bone collagen methods above (section 5.2). Because dentine is a much denser tissue than bone bulk collagen yields are generally higher than those for bulk bone. However, the mass of
collagen produced after filtration was still very low. In order to achieve sufficient sample to measure, the sections had to be combined, thus reducing the time resolution for each sample. In order to overcome this problem, the sections from the teeth embedded in plaster (method 1) were demineralised in microtubes rather than glass test tubes, and remained in these throughout the procedure. The demineralised root sections from method 2 were placed into microtubes prior to gelatinization. No filtration was carried out, although the gelatinised samples were passed through a centrifuge prior to freezing. Any residue at the base of the sample was then discarded at the weighing stage. The proof that this approach was valid was that the C:N ratios and elemental mass percentages of the measured collagen remained within the range deemed acceptable by Ambrose (1993) and van Klinken (1999).

5.5.2 Cleaning

The surfaces of the roots of the teeth were gently abraded with aluminium oxide powder (grains of 53μm diameter) to remove any surface debris: this procedure will also remove any adherent calculus and most of the cementum layer.

5.5.3 Method 1, embedding prior to sectioning

The palatal root and the corresponding portion of coronal dentine were sectioned using a diamond saw in a straight, motor-driven dental handpiece, and the overlying enamel removed using dental burs and saws. Instruments were cleaned between samples with 4M nitric acid. The dentine was embedded in a block of a 50:50 mixture of dental plaster and dental stone measuring 1cm x 1cm x 10cm, with the root tip to the end of the block. The block was then sectioned transversely using a Buehler Isomet slow speed saw fitted with a micrometer gauge, abrasive wafering blade and cooling water bath. Accurately measured sections were produced throughout the length of the dentine, starting from the root apex (figures 5.13 and 5.14). The dentine slices were then removed from the plaster, and placed in labelled microtubes. In order to achieve sufficient collagen for duplicate analyses, a minimum dentine weight of 10mg was required before demineralisation.

5.5.4 Method 2, sectioning after demineralization

Using a diamond saw in a dental handpiece as above, a single root and the corresponding portion of crown was removed from a molar tooth. As much as possible of the enamel was carefully removed, leaving the EDJ intact. The complete dentine section was
demineralised (see method below). The demineralised dentine section retained its original shape and was divided into transverse samples at 1mm intervals by hand using a sterile scalpel and optical loupes, measured by metal ruler along its length (figure 5.15). In these teeth, the sectioning commenced from the coronal dentine horn (i.e. the opposite direction from method 1). Each sample was labelled for identification before processing. In order for each dentine section to produce sufficient collagen for duplicate measurements, a minimum weight after demineralization of 2.5mg was required.

Figure 5.13 Diagram showing direction of sectioning procedure, method 1 (drawn by P.Montgomery).
Figure 5.14 Embedded human tooth root is sectioned using fixed rotating saw

Figure 5.15 Demineralised human tooth root is sectioned using a scalpel blade
5.5.5 Collagen extraction

The same method for collagen extraction and isotopic analysis was applied to all samples and is similar to the method for bone collagen extraction. Collagen was prepared from the dentine sections using a protocol based on the modified Longin method, but omitting any filtration (Brown et al. 1988; O’Connell and Hedges 1999). The samples, after sectioning in method one (5.5.3), and prior to sectioning in method two (5.5.4), were demineralised in 0.5M hydrochloric acid at 4° Celsius. The pre-cut sections demineralised quickly, within 7-10 days, while the whole roots took 21-28 days with the acid replenished about every 4-5 days. The demineralised sections were rinsed with de-ionised water and placed in sealed microtubes with a pH 3 hydrochloric acid solution at 70° Celsius for 24 hours to denature the collagen. No filtration was carried out, although any debris at the base of the microtubes was removed after centrifugation. The samples were frozen and then freeze dried, and stored in the microtubes before weighing and measurement by mass spectrometry.

5.5.6 Determining the time of life represented by each section

For all permanent teeth, crown initiation occurs when the ameloblasts and odontoblasts begin to move away from the EDJ secreting enamel and dentine matrix respectively (and see section 4.4). If the dentine within a permanent tooth is forming at about 3-5µm per day (Dean and Scandrett 1995) then it will take at least 200 days for the dentine to reach a thickness of 1mm. This means that the first 1mm sample of crown dentine represents at least the first 9 months of dentine formation. Thus the isotope values will be an average from the date of crown initiation over approximately 9-12 months. For this reason, each sample is shown as representing the mid-point of the age during which the section would form, e.g. the first section for the M1s is shown as representing 0.5 years. Deciduous teeth begin to form in utero: deciduous molars initiate at 30 weeks gestation (2 months before birth) and are complete at 3±0.25 years (DM1) and 3.5±0.25 years. This means a total development time of 38±3 months for DM1 and 42±3 months for DM2. The roots of the complete deciduous molars sampled in this study were approximately 9-10mm in length, so each 1mm section will represent ≤4.5 months of dentine formation, and the midpoint of the first section is shown as representing birth.

In order to check that these estimates are reasonable, measurements have been obtained from micro-CT scans of developing deciduous molars and first permanent molars from
the Stack collection of known-age teeth (by kind permission of the Royal College of Surgeons). These were scanned using a SkyScan 1172 as part of a NERC standard grant (NE/F018096/2, PI Dr Janet Montgomery), investigating patterns of enamel mineralization. CT slices were selected which represented the sub-cuspal (i.e. first-forming) section of the tooth and, using SkyScan software, measurements were taken of the depth of dentine from the EDJ to the pulp chamber. These measurements confirm that 0.85mm of dentine was present at 8 months and 1.5mm of dentine present at the age of 11.5 months in M1, and 1.4 mm of dentine at the age of 8 months in deciduous molars (Montgomery and Beaumont, unpublished).

The length of roots of the same tooth varies between individuals (Hillson 1996). In this pilot study, sampling widths were used regardless of the actual length of the root. This has required calculating an approximate age for each section based on the developmental ages at commencement and completion of the dentine, the actual length of the root and the number of sections. For example, using the AlQahtani Atlas (2009), the age at which an M2 begins to form is approximately 2.5 years ± 0.5 years, and the age at apex closure is 15.5 years ± 0.5 years. Thus the tooth takes approximately 13 years to fully form. Where a fully-formed tooth measures 15mm from the tip of the coronal dentine to the apex, and 1 mm increments were cut, each increment represents 1/15th of 13 years. The midpoint for each age range was used as the value for the x-axes. Where 0.75mm increments were cut, and with a longer tooth with more sections, temporal resolution is higher. For samples where the tooth was still developing, the stage of development at death was assessed using the descriptions of Moorrees et al. (1963) and the average age at that stage established from AlQuahtani (2009). The number of years taken to reach that stage (i.e. average age at death – average age at initial tooth formation) was then divided by the number of increments obtained to achieve an estimate of the age for each increment. Where two teeth were sampled from the same individual, it was assumed that any variation in developmental age would be the same for both teeth.

5.6 Hair keratin analysis

The bulk hair samples were cleaned prior to measurement following the protocol by Wilson and Gilbert (2007) to remove any residue, natural or cosmetic. The hair was soaked overnight in a 2:1 (V/V) solution of methanol: chloroform and sonicated (10
minutes) three times. The hair was then rinsed three times in deionised water, frozen and lyophilised prior to analysis by isotope ratio mass spectrometry.

5.7 Stable isotope ratio mass spectrometry

All the isotopic measurements in this study were carried out at the University of Bradford Stable Light Isotope Laboratory, using isotope ratio mass spectrometry (IRMS).

5.7.1 Principles of mass spectrometry

Mass spectrometry uses the different weights of isotopes as a means of separating and then measuring the proportion of isotopes: because the isotopes have different mass, when they are propelled through a low pressure system they will move at different speeds.

A mass spectrometer can be simply described as an instrument which contains a source of charged ions, a means of deflecting those ions using a magnetic or electronic system which will cause them to separate, and a method of collecting and counting the numbers of ions of each mass (figure 5.16)(Pollard et al. 2007). For light stable isotopes the source is usually gaseous, including the two instruments used for this study, which are continuous flow mass spectrometers.

![Diagram of the basic components of a mass spectrometer (P.Montgomery and author)](image)

Figure 5.16 Diagram of the basic components of a mass spectrometer (P.Montgomery and author)
5.7.2 Measurement of the samples

All the collagen samples were weighed into tin capsules. Bone collagen samples were measured in duplicate using a Europa/Sercon Scientific 20/20 mass spectrometer interfaced with a Europa Roboprep elemental analyser. The samples are compared to an internal reference standard, in this case fish gelatine, included in the sample run at about every 10th position. The optimum sample size for the Europa is 1.0mg±0.1mg. Hair samples were also placed in tin capsules and measured in duplicate using the Europa.

Dentine samples were measured in duplicate by combustion in a Thermo Flash EA 1112 and introduction of separated N₂ and CO₂ to a Finnigan Delta plus XL via a Conflo III interface. The samples are compared to reference gases, CO₂ and N, which are measured before each sample. Blanks are also included for correction to account for the effect of the tin capsules. The optimum sample size for the Finnigan is 0.5mg±0.1mg. The potato and buttermilk samples were also measured on this instrument.

The collagen samples were interspersed throughout the run with both internal standards and international standards, values are shown in table 5.1. Calibrated against these standards, the analytical error at 1 standard deviation was ±0.2‰ or better.

<table>
<thead>
<tr>
<th>International standard</th>
<th>$\delta^{13}C$‰</th>
<th>$\delta^{15}N$‰</th>
</tr>
</thead>
<tbody>
<tr>
<td>IAEA 600</td>
<td>-27.77±0.04</td>
<td>+1.0±0.2</td>
</tr>
<tr>
<td>IAEA CH6</td>
<td>-10.45±0.03</td>
<td></td>
</tr>
<tr>
<td>IAEA CH7</td>
<td>-32.15±0.05</td>
<td></td>
</tr>
<tr>
<td>N1</td>
<td></td>
<td>+0.43±0.2</td>
</tr>
<tr>
<td>N2</td>
<td></td>
<td>+20.41±0.2</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>University of Bradford Stable Light Isotope Laboratory standards</th>
<th>$\delta^{13}C$‰</th>
<th>$\delta^{15}N$‰</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fish gelatine</td>
<td>-15.52</td>
<td>+14.45</td>
</tr>
<tr>
<td>BLS</td>
<td>-21.59±0.25</td>
<td>+7.65±0.25</td>
</tr>
</tbody>
</table>

Table 5.1 Carbon and nitrogen isotope ratio values for international and laboratory standards used in this study
5.8 Quality parameters

5.8.1 Hair keratin

Hair can be subject to taphonomic alteration in the depositional environment from the action of keratinolytic fungi. However, where hair survives, as it is mainly composed of the protein keratin, the bulk amino acids are largely unaltered and it can usually be considered suitable for isotopic analysis (Thompson et al. 2013). Hair is morphologically assessed for signs of taphonomic damage, and the isotopic data subjected to the quality parameters as collagen (see sections 5.9.4 and 5.9.5 below).

5.8.2 Defining collagen

Brown et al. (1988) used the term “protein remnants” rather than “collagen” as other proteins from the bone such as osteocalcin may remain, along with contaminants such as humic and fulvic acids. Collagen itself is a robust protein (see section 4.2), but may be subject to denaturing as a result of the conditions and time spent in the burial environment. However, research has given a range of values which can be used as indicators that the substance produced is of a sufficient quality to give reliable data (DeNiro 1987; Ambrose 1993; van Klinken 1999). Throughout the thesis, the term collagen is used to describe the organic product of the bone and dentine extraction methods above, which was then measured for $\delta^{15}$N and $\delta^{13}$C values.

5.8.3 Collagen yield

The collagen yield (the percentage by mass of collagen produced from the original sample) is an indicator of the state of preservation of the bone, although this will be reduced by the filtration process (see section 5.4.3). Ambrose (1993) suggests a lowest acceptable yield of 1.2%, while van Klinken (1999) suggests a lower range of 0.5-1.0% although all parameters should be taken into account before rejecting the data produced.

5.8.4 Elemental mass percentages

Well-preserved archaeological bone should have elemental mass percentages which are comparable to modern bone. The acceptable ranges suggested by van Klinken (1999) are 30-50% carbon and 10-18% nitrogen by weight. Ambrose (1993) states that modern bone collagen contains more than 45% carbon and 18% nitrogen. Lower percentages can indicate the presence of inorganic contamination, while higher ones can be due to non-collagenous organic substances (van Klinken, 1999).
5.8.5 C:N ratios

Collagen protein has a characteristic amino acid composition (Smith et al. 2009), and any contamination or alteration of the protein will result in changes to this. Keratin has a different but also characteristic amino acid composition (O'Connell et al. 2001; Smith et al. 2009) The ratios of atomic carbon to nitrogen (C:N) have been used as a relatively simple way to gauge whether the collagen has the same amino acid composition as modern collagen (and keratin the same composition as modern keratin). The ratio is calculated by adjusting the mass by the atomic weights of the elements, i.e.

\[ \frac{C}{N}_{\text{atomic}} = \left( \frac{\%C}{\%N} \right) \times \left( \frac{14}{12} \right) \]

DeNiro (1987) showed that a range of 2.9-3.6 was acceptable and probably close to the values of fresh collagen: outside this range the collagen is likely to have been altered by the burial conditions. In an assessment of the relative importance of the different parameters, van Klinken (1999) recommends using a narrower range of 3.1-3.5. For keratin O’Connell and Hedges (1999) recommend using the range of C:N ratios for modern hair samples which is 3.00–3.80.

The C:N ratios and collagen yield for the samples in this study are reported in chapter six, results.
Chapter Six

Results

6.1 Introduction

In this chapter, the results of carbon and nitrogen isotope ratio measurements of the bone collagen, hair keratin and incremental dentine collagen from Lukin Street and Kilkenny Union workhouse are presented. All the data tables are located in Appendix 1. The bone collagen and hair results have been published in Beaumont et al. (2013a). Some of the incremental dentine results have been published in Beaumont et al. (2013b). Developmental ages given for the teeth in this chapter are based on the Dental Atlas by AlQahtani et al. (2009; 2010).

6.2 Bone collagen

The bone collagen results from Lukin Street are shown in Table A.1 (appendix 1) with age and sex assessed by combining osteological analysis by MOLA with epigraphic evidence. The bone collagen results from Kilkenny are shown in Table A.2 with age and sex assessment by Geber (2012b). Hair analysis results are given in Table A.3. The bone collagen yield from both sites was in the range of 4-12% indicating the good state of preservation of the bone and well above the recommended lowest range of 0.5-1.2% (Ambrose 1993; van Klinken 1999). The C:N ratios of both dentine and bone collagen are within the range of 3.1-3.5 proposed by van Klinken (1999) as indicating acceptable quality. The C:N ratios of hair keratin are within the range proposed by O’Connell and Hedges of 3.0-3.8 (1999).

Figure 6.1 shows data for bone collagen from the Lukin Street cemetery and for the Kilkenny Union workhouse cemetery. Four named individuals from Lukin Street with epigraphic and documentary evidence are highlighted. John Broschan (LUK 1212) has the lowest value for δ15N in Lukin Street and Catherine Cotton (LUK 955) the highest, Miguel Pineda (LUK 1348) has the highest value for δ13C and Georgiana Neale (LUK 1312) is close to the mean for the site for both isotopic values (Figure 6.1).
The Kilkenny Union Workhouse data has a significantly lower mean δ^{15}N value than the Lukin Street data (Figures 6.1 and 6.2) (two tailed t-test p< 0.01 with a CI of 98%). All the Kilkenny individuals have δ^{15}N values lower than 12‰. In comparison, only 22 Lukin Street individuals have δ^{15}N values below 12‰ (Figure 6.1). There are three individuals in the Kilkenny population with a δ^{13}C value above -17‰; these values are consistent with the consumption of C_{4} plants (rather than marine foods, given the moderately low δ^{15}N values). The wide range of δ^{13}C values at 1 standard deviation (1SD) seen in Figure 6.4 are as a result of these three juveniles. Only one individual from Lukin Street (Miguel Pineda) approaches these higher δ^{13}C values and has been identified as an outlier within the dataset (Figure 6.3). At Lukin Street, the outliers with the highest δ^{15}N values were infants under 1.5 years of age (Figure 6.2, Table A.1). Figure 6.4 shows δ^{15}N values for bone collagen for all the Lukin Street infants up to the age of four years (n=36) against age at death and the mean value for adult females (n=33). The values for δ^{15}N of the infants reach a peak up to the age of one year and then reduce to within 1SD of the adult female value at about the age of two years (Figure 6.4).
Figure 6.2 Boxplots for $\delta^{15}$N values for bone collagen for individuals from Kilkenny (KUW) and Lukin Street (LUK) showing mean, median and outliers ($\geq 1.5$ times the interquartile range)

Figure 6.3 Boxplots for $\delta^{13}$C values for bone collagen for individuals from Kilkenny (KUW) and Lukin Street (LUK) cemeteries showing mean, median and outliers ($\geq 1.5$ times the interquartile range)
Figure 6.4 Plot of $\delta^{15}$N values for bone collagen for infants aged 0-4 years from Lukin Street Cemetery, London. Infants are plotted relative to the mean and one standard deviation (solid and dashed horizontal lines) of bone collagen values for adult females at the cemetery.

Figure 6.5 Plot of $\delta^{13}$C values for bone collagen for infants aged 0-4 years from Lukin Street Cemetery, London. Infants are plotted relative to the mean and one standard deviation (solid and dashed horizontal lines) of bone collagen values for adult females at the cemetery.
There are, however, three individuals whose δ\textsubscript{15}N exceeds 1SD of the adult female mean after this age, and four individuals with δ\textsubscript{15}N values less than 1SD below the adult female mean.

Figure 6.5 shows a similar trend to the δ\textsubscript{15}N for the δ\textsubscript{13}C values of infants, reducing relative to the adult female mean from a peak at about 1 year. However, seven individuals have δ\textsubscript{13}C higher than 1SD above the adult female mean after the age of 2 years, and the widest range of values with highest and lowest δ\textsubscript{13}C recorded in the infants is seen with a peak at the age of 3 years.

The youngest individual measured, LUK 1345, was a 30 week fetus found in situ with adult female LUK 1312. LUK 1345 has δ\textsubscript{15}N of 13.4‰, which is 1‰ higher than the mother, LUK 1312, with a δ\textsubscript{15}N of 12.4‰. The δ\textsubscript{13}C for this mother/fetus pair is -19.4‰ for LUK 1312, -18.1‰ for LUK 1345 making the fetus value 0.6‰ higher than the mother.

### 6.3 Hair keratin

![Figure 6.6 Plot showing the offset in isotope ratio between bone collagen and bulk hair keratin for δ\textsubscript{13}C and δ\textsubscript{15}N values of six individuals from Lukin Street](image-url)
The results from the hair analysis are given in Table A.3 (Appendix 1) and the offset between δ bone collagen and δ hair keratin

**δ bone collagen – δ hair keratin**

for each individual is shown in Figure 6.6. LUK 1567 shows the largest offset in δ^{15}N. The other 5 individuals show a smaller offset in δ^{15}N, with LUK 1129 displaying the largest offset in δ^{13}C.

### 6.4 Dentine collagen

While many dentine increments were small, they nonetheless produced sufficient collagen for duplicate measurements of optimal-weight samples normally required for the instrument, i.e. 0.5 mg. All C:N ratios were within the range of 3.1-3.5, indicating that collagen of acceptable quality had been recovered (van Klinken, 1999). Any covariation of δ^{13}C and δ^{15}N is therefore not caused by the measurement of less than optimal collagen in the IRMS. The collagen yield from the dentine samples from both methods and all teeth sampled was in the range of 10-19% by weight before demineralization. There was no correlation between the method used and the overall collagen yield.

#### 6.4.1 LUK 1567 M2: covarying δ^{13}C and δ^{15}N

![Graph](image)

**Figure 6.7** δ^{13}C and δ^{15}N values of dentine sections against age for LUK 1567, second maxillary permanent molar
Figure 6.8 $\delta^{13}C$ and $\delta^{15}N$ values against age for dentine sections for LUK 1404, first and second permanent maxillary molars
Figure 6.9 $\delta^{13}$C and $\delta^{15}$N values against age for dentine sections for LUK 1459, first and second permanent maxillary molars.
Figure 6.10 $\delta^{13}$C and $\delta^{15}$N values against age for dentine sections from LUK 47, first and second permanent maxillary molars
The carbon and nitrogen isotope ratios of the incremental dentine samples from LUK 1567 M2 are presented in Figure 6.7, and in Table A.6 (Appendix 1). This second molar contains dentine that formed between 2.5±0.5 to 15.5±0.5 years of age and demonstrates differences in isotope ratios throughout the period of growth of the tooth. Although the absolute δ^{13}C range is less than 2‰ and δ^{15}N up to 3‰, both profiles vary sequentially and increase gradually over time showing a strong positive linear correlation (r^2 = 0.9).

### 6.4.2 M1 and M2 pairs: extending the temporal range

Results for three individuals (Luk 1404, Luk 1459 and Luk 47) are presented in Figures 6.8, 6.9 and 6.10, respectively and in Tables 6.5 and 6.6 (Appendix 1). These plots show that δ^{13}C and δ^{15}N vary throughout the dentine increments of these teeth, and the temporal range can be extended by sampling two teeth from the same individual with overlapping developmental ages. Where the dentine sections overlap in date the isotope ratios are very close, in most cases within analytical error.

### 6.4.3 Short-term changes in δ^{13}C and δ^{15}N

Plots for δ^{13}C and δ^{15}N of dentine collagen increments from four juveniles, KUW 14, KUW 4, KUW 13 and LUK 1212 are presented in Figures 6.11, 6.12, 6.13, 6.14 respectively. The data can be found in Tables 6.5, 6.6 and 6.8 (Appendix 1).

![Figure 6.11 δ^{13}C and δ^{15}N values of dentine sections against age for second permanent molar, KUW 14](image-url)
Figure 6.12 $\delta^{13}$C and $\delta^{15}$N values of dentine sections against age for second permanent molar, KUW 4

Figure 6.13 $\delta^{13}$C and $\delta^{15}$N values of dentine sections against age for first permanent molar KUW 13
In the isotopic profiles for each of the teeth in Figures 6.11-6.14, it can be seen that there is a short-term (2-4 years) change in the $\delta^{13}$C. The roots of these teeth were still incomplete, so the last point of the profile represents the isotope ratios nearest to the time of death. For KUW 14 (Figure 6.11), there is a rise in $\delta^{13}$C of about 3‰ from the age of 6 years and it is still rising at the time of death. The $\delta^{13}$C rises by almost 7‰ from the age of 8 years for KUW 4 (Figure 6.12), and is still rising at the time of death. For KUW 13 (Figure 6.13), the $\delta^{13}$C rises gradually between the ages of 2 to 5 years by about 3.5‰, then falls in the last increment by 2‰ at time of death. LUK 1212 (Figure 6.14) shows a different profile, with $\delta^{13}$C falling by about 2‰ between birth and 2.5 years, followed by a gradual rise of 2.5‰ from 3-6 years, still rising at the time of death.

The $\delta^{15}$N profiles for these teeth also vary: the profile for KUW 14 is fairly flat with very little variation. For KUW 4 $\delta^{15}$N starts at age 2.5 years at about 10‰, falls by about 1‰ age 3-5 years, then rises to a peak age 6 of about 9.5‰, before returning to about 10‰ for the last 3.5 years of life. The $\delta^{15}$N falls gradually from birth for KUW 13 from 14.5‰ to 9.5‰ at age 5 years. This low point in the $\delta^{15}$N coincides with the peak value for $\delta^{13}$C (Figure 6.13) and then rises to just over 12‰ at time of death. The $\delta^{15}$N profile of LUK 1212 has a steep fall from 15.5 to 9.5‰ in the period from birth to age 4.
years, rising again by time of death to about 10.5 ‰, with a profile that appears to lag behind the earlier fall and rise in δ¹³C by about 2 years.

There appear to be different patterns of covariance of δ¹³C and δ¹⁵N in these four molar teeth, ranging from no obvious correlation in KUW 14, KUW 4, to a profile in KUW13 where the δ¹³C and δ¹⁵N appear to move in opposite directions at the same time, and LUK1212 where the δ¹³C and δ¹⁵N move in the same direction, after a time lag.

6.4.4 Profiles from individuals who lived beyond root formation, M1

First permanent molars (M1) begin to form just before birth and the root apices are completed at 9.5±0.5 years. Figure 6.15 presents the incremental dentine collagen isotopic profiles for δ¹⁵N and figure 6.16 for δ¹³C for all M1s sampled from the Lukin Street and Kilkenny Union workhouse individuals which had completed apices, i.e. the individual lived beyond the age of 9.5±0.5 years. The data can be found in Tables 6.5 and 6.6 (Appendix 1).

The profiles generally show little variation in consecutive values throughout the formation of the tooth, apart from KUW 9 who displays a fall in both values by about 1‰ at 1 year, then a rise of 1‰ to a steady δ¹³C from age 2, and a gradual rise of 2‰ in δ¹⁵N to the age of 5 years which then becomes more steady. LUK 1404 and 1459 show a gradual rise in δ¹⁵N of about 1.5‰ throughout the tooth although the change between consecutive increments is small.

6.4.5 Profiles from individuals who died during root formation, M1

The incremental dentine collagen δ¹³C and δ¹⁵N profiles of the individuals who died during root formation, Figures 6.17 and 6.18, display a wider variation in their profiles than the individuals who survived this period of life. The data is located in Tables 6.5 and 6.6 (Appendix 1). The profiles of LUK 419 and KUW 12 are fairly flat and resemble the flat profiles seen in figure 6.15, while LUK 413 shows a gradual rise of about 1‰ from birth to death. The other profiles show a more rapid fall of between 1 and 4.5‰ either just after birth, or following a rise between birth and 1 year.

The δ¹³C profiles again show some variation (Figure 6.18), with LUK 413, 419 and 259 producing relatively flat profiles resembling those in figure 6.16. The remaining individuals show greater changes between consecutive increments, with δ¹³C rising or
falling by between 1.5‰ and 4‰ overall (KUW 13), and in some cases both rising and falling during the lifetime of the individual.

Figure 6.15 $\delta^{15}$N values of dentine sections against age for first permanent molars of individuals who lived beyond root completion, Lukin Street and Kilkenny Union workhouse

Figure 6.16 $\delta^{13}$C values of dentine sections against age for first permanent molars of individuals who lived beyond root completion, Lukin Street and Kilkenny Union workhouse
The overall range of δ¹³C and δ¹⁵N and the variation between consecutive increments in some individuals who died during tooth formation is much larger than in any of those who survived.

Figure 6.17 δ¹⁵N values of dentine sections against age for first permanent molars of individuals who died during root completion, Lukin Street and Kilkenny Union workhouse

Figure 6.18 δ¹³C values of dentine sections against age for first permanent molars of individuals who died during root completion, Lukin Street and Kilkenny Union workhouse
Profiles of deciduous molars

The deciduous first molar (DM1) and second molar (DM2) teeth begin to form about 30 weeks in utero, and their roots are completed at the age of 3± 0.5 years (DM1) and 3.5± 0.5 years (DM2). Thus the first dentine collagen increment will include some tissue formed before birth. Figures 6.19 and 6.20 present δ¹⁵N and δ¹³C profiles respectively for the dentine collagen increments for two DM1s which were still forming at time of death, six DM2s forming at time of death, and LUK1033 whose roots were complete, but apex not closed: epigraphic evidence shows he was aged 3 at death. The data for these teeth can be found in Table A.9 (Appendix 1).

LUK 1033 has a δ¹⁵N profile which rises from birth by about 0.7‰ peaking at the age of about 0.5 years, and then falls gradually by 2‰ to achieve a flat profile after the age of 1.5 years. Three of the other individuals also show a profile which rises from birth between 1‰ and 1.5‰, LUK 955, 316, and 567, and reaches a peak at between 0.5 and 1 year before falling. LUK 955 then rises again by a further 1.5‰ before death at 1.5 years, while the LUK 316 and 567 show a more gradual drop to a flatter profile at about 1.5 years. Four individuals, LUK 923, 517, 613 and 724 have a drop in δ¹⁵N of between 1.5‰ and 4‰ starting immediately after birth and achieving a fairly flat profile at the age of about 1.5 years. The first forming increment was missing from the profile of LUK 431, but from the second, there is a gradual fall of about 2‰ until death aged 2.5 years.

The δ¹³C profiles also show two main patterns: a slight rise or a drop after birth. LUK 955, 923, 316, and 567 δ¹³C profiles rise between 0.1‰ and 1.5‰ from the first increment and then gradually fall. LUK 431, while missing the first increment, appears to follow the profile from the rising group.

LUK 517, 613, 724 and 1033 show δ¹³C profiles which drop between 0.1‰ and 1.2‰ from the first increment and then continue to fall gradually. The longest surviving individuals, LUK 1033, 923 and 724, achieve a flatter profile after the age of 1 year, while the other six δ¹³C profiles appear to still be falling at time of death.
Figure 6.19 δ¹⁵N values of dentine sections against age for first (DM1) and second deciduous molars from Lukin Street

Figure 6.20 δ¹³C values of dentine sections against age for first (DM1) and second deciduous molars from Lukin Street
6.4.7 Profiles of second molars

Second permanent molars (M2) develop between the age of 2.5±0.5 years and 15.5±0.5 years. The data for the M2s is located in Tables 6.7 and 6.8 (Appendix 1). Figure 6.21 and 6.22 present the $\delta^{15}$N and $\delta^{13}$C profiles respectively for the dentine collagen increments from M2s from individuals from Lukin Street and Kilkenny Union workhouse who survived beyond the age of completion of these teeth. With the exception of LUK 1404, there are some features which appear common to all the M2 profiles in Figure 6.21. It appears that all profiles have a rise in $\delta^{15}$N in the last 1 to 1.5 years of the period of growth, and a change in the direction of profile, up or down, at about the age of 4 to 6 years. Figure 6.22 shows a variety of $\delta^{13}$C profiles, both flat and variable, with no discernible common features. LUK 755 has a $\delta^{13}$C profile consistently higher by about 1.5‰ than any other individual in this plot.

Figures 6.23 and 6.24 present the $\delta^{15}$N and $\delta^{13}$C profiles respectively for dentine collagen increments of M2s from individuals from Lukin Street and Kilkenny Union workhouse who died while the teeth were forming. Three profiles, LUK 1459, KUW4 and 10 appear to show the same trend for a rise in $\delta^{15}$N towards the end as the completed teeth; Luk 47 and 1495 have a rise towards the end of the profile with a drop for the time of death increment. All the profiles show a change in direction of $\delta^{15}$N at about 4 to 5 years. The $\delta^{13}$C profiles are variable: LUK 1349 shows a downward trend towards the time of death, while the others all rise, KUW 4 by 6‰ and KUW 14 by 4‰.
Figure 6.21 $\delta^{15}$N values of dentine sections against age for second permanent molars with completed roots from Lukin Street and Kilkenny Union workhouse.

Figure 6.22 $\delta^{13}$C values of dentine sections against age for second permanent molars (M2) with completed roots from Lukin Street and Kilkenny Union workhouse.
Figure 6.23 δ¹⁵N values of dentine sections against age for second permanent molars with incomplete roots from Lukin Street and Kilkenny Union workhouse.

Figure 6.24 δ¹³C values of dentine sections against age for second permanent molars with incomplete roots from Lukin Street and Kilkenny Union workhouse.
6.4.8 Second premolar and permanent canine from named individuals

Figure 6.25 is a biplot of the δ¹⁵N and δ¹³C profiles for the dentine collagen increments for a single second premolar (PM2) and Figure 6.26 for a single permanent canine (C), from two individuals from Lukin Street. The data is located in Table A.10 (Appendix 1). These are from individuals named in Figure 6.1, LUK 1348, Miguel Pineda (PM2), and LUK 1312, Georgiana Neale (C). Both tooth types have development times which are broadly similar to the M2s in Figures 6.21 to 6.24, second premolars (PM2) between 3.5±0.5 years and 14.5±0.5 years, and permanent canines (C) between 0.75±0.25 years and 14.5±0.5 years. The incremental dentine collagen profiles share some common features with the M2s: both have rising δ¹⁵N towards the end of the period of formation and LUK 1348 shows a definite change of direction for δ¹⁵N at about 4 to 6 years, while LUK 1312 has less of a change. The δ¹³C profiles appear to covary with the changes in δ¹⁵N. For LUK 1348, the peak and trough in the δ¹⁵N appears to follow one increment after the δ¹³C peak and trough, and then the two values rise together. LUK 1312 shows the two isotope ratios moving in opposite directions at the same time.

![Figure 6.25 δ¹³C and δ¹⁵N values of dentine sections against age for second premolar, LUK 1348 (Miguel Pineda)](image-url)
Figure 6.26 δ¹³C and δ¹⁵N values of dentine sections against age for second premolar, LUK 1348 (Georgiana Neale)
CHAPTER SEVEN
DISCUSSION

7.1 Introduction

In this chapter, the bone collagen and hair keratin data are analysed with reference to contemporaneous sites in Britain (see figure 1.1). The importance of bone turnover rates is emphasised by the data from Kilkenny Union workhouse and epigraphic and isotopic evidence are combined. The four dietary regimes discussed in the text of this chapter relate to section 3.10.1 and figure 3.6.

The incremental dentine profiles are employed to reconstruct nutritional changes in individuals during the time of tooth formation and as part of lifeways using the bone collagen data, and where available, hair data. The impact of producing incremental data rather than bulk data is discussed.

The current model for breastfeeding and weaning using bone collagen is challenged using the bone collagen and incremental dentine collagen data. New methods are suggested for investigating the health of mothers and juveniles from past populations and evaluated.

Parts of this chapter have been published in Beaumont et al. (2013a ; 2013b)

7.2 Bone collagen and hair keratin

7.2.1 Comparison with contemporaneous British sites

The bone collagen data from this study are compared with data from four contemporaneous published English sites (figures 1.1 and 7.1). These are the sites of Chelsea (Trickett 2006) and Spitalfields (Nitsch et al. 2010) in London, and Coventry (Trickett 2006) and Birmingham (Richards 2006) both in the English Midlands. Spitalfields has the highest mean $\delta^{15}N$ value, and Kilkenny Union Workhouse the lowest. At one standard deviation, the values for Lukin Street overlap the mean of all the other English sites. The range of bone collagen $\delta^{13}C$ and $\delta^{15}N$ values measured in the Lukin Street individuals is greater than the other London sites (figure 7.1). This may be because the Lukin Street sample includes juveniles and migrants. Of the comparative English sites, only the data from St Martin’s, Birmingham includes children (2 of the 17 individuals).
The London sites have higher mean $\delta^{15}N$ values than the sites from elsewhere in England suggesting that the diet in London may differ from other cities. The mean $\delta^{15}N$ value (12.7‰) of the Lukin Street adults alone (n=79) is higher than the mean for all Lukin Street individuals (n=119) (12.6‰) (figure 7.1) thus showing that juveniles are not the source of the higher values from this site. Any putative rise in infant bone collagen $\delta^{15}N$ from breastfeeding is not affecting the population mean $\delta^{15}N$.

There is a statistically significant difference in the $\delta^{15}N$ values of the Kilkenny Union Workhouse individuals and those from Lukin Street. The Kilkenny Union Workhouse data has a significantly lower mean $\delta^{15}N$ value than the Lukin Street data (Figures 6.1 and 6.2) (two tailed t-test $p< 0.01$ with a CI of 98. None of the individuals from Kilkenny are consistent with dietary regime 4 (i.e. elevated $\delta^{15}N$ resulting from nutritional deprivation) (figure 3.6). This may be due to the slow rate of turnover in bone, thereby averaging short-term changes in $\delta^{15}N$ values. Such shifts are visible in studies using the hair of living individuals with short-term nutritional deprivation (Fuller et al. 2004 ; Hatch et al. 2006 ; Mekota et al. 2006). Consequently, it may not be
possible to identify famine in ancient populations by measuring isotope ratios in adult bone collagen.

Hair samples from 19\(^{th}\)-century British sites are rare and sample sizes small due to variable preservation. Samples from City Bunhill, London (a cemetery close to Lukin Street), (Wilson and Cadwallader 2010), Spitalfields, London (O’Connell and Hedges 1999) and West Butts, Dorset, on the south coast of England (Wilson 2008)(see figure 1.1) also suggest higher mean $\delta^{15}N$ values for the London sites, although the number of samples for West Butts ($n=2$) is small. The mean $\delta^{15}N$ is 11.5\(\%\) for Lukin Street, 11.1\(\%\) for Spitalfields and 11.2\(\%\) for City Bunhill. The mean $\delta^{15}N$ for West Butts is 10.1\(\%\).

Individuals analysed from St Martin’s, Birmingham were buried in brick-lined vaults, an indicator of higher socio-economic status (Richards 2006). Chelsea was deemed an area of high socio-economic status in this period and this is borne out by the high quality of the coffins and artefacts in the cemetery and supporting contemporary documentation regarding the family members buried here (Trickett 2006). Lukin Street and the Coventry burials were classified as low socio-economic status both in terms of the populations they served and the artefacts within the graves (Miles and Powers 2006; Trickett 2006). Spitalfields is a cemetery which served a population whose socio-economic status decreased as the silk industry, founded by skilled Huguenot refugees in the late 17th century, suffered when cheap imports, low-paid provincial workers and depressed demand caused unemployment and reduction in wages in the early 19\(^{th}\) century (Nitsch \textit{et al.} 2010). No significant changes were found in the $\delta^{15}N$ values between the identified status groups within Spitalfields (Nitsch \textit{et al.} 2010). Given the evidence above it appears that the higher mean $\delta^{15}N$ values found in bone collagen from the London sites (Chelsea, Spitalfields and Lukin Street) are not related to elevated socio-economic status.

The higher $\delta^{15}N$ values in the London populations may result rather from local agricultural practices. Plants grown on estuarine or salt marsh environments, such as the banks of the Thames in London, can display higher $\delta^{15}N$, thus elevating the values in consumers (Britton \textit{et al.} 2008). Drummond and Wilbraham (1939) state that the waste from the privies of large towns was of great value as manure; this was confirmed in a case study of recycling in 19\(^{th}\)-century dustyards by Velis \textit{et al.} (2009). Because of
the size and population density of London, market gardens had used intensive manuring methods for over 100 years (Strype 1720). Mayhew, in 1846, describes the work of dustmen recycling waste within a “patent manure factory” in the East End (1985). Chadwick, in his report for the Poor Commission on the Sanitary Conditions of the Labouring Population (1842) calculated that “in one year the liquid and solid excrements of a man would produce 16.41lbs of nitrogen, sufficient for...800lbs of wheat or... 900lbs of barley”. The practice of manuring represents a potential cause of higher $\delta^{15}N$ values in London, since this has been shown to raise crop and consumer $\delta^{15}N$ values (Bogaard et al. 2007; Fraser et al. 2011). It was not possible to use $\delta^{15}N$ and $\delta^{13}C$ values from faunal remains to compare trophic levels in the reconstruction of diet as none were available for analysis.

7.2.2 Marine protein consumption

Given the documentary evidence for the consumption of cheap marine foods in London (Mayhew 1985; Tames 2003; Picard 2005) there is little isotopic evidence to support this within the London populations. The combined $\delta^{15}N$ and $\delta^{13}C$ values from the bone collagen of LUK 1348 (Miguel Pineda) (table A.1) and the bone collagen and hair keratin of LUK 755 (Tables 6.1 and 6.3) are consistent with significant marine consumption without the influence of manuring on $\delta^{15}N$; these individuals may be immigrants to London but not from Ireland.

7.2.3 Short-term changes in $\delta^{13}C$ values

The age at death of individuals is of critical importance when interpreting stable isotope data in bone collagen. The International Commission on Radiological Protection (2003) produced a set of reference values for bone remodelling by age (table 7.1).

The individuals from Kilkenny who display $\delta^{13}C$ values indicative of the consumption of C$_4$ plants (figure 6.1 and table A.2) as per dietary regime 3 (figure 3.6), are juveniles aged 6, 7 and 13 years. In such juveniles, bone turnover would be as high as 30-48% per year; hence, there is a strong implication that dietary change in the last year of life will be recorded in their bone collagen. In contrast, the much lower bone turnover rates of adults imply that any significant dietary change in the last one or two years of life is unlikely to make a measurable impact on the isotope ratios of bone collagen (Hedges et al. 2007).
<table>
<thead>
<tr>
<th>Age</th>
<th>Cortical</th>
<th>Trabecular</th>
</tr>
</thead>
<tbody>
<tr>
<td>Newborn</td>
<td>300</td>
<td>300</td>
</tr>
<tr>
<td>1 year</td>
<td>105</td>
<td>105</td>
</tr>
<tr>
<td>5 years</td>
<td>56</td>
<td>66</td>
</tr>
<tr>
<td>10 years</td>
<td>33</td>
<td>48</td>
</tr>
<tr>
<td>15 years</td>
<td>19</td>
<td>35</td>
</tr>
<tr>
<td>Adult</td>
<td>3</td>
<td>18</td>
</tr>
</tbody>
</table>

Table 7.1 Reference values for the rate (in percentages per year) of remodelling of human bone with age (Valentin, 2003).

For the adults in the Kilkenny workhouse, therefore, the change in dietary staple from potatoes ($C_3$) to a short-term maize ($C_4$) relief diet over the duration of the Famine will not be apparent in the isotope ratios of their bulk bone collagen. For the same reason, it is probable that adults from Lukin Street exhibiting the lowest $\delta^{15}N$ are more likely to have ingested a mainly $C_3$ plant-based diet (dietary regime 2) without night soil manuring, estuarine influences or marine foods and, therefore, have originated from outside London. Conversely, children and adolescents who migrated from Ireland and survived the Famine would assimilate the isotope ratios characteristic of a local diet quickly as their bone is remodelled at a much faster rate than adults. The historical evidence for the Famine suggests that the very poorest in Ireland were those who had to survive on dietary regime 3. No individuals exhibiting consumption of maize were identified in the Lukin Street population. Whilst this may be a product of a small sample, it is likely to be the case that individuals with the resources to pay for passage from Ireland to London may have been fortunate enough not to require Famine relief or Workhouse food. Given these constraints, the hair recovered from 6 individuals offers an opportunity to examine their diet in the weeks before death.

7.2.4 Changes between bone collagen and hair keratin

Because of differences in the amino acid composition of the tissue types and formation mechanisms $\delta^{13}C$ and $\delta^{15}N$ values from keratin are usually offset from bone collagen
values with bone collagen showing higher $\delta^{15}N$ values relative to hair keratin by approximately 1-1.5‰, and bone collagen showing higher $\delta^{13}C$ relative to hair keratin by approximately 1.4‰ (O'Connell and Hedges 1999; O'Connell et al. 2001; Cadwallader 2009). The results obtained in this study appear to conform to this model, with the exception of LUK 1567 where $\delta^{15}N$ of bone collagen is almost 2.5‰ higher than hair keratin and LUK 1129, where $\delta^{15}N$ of bone collagen is only 0.2‰ higher than hair keratin (figure 6.6). LUK 755 has bone collagen and hair keratin $\delta^{15}N$ and $\delta^{13}C$ values consistent with a diet rich in marine protein until he died, suggesting that he may have been a recent migrant from somewhere with a diet which differs from that prevalent in London. LUK 1179 has a change in $\delta^{13}C$ with a drop of 1.5‰. This takes her values from -19.0‰ to -20.5‰, and would be consistent with a reduction in the marine component of a mixed C$_3$ plant-based diet. It is possible that LUK 1567 and LUK 1179 may have had a transient dietary change or that the change in values was as a result of the illness that caused their death.

7.3 Combining isotopic and epigraphic evidence

Forty-nine individuals from Lukin Street had fully or partially discernible coffin plates. Of the 22 Lukin Street skeletons with a $\delta^{15}N$ value of less than 12‰, nine have whole or partial surnames, seven of which are of Irish origin. Twenty-five of the sample bearing Irish surnames have $\delta^{15}N$ values above 12‰, and, given the long-term averaging of adult bone collagen discussed above, are unlikely to have consumed the same diet as those from the Kilkenny Union Workhouse site prior to death. These individuals could, therefore, be second generation Irish, women married to a man with an Irish surname, or long-term migrants.

John Broschan (LUK 1212, figures 6.1 and 6.2) has the lowest $\delta^{15}N$ value measured in the Lukin Street sample, and died at the age of 6 in October 1847. His surname could be interpreted as being of Scandinavian origin as “Broschan” means “brother” in Swedish. It could also be a corruption of the Irish name “Brosnan”: in a group with low literacy in English, mistakes and inconsistencies occurred in the recording of names. There are, for example, four different spellings of “Reagan” within this cemetery. It is possible that he was one of the early Irish Famine migrants who died shortly after arrival in London, retaining within his collagen $\delta^{15}N$ values representing a non-manured C$_3$ plant-based diet (dietary regime 2). The presence of cribra orbitalia in his left orbit also suggests that
he experienced systemic stress before death. The other individuals with Irish surnames and low δ¹⁵N values could also be recent immigrants to London. However, Ireland was not the only provider of migrants to London at this time and there is evidence that people from other rural areas also had a restricted diet. Individuals from Scotland, for example, consumed a similarly limited range of foods (oats, pulses and dairy products, or even potatoes) (Floud et al. 1990; Hunter 2000) and thus could have comparable C₃ plant-based δ¹⁵N values to Kilkenny Union Workhouse individuals. A further complication is the tendency for migrants to choose to continue eating a diet similar to the one they left behind. For example, the Registrar General inquired of his District registrars for London in 1843 what was the principal food consumed by the inhabitants of their District. Those who replied for the districts around Lukin Street indicated that mainly bread, potatoes and fish were eaten and “very little butchers meat” (1843). Those still relying for most of their protein on potatoes or bread could still display dietary regime 2 (C₃ plant values for δ¹³C and δ¹⁵N in the bone collagen).

Two of the other named individuals in figure 6.1 have surnames which are common in 19th-century England, although not especially so in London (Archer 2003). Catherine Cotton (LUK 955), the outlier with the highest δ¹⁵N value (figures 6.1 and 6.2, table A.1), died in March 1848 at the age of 11 months. Her high δ¹⁵N value could be explained as the result of a trophic level shift from breastfeeding with a mother who also had a relatively high δ¹⁵N value. It is also possible that she was suffering from nutritional or physiological stress and this could appear as elevated δ¹⁵N in the body tissues of a small child with rapid bone turnover. It seems likely that she was a Londoner.

The other English-named individual is LUK 1312: Georgina Sarah Neale, wife of Andrew Neale, a ballast getter, of 43 Queen Street, who died in 1845 aged 26 of consumption (tuberculosis). Her δ¹⁵N and δ¹³C values at 12.4 ‰ and -19.4‰ fall close to the mean for the Lukin Street population and are consistent with dietary regime 1 (figure 6.1) There is no evidence of raised δ¹⁵N as a result of the chronic illness which caused her death. The entry for her family in the 1841 census records show that she was born in the same district of London in which she died.

Finally, Miguel Pineda, LUK 1348 (also recorded as Penuthera, demonstrating the difficulties of recording the names of those who were illiterate or foreign) died on the
18 January 1846 at 8 Glasshouse Street, aged 30, of “continued fever”. His occupation is recorded on his death certificate as “Mariner” and his name is believed to be Portuguese. A foreign origin and a sea-going occupation concur with his $\delta^{13}C$ and $\delta^{15}N$ bone collagen values of -15.5‰ and 13.3‰ which strongly suggest he was a consumer of marine protein (figures 6.1 and 6.4) and an immigrant.

7.4 Incremental dentine collagen data

Both methods 1 and 2 (chapter 5) showed that it was possible to produce sufficient good quality collagen to obtain duplicate $\delta^{13}C$ and $\delta^{15}N$ measurements from very small (approximately 10 mg) samples of dentine. Samples of this size permit high resolution intra-dentine profiles to be obtained over a range of up to 13 years of childhood from a single tooth, and more when sequentially-forming teeth are combined.

7.4.1 Comparison of the methods

Method 1, where the dentine is still hard and embedded in plaster, permitted accurately measured sections to be produced. However, dentine is lost as the rotating saw grinds away tissue during the process. Using method 2, the softened dentine is cut into sections with a scalpel: it can be difficult to achieve as high a level of accuracy as with method 1, but less tissue is lost. Since each incremental sample contains tissue from a developmental period of several months, the precision of the measurement of the increment width probably does not greatly affect the result (Zazzo et al. 2006).

Method 2 is more appropriate for well-preserved teeth; less dentine is lost in the cutting process, giving better time resolution. Cutting by hand also offers the potential to sample in a way that is more sensitive to the tooth morphology, for example for curved roots, or the thinner tip of a developing or resorbing root. While the process of demineralization takes longer, the need for embedding and access to a cutting blade is not required. Method 1 would be appropriate where site conditions suggest that collagen preservation would be poor, allowing the tooth to be cut while still hard, permitting the production of accurately measured increments.

7.4.2 Comparison of the dentine collagen profiles

The $\delta^{15}N$ and $\delta^{13}C$ profiles for the M2 from LUK 1404 (figure 6.8) suggest that, because only five sections were taken, the values are averaged over the time of growth of the tooth when compared with the larger variations seen in the first molar. With both
LUK 1459 (figure 6.9) and LUK 47 (figure 6.10), the profiles suggest that the variations seen in the first and second molars are related to age: the overlapping $\delta^{15}$N and $\delta^{13}$C profiles show that the small variations within the dentine are generally the same in both teeth, mostly within analytical error. Where there are larger variations, these can be seen in the profiles of both M1 and M2 at the same age, e.g. LUK 1459 (figure 6.9), $\delta^{15}$N at age six to nine years, and LUK 47 (figure 6.10), $\delta^{13}$C at age seven to nine years. This confirms that the profiles reflect changes in the diet over time in teeth with overlapping developmental ages. This finding extends the age range which can be investigated using this technique.

7.5 Interpreting $\delta^{13}$C in dentine collagen increments

As discussed in chapter three, $\delta^{13}$C combined with $\delta^{15}$N can indicate the consumption of aquatic resources and also distinguish between C$_3$ and C$_4$ plants. A time lag in $\delta^{13}$C relative to $\delta^{15}$N may also be possible before changes in the isotope ratios are seen due to the turnover of amino acids in the tissues, and the averaging discussed in chapter three, section 3.8.4, as seen in dietary studies in hair (Huelsemann et al. 2009) and this seems apparent, for example, in the profiles of both LUK 1567 (figure 6.7) and LUK 1212 (figure 6.14).

As seen in section 7.2.3, the bone collagen $\delta^{13}$C seen in some of the juveniles from Kilkenny demonstrate that the short-term maize diet is identifiable. The dentine collagen increment profiles for both $\delta^{15}$N and $\delta^{13}$C from the three individuals with the higher $\delta^{13}$C bone collagen, KUW 14, 4 and 13 are shown in figures 6.11, 6.12 and 6.13 respectively. Figures 7.2 (KUW 12) and 7.3 (KUW 16) show the isotopic profiles for Famine cemetery juveniles whose $\delta^{13}$C values also show changes over time. It would seem from the profiles of the teeth in this study that $\delta^{13}$C is changing as a direct result of changes to the diet. For example:

1) Where $\delta^{15}$N rises at the same time as $\delta^{13}$C, it would seem reasonable to interpret this as a move towards a mixed diet containing more marine protein input (e.g. LUK 1567). LUK 1567 appears to have a gradual change in both $\delta^{15}$N and $\delta^{13}$C from the age of 2.5 years until 15.5 years. These changes are consistent with a change from a terrestrial, plant-based diet to a higher trophic level diet with a marine component. Similar dietary differences were seen between low-status and high-status individuals in Medieval England (Müldner and Richards 2005).
Within the tissues of one individual, this could represent a change in diet after the age of three when the first dentine increment would have formed.

2) The high and consistent δ¹³C profile, and relatively flat δ¹⁵N profile of LUK 755 (figures 6.21 and 6.22) appear to show a diet rich in marine protein input throughout the period of growth of the tooth, and this matches with his bone collagen values (section 7.2.2).

3) Where there is a marked change in δ¹³C, but δ¹⁵N appears to remain fairly stable (KUW 14) or the profile for δ¹⁵N appears to change independently of δ¹³C (KUW 4), given the historical context of the short-term introduction of maize, this could be interpreted as a shift from a diet consisting of C₃ terrestrial plants to C₄, or vice-versa.

4) Where there is a marked rise in δ¹³C and a corresponding fall in δ¹⁵N, this could also represent a change from a mixed diet with some higher trophic level components to a C₄ plant-based diet (KUW 13) and in the case of KUW 12, a short-term change aged 1-3 years, with a return to a more mixed diet later.

There is a possibility of changes in δ¹³C as a result of recycling of essential amino acids: if a trophic level shift can be identified in δ¹⁵N when nitrogen balance changes, the amino acids to which both the carbon and nitrogen atoms are attached will be affected. This could be important, for example in scurvy which was identified in a large proportion of the Kilkenny burials (Geber and Murphy 2012). A deficiency in vitamin C in the diet causes a disturbance in the production of the amino acid hydroxyproline from proline. If this results in a rise in the δ¹³C of this amino acid, the values for collagen as a whole would be proportionately affected.
Figure 7.2 δ¹³C and δ¹⁵N values of dentine sections against age for developing M1, KUW 12

Figure 7.3 δ¹³C and δ¹⁵N values of dentine sections against age for developing M1, KUW 16
7.6 Interpreting δ¹⁵N in dentine collagen increments

As discussed in Chapter Three, δ¹⁵N in body tissues can be affected not only by the trophic level of the foodstuffs consumed and indirectly by agricultural/manuring practices, but also by changes in the nitrogen balance of an individual. Where there is clear evidence for the dentine collagen incremental δ¹⁵N and δ¹³C profiles in individuals to co-vary, that is to change at the same time in the same or opposite directions, these changes can be interpreted as dietary changes which are consistent with previous published studies of bone collagen (see the examples in section 7.5).

In this study, all the M1 teeth where development was complete (i.e. the apex closed) show similar shaped profiles, regardless of the absolute isotope ratios and from both sites (figure 6.15 and 6.16). This would suggest that there may be an underlying physiological trend. Figures 7.4 and 7.5 show the rate of change of δ¹⁵N per year for completed and incomplete M1s respectively. Where there is a more marked rate of change in δ¹⁵N, and where the absolute values change by more than 2‰, these could represent a change in the diet or possibly a physiological response to a major life event. Amongst the incomplete M1s, the δ¹⁵N profiles of LUK 413 and LUK 419 (figure 6.17) are fairly flat and similar to the completed teeth, but all the other teeth have much larger changes in the δ¹⁵N.

The human body attempts to maintain homeostasis (see section 3.4.2), and it appears that this can be seen in the δ¹⁵N dentine collagen profiles of the individuals who survive M1 growth from either Lukin Street or Kilkenny Union workhouse. However, those who died in childhood show a much wider variation in their dentine collagen δ¹⁵N, in both M1s and deciduous molars, and from both sites. There are still some individuals who maintain fairly steady profiles, and some whose profiles are steady for some portion of their lives. Where the greater δ¹⁵N changes cannot be explained by corresponding changes in the δ¹³C as diet related, a physiological response to some form of stress could be the cause.

The historical evidence for these two populations (chapter two) confirms that these individuals were likely to have suffered from a range of stresses as children. Those buried in the Famine cemetery at Kilkenny have experienced a catastrophic famine. The Londoners were likely to be the offspring of low socio-economic status mothers who may themselves have been nutritionally stressed (Miles 2013).
Figure 7.4 Rate of change of $\delta^{15}N\%$ per year for dentine collagen profiles of completed M1s from Lukin Street and Kilkenny Union workhouse.

Figure 7.5 Rate of change of $\delta^{15}N\%$ per year for dentine collagen profiles of incomplete M1s from Lukin Street and Kilkenny Union workhouse.
They would live in overcrowded, poorly heated and ventilated accommodation with inadequate clothing and parents who would need to work to maintain their income (Gaskell 1833). This may have led to difficult choices about childcare: mothers who worked could not breastfeed (Fildes 1986; Nitsch et al. 2011), and evidence for preferential feeding of males and working members of the family (Hollen Lees 1979) suggest a reduced standard of nutrition for females and younger siblings. Infectious diseases such as tuberculosis were easily transmitted in the overcrowded homes (Stein 1950). Not all who were infected with the tubercle bacillus developed the disease: the worst affected were those with compromised immunity (Barnes 1995). Contaminated and badly-stored food and drink could be another source of infections (Drummond and Wilbraham 1939). Those who were not breastfed did not benefit from maternal immunity to local infections (Fildes 1986), and those already suffering from nutritional stress have been seen to be less able to fight off the diseases endemic in the population at the time (Various 1838-1856).

The stress on an individual is the sum of all the different problems they face: see, for example, the discussion in section 2.6 of the causes and effects of long-term chronic undernutrition on the height of the human body. It is possible that adequate nutrition in an individual will manifest as stable $\delta^{15}$N and $\delta^{13}$C dentine collagen profiles, while periods of stress, such as the perinatal period, rapid growth, or famine, will result in wider variations in the isotope values as the individual attempts to utilise body tissues to maintain homeostasis. A short period of acute stress may not be visible (as in LUK 413 and 419) leading to death, but chronic stress may cause the variations seen in the other deciduous teeth and M1s of those who died. Chronic nutritional stress will also make an individual more susceptible to infections, which will also be more severe, increasing the likelihood of mortality from survivable illness.

The isotopic profiles of the M2s are generally less flat, more varied than the completed M1s, with some features common to most individuals. There appear to be changes in direction of the $\delta^{15}$N at the age of 4-6 years with 1-2 year duration, and again at 10-12 years, with a trend upward or downward which continues to the end of the tooth. These may be physiological trends. The ages at which these changes occur coincide with peaks in the growth rate of juveniles, with a small rise in growth rate at 4-6 years and the onset of puberty at about 10-12 years (which differs in males and females). Figure 7.6 shows
growth curves for modern healthy British children (Cole et al. 1998): the timing of the changes in rate of growth may be slightly different in ancient populations or in deprived modern individuals, but shows the potential curves for juveniles from any period who

Figure 7.6 Rate of growth with age for modern males and females, British 1990 reference (Cole et al. 1998)

Figure 7.7 Dentine collagen profiles for δ¹⁵N for M2s from Lukin Street and Kilkenny Union workhouse

143
have adequate nutrition for their body requirements. The changes in the δ^{15}N profiles of the M2s in this study may be a response to the demands of growth by reducing where nutrition is adequate (anabolism) and rising where it is not (catabolism) (figure 7.7). With such a small sample from a 19th-century population where biological stressors are known to have been present (see sections 2.6, 2.7) it may be that this interpretation of the δ^{15}N profiles as reflecting physiological changes which would be common to all humans is wrong, but it is also possible that a population such as this is more likely to express the changes precisely because of the chronic stresses they are experiencing.

**7.7 Reconstructing "lifeways"**

**7.7.1 Relating bulk bone collagen values to dentine averages**

As has been discussed in section 3.8.1 it is impossible to interpret the δ^{15}N and δ^{13}C from bone collagen as a “snapshot” of the diet of an individual because of the length of time it takes for bone turnover: the isotope values in the bone of adults are accepted to be an average of values from many years of life (Hedges et al. 2007). Attempts have been made to improve temporal resolution by analysing bones, or parts of bones, which may have different turnover rates e.g. (Cox et al. 2001), but it has been difficult to be sure exactly what period of life is represented by the isotope values obtained. The bone samples in this study were rib, and based on the turnover rates from Valentin et al. (2003), Table 7.1 and Hedges (2007), the collagen isotope values of the juveniles should match their bone collagen more closely than that of the adults.

The average value of the incremental dentine sections was used as a “bulk” value, and the difference between the δ^{15}N and δ^{13}C of dentine and bone was calculated as

δ\text{bone collagen} - δ\text{dentine collagen}

for both carbon and nitrogen for each individual. The results are given in table 7.2. The analytical error for both results is ±0.2‰, so values which are ≥0.4‰ can be deemed to be outside analytical error.
<table>
<thead>
<tr>
<th>Sample number</th>
<th>δ13C bone</th>
<th>δ15N bone</th>
<th>δ13C dentine average</th>
<th>δ15N dentine average</th>
<th>δ13C bone - dentine</th>
<th>δ15N bone - dentine</th>
<th>Approximate age at death</th>
</tr>
</thead>
<tbody>
<tr>
<td>LUK 955 DM2</td>
<td>-18.2</td>
<td>17.4</td>
<td>-18.0</td>
<td>17.6</td>
<td>-0.2</td>
<td>-0.2</td>
<td>1</td>
</tr>
<tr>
<td>LUK 136 DM1</td>
<td>-17.8</td>
<td>15.2</td>
<td>-18.5</td>
<td>15.8</td>
<td>0.7</td>
<td>-0.6</td>
<td>1.1</td>
</tr>
<tr>
<td>LUK 567 DM1</td>
<td>-18.8</td>
<td>13.8</td>
<td>-17.7</td>
<td>15.2</td>
<td>-1.1</td>
<td>-1.4</td>
<td>1.25</td>
</tr>
<tr>
<td>LUK 613 DM2</td>
<td>-19.1</td>
<td>10.6</td>
<td>-18.9</td>
<td>12.5</td>
<td>-0.2</td>
<td>-1.9</td>
<td>1.25</td>
</tr>
<tr>
<td>LUK 517 DM21</td>
<td>-18.3</td>
<td>13.3</td>
<td>-18.3</td>
<td>14.8</td>
<td>0.0</td>
<td>-1.5</td>
<td>1.5</td>
</tr>
<tr>
<td>LUK 431 DM1</td>
<td>-19.2</td>
<td>13.6</td>
<td>-18.7</td>
<td>15.3</td>
<td>-0.5</td>
<td>-1.7</td>
<td>2</td>
</tr>
<tr>
<td>LUK 923 DM2</td>
<td>-19.8</td>
<td>11.2</td>
<td>-19.3</td>
<td>13.4</td>
<td>-0.5</td>
<td>-2.2</td>
<td>2.5</td>
</tr>
<tr>
<td>LUK 259 M1</td>
<td>-19.5</td>
<td>11.5</td>
<td>-19.0</td>
<td>14.6</td>
<td>-0.5</td>
<td>-3.1</td>
<td>3</td>
</tr>
<tr>
<td>LUK 724 DM2</td>
<td>-19.8</td>
<td>12.1</td>
<td>-19.6</td>
<td>13.0</td>
<td>-0.2</td>
<td>-0.9</td>
<td>3</td>
</tr>
<tr>
<td>LUK 1033 DM2</td>
<td>-19.3</td>
<td>13.3</td>
<td>-19.3</td>
<td>14.1</td>
<td>0.0</td>
<td>-0.8</td>
<td>3.5</td>
</tr>
<tr>
<td>LUK 1212 M1</td>
<td>-20.8</td>
<td>9.5</td>
<td>-20.5</td>
<td>10.9</td>
<td>-0.3</td>
<td>-1.4</td>
<td>6.5</td>
</tr>
<tr>
<td>LUK 413 M1</td>
<td>-19.1</td>
<td>14.3</td>
<td>-19.4</td>
<td>11.9</td>
<td>0.3</td>
<td>2.4</td>
<td>8</td>
</tr>
<tr>
<td>LUK 419 M1</td>
<td>-19.5</td>
<td>11.4</td>
<td>-19.4</td>
<td>12.1</td>
<td>-0.1</td>
<td>-0.7</td>
<td>8</td>
</tr>
<tr>
<td>LUK 695 M1</td>
<td>-19.3</td>
<td>12.2</td>
<td>-19.1</td>
<td>13.4</td>
<td>-0.2</td>
<td>-1.2</td>
<td>8</td>
</tr>
<tr>
<td>LUK 1495 M2</td>
<td>-19.1</td>
<td>12.5</td>
<td>-19.8</td>
<td>12.0</td>
<td>0.7</td>
<td>0.5</td>
<td>11</td>
</tr>
<tr>
<td>LUK 1459 M1/M2</td>
<td>-19.6</td>
<td>12.3</td>
<td>-19.7</td>
<td>11.9</td>
<td>0.1</td>
<td>0.4</td>
<td>12</td>
</tr>
<tr>
<td>LUK 47 M1/M2</td>
<td>-19.7</td>
<td>11.9</td>
<td>-20.0</td>
<td>12.0</td>
<td>0.3</td>
<td>-0.1</td>
<td>12</td>
</tr>
<tr>
<td>LUK 1129 M2</td>
<td>-19.0</td>
<td>12.5</td>
<td>-19.6</td>
<td>12.6</td>
<td>0.6</td>
<td>-0.1</td>
<td>19</td>
</tr>
<tr>
<td>LUK 1312 C</td>
<td>-19.4</td>
<td>12.4</td>
<td>-19.6</td>
<td>12.0</td>
<td>0.2</td>
<td>0.4</td>
<td>26</td>
</tr>
<tr>
<td>LUK 1348 PM2</td>
<td>-15.9</td>
<td>13.3</td>
<td>-18.9</td>
<td>11.1</td>
<td>3.0</td>
<td>2.2</td>
<td>30</td>
</tr>
<tr>
<td>LUK 1404 M1/M2</td>
<td>-19.0</td>
<td>12.8</td>
<td>-19.6</td>
<td>12.0</td>
<td>0.6</td>
<td>0.8</td>
<td>18-25</td>
</tr>
<tr>
<td>LUK 1567 M2</td>
<td>-19.1</td>
<td>13.9</td>
<td>-20.0</td>
<td>12.6</td>
<td>0.9</td>
<td>1.3</td>
<td>36-45</td>
</tr>
<tr>
<td>LUK 755 M2</td>
<td>-16.9</td>
<td>12.6</td>
<td>-17.8</td>
<td>11.4</td>
<td>0.9</td>
<td>1.2</td>
<td>36-45</td>
</tr>
<tr>
<td>KUW 16 M1</td>
<td>-20.3</td>
<td>10.3</td>
<td>-19.8</td>
<td>11.0</td>
<td>-0.5</td>
<td>-0.7</td>
<td>5.5</td>
</tr>
<tr>
<td>KUW 12 M1</td>
<td>-19.2</td>
<td>10.3</td>
<td>-19.3</td>
<td>10.7</td>
<td>0.1</td>
<td>-0.4</td>
<td>5.5</td>
</tr>
<tr>
<td>KUW 13 M1</td>
<td>-16.6</td>
<td>8.7</td>
<td>-18.2</td>
<td>11.8</td>
<td>1.6</td>
<td>-3.1</td>
<td>6</td>
</tr>
<tr>
<td>KUW 14 M2</td>
<td>-16.5</td>
<td>9.4</td>
<td>-19.2</td>
<td>11.1</td>
<td>2.7</td>
<td>-1.7</td>
<td>7.0</td>
</tr>
<tr>
<td>KUW 10 M2</td>
<td>-20.5</td>
<td>10.7</td>
<td>-20.7</td>
<td>10.8</td>
<td>0.2</td>
<td>-0.1</td>
<td>8.5</td>
</tr>
<tr>
<td>KUW 4 M2</td>
<td>-16.2</td>
<td>9.7</td>
<td>-19.8</td>
<td>10.0</td>
<td>3.6</td>
<td>-0.3</td>
<td>13.0</td>
</tr>
<tr>
<td>KUW 9 M1</td>
<td>-20.2</td>
<td>10.5</td>
<td>-20.6</td>
<td>10.9</td>
<td>0.4</td>
<td>-0.4</td>
<td>18-28</td>
</tr>
<tr>
<td>KUW 1 M1</td>
<td>-17.2</td>
<td>11.6</td>
<td>-20.0</td>
<td>11.5</td>
<td>2.8</td>
<td>0.1</td>
<td>23-37</td>
</tr>
<tr>
<td>KUW 18 M2</td>
<td>-18.9</td>
<td>11.4</td>
<td>-20.2</td>
<td>12.0</td>
<td>1.3</td>
<td>-0.6</td>
<td>32-52</td>
</tr>
<tr>
<td>KUW 20 M2</td>
<td>-19.2</td>
<td>10.8</td>
<td>-20.5</td>
<td>11.4</td>
<td>1.3</td>
<td>-0.6</td>
<td>37-63</td>
</tr>
</tbody>
</table>

Table 7.2 differences between bone collagen and average dentine isotope ratios by age
Figure 7.8 Differences between bone collagen and dentine collagen $\delta^{15}$N and $\delta^{13}$C for Lukin Street individuals aged 0-3 years at death

Figure 7.9 Differences between bone collagen and dentine collagen $\delta^{15}$N and $\delta^{13}$C for Lukin Street individuals aged 5-12 years at death
Figure 7.10 Differences between bone collagen and dentine collagen $\delta^{15}$N and $\delta^{13}$C for Lukin Street adults

Figure 7.11 Differences between bone collagen and dentine collagen $\delta^{15}$N and $\delta^{13}$C for Kilkenny Union workhouse individuals, by increasing age at death from left to right
When the differences between the tissues are plotted by age (figures 7.8-7.11) it can be seen that the differences between bone and dentine isotope values in many of the juveniles are much larger than expected, and some trends can be seen. Four groups can be identified:

1) Adults LUK 1348, 1404, 1567 and 755 have higher δ¹³C and δ¹⁵N bone collagen than dentine collagen.
2) LUK 955, 1459, 1312 and KUW 12, 9, 10 all have values which closely match in both tissues.
3) δ¹³C is higher in the bone collagen than dentine collagen of juveniles LUK 316 and KUW 13,14 and 4, and in the adults LUK 1129, KUW 1, 18 and 20. Within this group, δ¹⁵N of bone collagen is either the same or lower than the dentine collagen.
4) Apart from LUK 413, the δ¹⁵N of the bone collagen of the juveniles is lower than the dentine collagen.

These four groups are discussed below, using detail from plots of the individual dentine profiles with bone collagen values.

7.7.2 Group 1

It is not unexpected to find differences between the childhood dentine isotope values and adult bone isotope values because they will have formed at different times of life, and in the case of group 1, this has been interpreted as migration (especially LUK 1567 because of the gradual change during the formation of the M2) or a change of occupation to mariner (LUK 1348). In all cases it appears that more marine protein input is present in the adult diet.

Incremental dentine collagen of the M2 from LUK 1567 (figure 7.12) showed a profile of changing δ¹⁵N and δ¹³C values over the period of tooth formation consistent with a change from a restricted C₃ based diet at the age of 2.5 years (11.7‰ and -20.6‰) (dietary regime 2) to a mixed C₃ based diet at 15.5 years (14‰ and -19.1‰) (dietary regime 1). The final dentine values are extremely similar to the bone collagen values (13.9‰ and -19.1‰) (table A.1). The “lifeway” suggested by the two tissue types (dentine and bone collagen) indicates that LUK 1567 may have migrated as a child from Ireland (dietary regime 2) to London (dietary regime 1) remaining there for most of her life.
Figure 7.12 $\delta^{13}$C and $\delta^{15}$N values of dentine sections, hair keratin and bone collagen, LUK 1567

Figure 7.13 $\delta^{13}$C and $\delta^{15}$N values of dentine sections and bone collagen, LUK 1348 (Miguel Pineda)
adult life (estimated age at death 36-45 years). Hair keratin was also measured for LUK 1567 (Table A3, fig 7.11). The $\delta^{15}$N and $\delta^{13}$C values at 11.5‰ and -19.3‰, a rise of 2.5‰ in $\delta^{15}$N (1-1.5‰ greater than the expected offset between bone collagen and hair keratin), suggest either a short-term change in the diet consuming higher trophic level foods, or a period of stress, in the weeks before death.

The $\delta^{15}$N and $\delta^{13}$C profile obtained from LUK 1348 PM2 (figure 7.13) suggests an individual with a mixed terrestrial C$_3$ plant based diet similar to the Kilkenny Union workhouse population from 2.5-10 years, (10.1 to11.1‰ $\delta^{15}$N, and -19.0 to -18.5‰ for $\delta^{13}$C). There is a fall then rise in $\delta^{15}$N between the ages of 5-7 years, which could be consistent with the growth curve changes seen in the M2 teeth. The $\delta^{13}$C rises slightly at the same time, which shows that it is not related to a change in marine protein input to the diet. There is a trend from age 10 years for both values to rise. This could be showing the same trend as the M2s for $\delta^{15}$N to rise during puberty, or because of an increasing amount of marine input. The bone collagen values for LUK 1348 are 13.3‰ $\delta^{15}$N and -15.9‰ $\delta^{13}$C, interpreted as a diet rich in marine protein, so the “lifeway” suggested is a childhood residence where the prevailing diet is terrestrial C$_3$ plant based, with a move as an adolescent to a place (or occupation) where the diet is rich in marine foods. We know that LUK 1348 is Miguel Pineda, a mariner, with a Portuguese name, so the isotopic “lifeway” is consistent with his possible life history.

LUK 755 (figure 7.14) has dentine collagen, bone collagen and hair keratin values (Table A3) which suggest he was a life-long consumer of marine foods with a rise in the proportion in his diet from childhood to adulthood. The dentine collagen $\delta^{13}$C remains between -18.1‰ and -17.5‰, bone collagen is -16.9‰, and hair keratin is -17.0‰. The dentine collagen $\delta^{15}$N rises gradually from 10.5‰ to 12.5‰, the bone collagen value is 12.6‰ and hair keratin 11.1‰ (consistent with the expected offset between bone collagen and hair keratin of 1-1.5‰). The rising $\delta^{15}$N could be the result of a change from consuming small (lower trophic level) fish to larger (higher trophic level) fish as an adult.
Figure 7.14 $\delta^{13}$C and $\delta^{15}$N values of dentine sections, hair keratin and bone collagen, LUK 755

Figure 7.15 $\delta^{13}$C and $\delta^{15}$N values of dentine sections and bone collagen, LUK 955

151
Figure 7.16 $\delta^{13}$C and $\delta^{15}$N values of dentine sections and bone collagen, LUK 1459

Figure 7.17 $\delta^{13}$C and $\delta^{15}$N values of dentine sections and bone collagen, KUW 10
Figure 7.18 δ¹³C and δ¹⁵N values of dentine sections and bone collagen, KUW 9

Figure 7.19 δ¹³C and δ¹⁵N values of dentine sections and bone collagen, LUK 1312 (Georgiana Neale)
7.7.3 Group 2

Group 2 includes the youngest juvenile, LUK 955 (figure 7.16) for whom the bone will be forming at the same time as, or soon after, the dentine. The juvenile LUK 1459 (figure 7.15) does show a rising trend for $\delta^{15}$N dentine collagen over time, but the bone collagen is close to an average value across the M1/M2 dentine increments. The combination of M1/M2 profiles increases the timescale for comparison with the bone collagen. KUW 10 (figure 7.17) and the adults KUW 9 and LUK 1312 (figures 7.18 and 7.19) have flat, stable dentine profiles: the bone collagen values imply that this dietary and physiological stability continued into adulthood.

7.7.4 Group 3

Group 3 contains the Kilkenny juveniles whose dentine profiles demonstrate changes in $\delta^{13}$C consistent with the short-term introduction of maize to their diet. LUK 316 (figure 7.20) could be demonstrating the same short-term change, possibly from mother’s breastmilk, and therefore be a juvenile migrant to London. Her name is Mary Angel Beadles. However, four adults show what appears to be a rapid change in the $\delta^{13}$C values of the bone collagen. KUW 1, 18 and 20 (figures 7.21-7.23) all have dentine profiles which are consistent with a mainly C$_3$ plant based diet during childhood. The bone collagen $\delta^{15}$N is fairly similar to, or even slightly below the childhood values, but the $\delta^{13}$C is raised by 0.6-2.8‰. With the knowledge that the introduction of maize as a famine relief food in Ireland was only for a 2-year period at most (O’Neill 1976), this suggests that the bone collagen turnover for these individuals has been more rapid than would be expected, and shows the presence of the C$_4$ dietary input. It is possible that, because the maize was such a large component of the diet, most of the dietary protein came from this source and is visible in the $\delta^{13}$C. LUK 1129 (figure 7.24) has the smallest rise in $\delta^{13}$C for this group (0.6‰) but also has bone collagen and dentine collagen $\delta^{15}$N consistent with life in London. She may also fit into group 1 as her bone collagen values may suggest a slightly higher marine input as an adult.
Figure 7.20 $\delta^{13}C$ and $\delta^{15}N$ values of dentine sections and bone collagen, LUK 316

Figure 7.21 $\delta^{13}C$ and $\delta^{15}N$ values of dentine sections and bone collagen, KUW 1
Figure 7.22 $\delta^{13}$C and $\delta^{15}$N values of dentine sections and bone collagen, KUW 18

Figure 7.23 $\delta^{13}$C and $\delta^{15}$N values of dentine sections and bone collagen, KUW 20
The differences between bone collagen and dentine collagen δ\(^{15}\)N in group 4 are more difficult to understand. The largest group is of those juveniles who have lower δ\(^{15}\)N in their bone collagen than in the dentine profiles. LUK 316 (figure 7.20) could be explained as a shift from a more mixed diet to a C\(_4\) plant-based diet (and see group 3 section 7.7.4).

For LUK 567, 419, 517, 724, 259, 923 (figures 7.25-7.30) and KUW 13, 14 and 16 (figures 7.31-7.33-31), the dentine δ\(^{15}\)N values are always higher than the bone collagen value. KUW 13 and 14 have δ\(^{13}\)C values for bone collagen which are higher than would be suggested by the dentine profiles, but may be exhibiting the same rapid assimilation of the C\(_4\) values as the adults in group 3, thus the lower δ\(^{15}\)N in the bone collagen could be part of this shift to a maize-based diet.
Figure 7.25 $\delta^{13}$C and $\delta^{15}$N values of dentine sections and bone collagen, LUK 567

Figure 7.26 $\delta^{13}$C and $\delta^{15}$N values of dentine sections and bone collagen, LUK 419
Figure 7.27 δ¹³C and δ¹⁵N values of dentine sections and bone collagen, LUK 517

Figure 7.28 δ¹³C and δ¹⁵N values of dentine sections and bone collagen, LUK 724
Figure 7.29 $\delta^{13}C$ and $\delta^{15}N$ values of dentine sections and bone collagen, LUK 259

Figure 7.30 $\delta^{13}C$ and $\delta^{15}N$ values of dentine sections and bone collagen, LUK 923
Figure 7.31 $\delta^{13}C$ and $\delta^{15}N$ values of dentine sections and bone collagen, KUW 13

Figure 7.32 $\delta^{13}C$ and $\delta^{15}N$ values of dentine sections and bone collagen, KUW 14
Figure 7.33 $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ values of dentine sections and bone collagen, KUW 16

Figure 7.34 $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ values of dentine sections and bone collagen, LUK 1212
Figure 7.35 δ¹³C and δ¹⁵N values of dentine sections and bone collagen, LUK 695

Estimated age at death 8 years

Figure 7.36 δ¹³C and δ¹⁵N values of dentine sections and bone collagen, LUK 1033

Estimated age at death 3.5 years
The bone collagen of some juveniles appears to have δ\(^{15}\)N and δ\(^{13}\)C values which are more consistent with the dentine collagen from about 3 years of age onwards. The dentine profiles for LUK 1212 (figure 7.34) cross the bone collagen values, while LUK 695, 1033 (figures 7.35 and 7.36), and KUW 4 (figure 7.37) all have large changes in their dentine profiles but it appears that the last months/years of life have had the most effect on the bone collagen.

The evidence from the plots above suggests that the effect of bone turnover on the δ\(^{15}\)N and δ\(^{13}\)C of bone collagen is more complicated than expected. Some of the bone collagen and dentine collagen isotope values are as expected where there appears to be homeostasis and a consistent, unchanging diet throughout life, or where there is evidence for a change due to migration, adult occupation, or dietary shift. It is surprising that C\(_4\) maize dietary input can be seen to have an effect on the δ\(^{13}\)C of bone collagen after such a short-term change in the diet of adults, and in children even continuing to rise in the bone collagen after last increment of dentine has formed.

In the case of the large group where the δ\(^{15}\)N in bone collagen is lower than in the dentine, an offset between the tissues has been considered. However, in both tissues it is collagen that is analysed, and amino acid studies have found no difference in the

---

**Figure 7.37** \(\delta^{13}C\) and \(\delta^{15}N\) values of dentine sections and bone collagen, KUW 4

![Graph showing δ\(^{15}\)N and δ\(^{13}\)C values for KUW 16 and bone collagen, with noted offsets and trends over age.](image_url)
composition of collagen from the two tissues (Smith et al. 2009). There are sufficient examples within this study which demonstrate agreement between the values in both tissues to confirm this. The difference in the δ^{15}N of the two tissues could be demonstrating a difference in the rate of development of bone and teeth. Section 5.1 has already discussed that the rate of growth of teeth during childhood is extremely robust regardless of genetic origin or socioeconomic status (Reid and Dean 2006; Cardoso 2007; Conceição and Cardoso 2011). This suggests that there is some mechanism that protects the growth of the dentition, even when stunting has occurred to the rest of the body. It is possible that the differences in the δ^{15}N and δ^{13}C of the dentine are caused by a protective effect on the odontoblasts. The odontoblasts may have a higher threshold for stress, and continue to function when osteoblasts cease formation of new bone. This could explain the δ^{15}N changes in group 4. The effect seems to be age-related, is present pre-puberty and is seen in both deciduous and permanent teeth.

LUK 413 (figure 7.38) does not appear to follow any of the patterns seen in the groups above, and has higher δ^{15}N than expected from the dentine profile. It is possible that the high δ^{15}N in the bone collagen is preserved by a difference between odontoblastic and osteoblastic activity as in the juveniles with low δ^{15}N bone collagen.

![Figure 7.38 δ^{13}C and δ^{15}N values of dentine sections and bone collagen, LUK 413](image-url)
The varying patterns of the differences between $\delta^{15}\text{N}$ in the bone collagen and dentine collagen underline the importance of measuring the tissues of juveniles within a population, as the dentine profiles appear much more sensitive to physiological changes. It is also important to include the $\delta^{13}\text{C}$ of the collagen in any interpretation of the values as this allows an objective assessment of the impact of dietary changes on the $\delta^{15}\text{N}$. The $\delta^{13}\text{C}$ appears to relate more to diet and $\delta^{15}\text{N}$ to diet plus physiology, as proposed in section 7.6.

7.8 Breastfeeding

Breastfeeding has been inferred in populations where infants exhibit $\delta^{15}\text{N}$ values above the mean for adult females (Jay et al. 2008) (figure 7.39) (and see section 3.9)

![Isotopic trend for infants and young children showing expected pattern for bone collagen $\delta^{15}\text{N}$ values when plotted against age for a period of breastfeeding followed by weaning. The dotted line represents the average value for adult females (Millard 2000 ; Jay et al. 2008)](image)

Using the current model at Lukin Street, $\delta^{15}\text{N}$ values are highest at one year of age and then fall towards the adult value with increasing age at death (figure 6.4) suggesting mixed feeding starts at about the age of one year and cessation of breastfeeding occurs at about the age of two years. There are, however, some individuals whose $\delta^{15}\text{N}$ value remains above the adult female mean after two years. This could be interpreted as prolonged breastfeeding, a high-protein diet immediately after cessation of breastfeeding, or given the rapid turnover rate in infant bone possibly a response to nutritional stress (Hatch, 2006; Mekota et al., 2006) consistent with famine (dietary regime 4) or chronic illness (Katzenberg and Lovell, 1999). Febrile illnesses, while common in infants in mid-19th century London as recorded in the Bills of Mortality (Roberts and Cox, 2003) and the reports of the Registrar General (1838-52), were unlikely to last long enough to affect the bone collagen isotopic values. The infants with
lower δ\textsuperscript{15}N values may have been minimally breastfed, and this is consistent with
documentary evidence from the period (Drummond and Wilbraham 1939; Nitsch et al. 2011). This implies that their mothers may have had to work, leaving the infants to be
fed a “dry” diet (Fildes 1986; Nitsch et al. 2011). The plot for δ\textsuperscript{13}C shows a similar
trend for the higher values to peak at around one year and fall, although again there is a
spread of values below the female mean, and high values in the older infants.

7.8.1 The current model for estimating weaning age

The current model for estimating breastfeeding and weaning behaviour in past
populations using δ\textsuperscript{15}N and δ\textsuperscript{13}C values from bone collagen relies on three assumptions:

1) That mother and fetal bone collagen will have the same isotope ratios at birth.

2) That the δ\textsuperscript{15}N and δ\textsuperscript{13}C values from the bone collagen of the infants represent their
diet at approximately the time of death.

3) That the infants who died are representative of the diet and physiology of the whole
population at that age, i.e. the osteological paradox (Wood et al. 1992)

The first assumption is that the δ\textsuperscript{13}C and δ\textsuperscript{15}N values of the same tissues of the mother
and her newborn will match. This has been shown to be the case where modern samples
are taken of tissues that are forming at the same time in mother and baby, i.e. hair or
fingernail (Fogel et al. 1989; Fuller et al. 2006a). However, because of the slow
turnover rate of bone, if there is a short-term change in the δ\textsuperscript{13}C and δ\textsuperscript{15}N of the mother,
this may not match the newly-formed bone collagen of the neonate.

In this study, the mother and fetus LUK 1312 and LUK 1345 do not have the same bone
collagen δ\textsuperscript{13}C and δ\textsuperscript{15}N (table A.1 and section 6.2). For LUK 1345, a 30 week fetus
found in the pelvis of LUK 1312, the bone collagen δ\textsuperscript{15}N is 1‰ higher and δ\textsuperscript{13}C is 0.6‰
higher for the fetus than the mother. LUK 1312 is one of the named individuals,
Georgiana Neale, who died of consumption (tuberculosis). As a sufferer from a chronic
disease and in late pregnancy, she may have a rise in her δ\textsuperscript{15}N which reflected her short-
term health status which was not evident in her bone collagen, but was recorded in the
tissues of her child. LUK 1345 died \textit{in utero}, so any rise in the isotope values was not
due to a trophic level shift from breastfeeding. Unpublished data from Nicholls (2012)
demonstrates higher neonatal bone collagen $\delta^{15}N$ in a further 4 archaeological mother/neonate pairs.

The second assumption is that the $\delta^{13}C$ and $\delta^{15}N$ values measured in bone collagen of the juveniles who have died in early infancy represent their diet at the approximate time of death. If the final increment of dentine from a tooth which is still forming is taken to represent tissue forming at the time of death, then the isotope ratios of the collagen should represent the diet and physiology of the individual at that time. Figure 7.40 shows the differences between the $\delta^{15}N$ and $\delta^{13}C$ values measured in bone collagen and the final increment of dentine for the individuals from Lukin Street and Kilkenny Union workhouse. The $\delta^{15}N$ values for dentine collagen for 17/19 of the juveniles are higher than the bone collagen $\delta^{15}N$. There is no difference between the two tissues for LUK316, and the $\delta^{15}N$ of the dentine collagen is 2‰ lower than the bone collagen of LUK413. The $\delta^{13}C$ difference is greater than 0.3‰ in 9/19 of the individuals. The individuals are placed in age order in figure 7.40 from left to right. LUK 955 to LUK 1033 are juveniles under the age of 3.5 years and thus are individuals who would be included on a weaning plot using the current model. These data suggest that the bone collagen, even in very young juveniles, may not be turning over fast enough to be representative of the diet and physiology at the time of death.

The third assumption is that the infants who died are representative of the diet and physiology of the whole population at that age. The dentine collagen profiles shown in results section 6.4.4 and figure 6.15 demonstrate that there is no match with the expected pattern of changes in the $\delta^{15}N$ seen in figure 7.39 from the individuals who survived formation of the M1: the profiles remain fairly flat. In the individuals who died during the period of formation of the teeth, whether M1 or deciduous molars, the profiles show a number of patterns, some of which could be interpreted as showing the expected rise and fall in $\delta^{15}N$ which has been seen as diagnostic of breastfeeding and weaning (figure 6.17, M1s and figure 6.19, deciduous teeth). The $\delta^{13}C$ profiles are also fairly flat for the survivors of M1 formation, and varied for the infants who died. In light of the differences between those who died during childhood and those who survived, it cannot be assumed that the bone collagen isotope ratios of those who died are representative of the population at that age.
Figure 7.40 Differences in $\delta^{13}C$ and $\delta^{15}N$ values between the bone collagen and the final increment of dentine for the individuals from Lukin Street and Kilkenny Union workhouse.

7.8.2 A new interpretation

An alternative interpretation of the isotopic profiles from the dentine would be that the individuals who survived the age of tooth completion are healthy, with an adequate nutrition, and therefore maintain homeostasis, resulting in a steady $\delta^{15}N$ and $\delta^{13}C$ profile. The infants who died but also have flat profiles were healthy until some acute problem which caused death. Those with the wide variation in the $\delta^{15}N$ profile are exhibiting anabolic or catabolic responses to physiological stress, whether that is caused by poor diet alone or undernutrition (including the physiological demands on the body of infections) from a combination of causes.

If the new interpretation is chosen, it follows that the bone collagen profiles from the infants who died will also be reflecting an averaged value for any chronic stress experienced by that child, or even a cessation of bone collagen synthesis suggested by the lower $\delta^{15}N$ values seen in bone collagen when compared with the last-forming dentine in the juveniles in this study. This could also explain the anomalous low values seen in the bone collagen plots currently used to investigate weaning. If the comments from Wood et al. (1992) regarding the “osteological paradox” are taken into account, it becomes more compelling to argue that what is being recorded in the tissues of dead
infants will not necessarily reflect the state of health, diet and therefore δ^{15}N and δ^{13}C collagen values of healthy individuals in the population at the same age. However, the collagen from dentine sections from the teeth of survivors offers the possibility of comparing those who have died with those who survived, at the same age.

7.9 New methods to interpret maternal and infant health

If the new interpretation of the infant values for bone collagen δ^{15}N in section 7.8.2 above is accepted, then it becomes possible to use bone collagen and dentine collagen increments to investigate maternal health status and infant health in a population using a number of methods:

1) Bone collagen values of pre- and perinatal individuals will give a range of δ^{15}N and δ^{13}C collagen values which will reflect the values of the mother during pregnancy. Compared, as now, with the female adult mean values, the ability of the mothers to maintain homeostasis could be assessed. It would be of enormous benefit to test mother and fetus pairs wherever possible.

2) Accepting that the first (earliest) increment of dentine from a deciduous tooth (and an M1 or permanent incisor tooth) contains collagen formed in utero, the δ^{15}N and δ^{13}C values could be used as in method 1, compared with the adult female mean.

3) The δ^{15}N and δ^{13}C values from those who died early can be compared, at the same age, with those who survived, or those with flat dentine collagen profiles with those who show wide variations. This could give a measure of the health of the early years for the population. Other comparisons could be made with other groups: for example, profiles from high and low socio-economic status cemeteries, profiles from different periods.

4) The dentine collagen δ^{15}N and δ^{13}C profiles could be examined for individuals who show osteological evidence for diseases linked to poor nutrition in childhood: for example, small stature for age, scurvy, rickets. These can be compared with juveniles who are apparently free of chronic disease at death (although see Wood et al. (1992)).
7.9.1 Testing the new methods

The data from this study has been used to test method 2 and 4 above (sections 7.9.2 and 7.9.3). Data from this and three other published studies are used to test method 1 (Pearson et al. 2010)(section 7.9.4) and 3 (Fuller et al. 2003 ; Eerkens et al. 2011)(section 7.10.4, 7.10.5).

7.9.2 First dentine increment as a measure of in-utero δ¹⁵N

Figure 7.40 shows the δ¹⁵N collagen values for the first increment from each M1 and figure 7.41 for each deciduous tooth on the Y-axis at birth. Each of these first increments is linked to a second value: that of the bone collagen δ¹⁵N for the same individual, shown either at the age of death, or age 18 years if the tooth is from an adult. The individuals who have survived the formation of M1 all appear to have birth values close to or lower than the female mean, which would suggest that their mothers had stable δ¹⁵N and δ¹³C values during pregnancy or exhibit anabolism during a healthy pregnancy.

Their bone collagen also falls close to the adult female mean, and does not vary from the birth value by more than 1‰ suggesting their life-long nitrogen balance was also stable (and this is borne out by the dentine collagen profiles in figure 6.15). By comparison, the infants who died early have a range of birth values for δ¹⁵N, with two M1s >2.5‰ higher than the adult female mean, and all the deciduous teeth >1‰ higher than adult female mean, suggesting that some of the mothers were experiencing stress leading to a rise in δ¹⁵N during pregnancy. Only 1/5 of the bone collagen values for the individuals with incomplete M1s and 4/9 of the bone collagen paired with deciduous teeth reach within 1SD of the adult female bone collagen mean by death, and the direction of change also varies.

Although that this is a very small dataset, it does appear that maternal values close to the adult female mean for δ¹⁵N predict infant survival and long-term δ¹⁵N in the child.
Figure 7.41 Birth values (first dentine increment from M1) and bone collagen values for individuals from Lukin Street shown with adult female mean bone collagen values

Figure 7.42 Birth values (first dentine increment from deciduous teeth) and bone collagen values for individuals from Lukin Street shown with adult female mean bone collagen values
However, it must be noted that the first 1mm increment for an M1 has been judged to represent about 9 months of life, and 1mm increment for a deciduous molar about 4.5 months of life. It is possible that the values for δ^{15}N in the dentine collagen also include some influence from the diet. It is worth noting, then, that if breastfeeding is healthier and produces a trophic level shift in the infant tissues, the patterns seen are counter-intuitive: those who definitely show no rise in δ^{15}N either in this first dentine increment or in the dentine profile are the survivors of this period of childhood.

7.9.3 Dentine profiles and osteological reports

The osteological reports for the individuals who have had incremental dentine analysis from both Lukin Street and Kilkenny Union workhouse have been consulted for any evidence of diseases linked to poor nutrition in childhood (table 7.3). The conditions present have been diagnosed from bone lesions, which have developed over a period of time. This can only happen when there has either been chronic stress, as suggested by the presence of cribra orbitalia (Walker et al. 2009) or a retained anterior fontanelle, or a chronic disease such as scurvy, rickets or TB (tuberculosis). If the individuals were suffering from an acute illness, there would not be time for the bone to respond with an identifiable lesion. Only 3/21 of the individuals show no bony pathology: LUK 419 is an individual with a flat δ^{15}N dentine collagen profile (figure 7.26) and LUK 923 has a flat profile for the last 1.5 years of life (figure 7.30). LUK 259, however, has a wide variation in δ^{15}N dentine collagen throughout life. While this is a small dataset, it would suggest that there is some correlation between chronic disease and unstable δ^{15}N recorded in the dentine collagen.
<table>
<thead>
<tr>
<th>Skeleton number</th>
<th>Age</th>
<th>Pathology from osteological report</th>
<th>flat δ&lt;sup&gt;15&lt;/sup&gt;N profiles</th>
</tr>
</thead>
<tbody>
<tr>
<td>KUW 4</td>
<td>13 years</td>
<td>scurvy</td>
<td></td>
</tr>
<tr>
<td>KUW 10</td>
<td>8-9 years</td>
<td>scurvy and TB</td>
<td></td>
</tr>
<tr>
<td>KUW 12</td>
<td>5-6 years</td>
<td>TB</td>
<td></td>
</tr>
<tr>
<td>KUW 13</td>
<td>6 years</td>
<td>scurvy</td>
<td></td>
</tr>
<tr>
<td>KUW 14</td>
<td>7 years</td>
<td>scurvy</td>
<td></td>
</tr>
<tr>
<td>KUW 16</td>
<td>5-6 years</td>
<td>cribra orbitalia one side</td>
<td></td>
</tr>
<tr>
<td>LUK 47</td>
<td>12-17 years</td>
<td>cribra orbitalia</td>
<td></td>
</tr>
<tr>
<td>LUK 259</td>
<td>1-5 years</td>
<td>none</td>
<td></td>
</tr>
<tr>
<td>LUK 316</td>
<td>13 months</td>
<td>cribra orbitalia</td>
<td></td>
</tr>
<tr>
<td>LUK 413</td>
<td>6-11 years</td>
<td>cribra orbitalia</td>
<td></td>
</tr>
<tr>
<td>LUK 419</td>
<td>6-11 years</td>
<td>none</td>
<td>yes</td>
</tr>
<tr>
<td>LUK 431</td>
<td>1-6 years</td>
<td>rickets</td>
<td></td>
</tr>
<tr>
<td>LUK 517</td>
<td>18 months</td>
<td>rickets</td>
<td></td>
</tr>
<tr>
<td>LUK 567</td>
<td>15 months</td>
<td>rickets</td>
<td></td>
</tr>
<tr>
<td>LUK 613</td>
<td>15 months</td>
<td>cribra orbitalia</td>
<td></td>
</tr>
<tr>
<td>LUK 695</td>
<td>9 years</td>
<td>rickets, cribra orbitalia</td>
<td></td>
</tr>
<tr>
<td>LUK 724</td>
<td>3 years</td>
<td>rickets, cribra orbitalia</td>
<td></td>
</tr>
<tr>
<td>LUK 923</td>
<td>1-6 years</td>
<td>none</td>
<td>yes</td>
</tr>
<tr>
<td>LUK 955</td>
<td>11 months</td>
<td>retained anterior fontanelle</td>
<td></td>
</tr>
<tr>
<td>LUK 1033</td>
<td>3.5 years</td>
<td>rickets</td>
<td></td>
</tr>
<tr>
<td>LUK 1495</td>
<td>6-11 years</td>
<td>cribra orbitalia</td>
<td></td>
</tr>
</tbody>
</table>

Table 7.3 Diagnoses given in osteological reports for individuals with incomplete M1, M2 or deciduous teeth, Lukin Street (Miles and Powers 2006) and Kilkenny Union workhouse (Geber 2012b)

7.9.4 A new interpretation of bone collagen studies

Pearson et al. (2010) uses data for δ<sup>15</sup>N bone collagen for infants and adult females at two early Neolithic sites in Anatolia to compare the age at which exclusive breastfeeding (EBF) finishes (i.e. weaning starts) in each site. This information is then related to the mortality profiles for infants aged 0-5 years. Their conclusion is that the infants at Çayönü Tepesi are exclusively breastfed until the age of 2 years, while the
Figure 7.43 Plot of $\delta^{15}$N values for bone collagen for infants aged 0-5 years from Aşikh Höyük. Infants are plotted relative to the mean and one standard deviation (solid and dashed horizontal lines) of bone collagen values for adult females at the cemetery (data from Pearson et al. 2010)

Figure 7.44 Plot of $\delta^{15}$N values for bone collagen for infants aged 0-5 years from Çayönü Tepesi. Infants are plotted relative to the mean and one standard deviation (solid and dashed horizontal lines) of bone collagen values for adult females at the cemetery (data from Pearson et al. 2010)
infants at Aşikh Höyük start weaning at the age of 1 year. The infant mortality in the
site where EBF continues for 2 years is higher after the age of 24 months than in the site
where EBF ceases at 1 year, although this relies upon the demography of the cemetery
being the same as that of the past population. Pearson et al. (2010) conclude that the
introduction of weaning foods at 1 year improves the nutritional status of the infant, and
thus the ability to respond to infections. The infant weaned at 2 years is already
nutritionally deprived as a result of missing nutrients and calories from breastmilk
alone, and is less resistant to the pathogens encountered in weaning foods at this age.

The neonates from Çayönü Tepesi all have bone collagen δ^{15}N more than 1SD higher
than the adult female mean, while 1/3 of the neonates at Aşikh Höyük have bone
collagen δ^{15}N close to the adult female mean. If the new interpretation is applied, (that
the neonatal/fetal bone collagen δ^{15}N value is the same as the mother’s δ^{15}N during
pregnancy), this would suggest that the mothers of the neonates with higher δ^{15}N are
exhibiting stress during pregnancy. Although the dataset is small, this would imply
some difference in maternal health between sites.

If the new interpretation is taken further, and it is then assumed that the high infant bone
collagen δ^{15}N is reflecting not only the effect of diet (and in this case it is difficult to
evaluate because the bone collagen δ^{13}C is not reported) but also of physiological stress,
it is possible that what is seen in the two populations is a difference in the quality of the
weaning foods, rather than the effect of breastfeeding. It is difficult to imagine being
able to prevent any child eating foods other than breastmilk once they are able to put
their hands to their mouth: it is more likely, perhaps, that the diet of the mothers at
Çayönü Tepesi is insufficient, and the weaning diet given to the infants, as a version of
the adult diet, is also poor in nutrients and results in raised bone collagen δ^{15}N.

Pearson et al. (2010) report that there is a marked difference in subsistence strategies at
the two sites. The diet at Çayönü Tepesi is categorised as mainly pulses and domestic
pigs, while at Aşikh Höyük there is early farming of cereals, and the use of bovids
(although for meat, not milk). The bone collagen δ^{15}N mean of the Çayönü Tepesi adult
females is 6‰, 3.6‰ lower than that of the adult females from Aşikh Höyük, which
implies a higher input of animal protein in the adult diet at Aşikh Höyük. The weaning
foods at Aşikh Höyük could include animal protein and supply the juveniles with better
nutrients, allowing them to survive through the 2-5 year period of life. By contrast, the weaning food at Çayönü Tepesi, based on a lower intake of animal protein, may leave the juveniles undernourished: without some of the essential amino acids, they may be recycling their own proteins, causing catabolism and raising the bone collagen δ¹⁵N which mimics the effect of prolonged breastfeeding.

A modern study of health interventions at Narangwal, in the Punjab in the 1970s, showed that the biggest reduction in child mortality after the age of 1 year was due to improved nutrition: not only were the pregnant and nursing mothers better fed, but the quality of the weaning foods was also improved (Floud et al. 1990, 314f). This improvement occurred although the duration of breastfeeding remained the same. Death rates in the perinatal to 1 year age group, by comparison, were most improved by access to better medical care. This suggests that a poor weaning diet will increase the death rate in the over 1 year age group.

The new interpretation of the data from Pearson et al. (2010) takes into account the difference between the adult female δ¹⁵N and the reported differences in diets at the two sites. The reported dietary evidence suggests that the high bone collagen δ¹⁵N in the juveniles could be interpreted as representing increased nutritional stress caused by poor weaning diets, rather than evidence for prolonged breastfeeding practices.

This new interpretation could also be applied to weaning data from other published studies. For example, Schurr (1997) showed a difference in the peak age of infant mortality and the age at which the peak of bone collagen δ¹⁵N was reached in the Angel site (AD 1300-1450) in America, a site with evidence for maize-based subsistence. The new interpretation would be that the individuals with the high bone collagen δ¹⁵N are dying because they are suffering individual high stress levels although the death rate at this age is generally low, suggesting that they are the exception rather than representing the population bone collagen δ¹⁵N at that age.

The new interpretation should also be applied to the data from Lukin Street in this study. Figure 6.4 and section 7.8 were used to interpret the data according to the current model, interpreted as weaning commencing at about the age of 1 year, and low δ¹⁵N demonstrating little or no breastfeeding in some infants. The new interpretation would be that the juveniles whose δ¹⁵N is within the range of 1SD from the adult female mean
are the children of healthier mothers, or have achieved homeostasis, but have succumbed to an acute cause of death. The juveniles with high $\delta^{15}$N bone collagen values have experienced chronic stress whether through undernutrition, infection or a combination of factors and this has contributed to their early death. Those with low $\delta^{15}$N, in the context of the Irish Famine, could be survivors from Ireland with plant-based isotope values from their (or their mother’s) diet whose bone collagen $\delta^{15}$N has not had time to change to the local London dietary values, or could be demonstrating anabolic changes due to rapid growth. The subadult mortality profile for Lukin Street suggests that the highest death rate is at the age of 1-1.5 years (figure 5.7). This could be connected with the introduction of weaning foods at the age of 1 year and the associated problems from infection from contaminated food and vessels. 4/11 of the infant bone collagen $\delta^{15}$N values for infants 0.5-1.5 years of age are within 1SD of the adult female mean, and two of these are below the mean, suggesting that they had achieved homeostasis but died from an acute cause, which could include the sudden introduction of weaning foods. In fact, of the juveniles in the dataset, 15 have bone collagen $\delta^{15}$N below or equal to the adult female mean and 20 above. It is possible that the causes of death are divided between acute disease and chronic stress in this population. However, the last-forming increment of dentine has a higher $\delta^{15}$N collagen value than the bone collagen in most cases: if the current model was used, that would imply that breastfeeding was more prevalent, and of longer duration. However, the new interpretation would suggest higher levels of stress in these individuals with the higher $\delta^{15}$N.

Although it is probable that bone collagen $\delta^{15}$N in young infants is affected directly by breastfeeding, the effect of maternal stress producing elevated $\delta^{15}$N values at birth, and of any chronic disease or repeated infections on the nitrogen balance of the infant before death needs to be taken into account. It may be that some previously published sites could be re-interpreted with $\delta^{15}$N values from dentine collagen increments of the dead juveniles compared with the older children and adults who survived infancy.
7.9.5 A new interpretation of Eerkens et al. (2011)

Eerkens et al. (2011) produced dentine collagen profiles and bone collagen values for $\delta^{15}$N and $\delta^{13}$C for six individuals from the prehistoric hunter-gatherer site of Marsh Creek, California.

Figure 7.45 Comparison of $\delta^{15}$N and $\delta^{13}$C in serial sections of six first molars and adult bone collagen values from prehistoric Marsh Creek, California (Eerkens et al. 2011)
(4300-3100 BP). In each case, the M1 was used, and the profiles with bone collagen values as they appear in the paper are shown in figure 7.45.

Their M1 profiles are remarkably similar to those in this study. In their study, sampling widths (hence period reflected) varied from crown to root: this appears to have been to maximise the amount of collagen produced for measurement. In this study the same width of increment was used throughout each tooth to maintain clarity of the temporal resolution. A 1 mm section appears to be a reasonable choice for producing sufficient collagen from well-preserved teeth. Another difference is in the amount of wear on the tooth: this study used 19th-century samples with very little wear, while the samples used by Eerkens et al. (2011) have lost the earliest forming tissues due to heavy occlusal wear: where tissue is missing this will need to be taken into account in the interpretation of the results in relation to the average age assigned to each dentine increment, especially when addressing weaning.

Although there is individual variation between the six, patterns in δ¹⁵N and δ¹³C profiles suggest changes in the diet where both values co-vary (burial 92, 6mm-0mm from the root tip, and Burial 275) and cases where the δ¹³C remains fairly flat while the δ¹⁵N shows variation may be due to variation in nitrogen balance. Figure 7.46 shows the combined profiles from M1, M2 and M3 of burial 59. It appears that this individual shows a variation in δ¹⁵N at the age of 4-6 years and a rise at 10-14 years which matches the changes seen in the M2s of the 19th-century individuals interpreted in this study as matching the British 1990 growth curves (section 7.6, figure 7.6).
The purpose of Eerkens et al. (2011) obtaining values for $\delta^{15}$N and $\delta^{15}$C from the M1s was to investigate weaning ages. The profiles in figure 7.7 are interpreted as showing a range of weaning ages, and differences in the rate of weaning, for example burial 59 exhibiting prolonged breastfeeding until the age of 4 years, and 107 weaning early at the age of 1 year.

The interpretations are more difficult because some of the very early dentine has been lost in the older individuals because of attrition of the occlusal surface of the tooth and so the perinatal value is missing. However, using the interpretation that when variations in $\delta^{15}$N covary with $\delta^{15}$C there is a dietary change, this can be seen in burials 92 and 275, while burials 87 and 59 have wide variations in $\delta^{15}$N which seem unrelated to $\delta^{15}$C, and could represent a physiological response to chronic stress.

The $\delta^{15}$N value of the dentine collagen of burial 107 does appear to fall rapidly and both $\delta^{15}$N and $\delta^{13}$C then remain stable. In light of the findings from the 19th-century dentine profiles, this implies that he reaches a homeostatic, healthy state at an earlier age than the other individuals. Burial 107 has been interpreted as a high-status burial on the basis of the associated grave goods, while the other 5 are from low-status graves. This would suggest that the high status individual (107) is displaying less stress during the
formation of his M1 than the other 5 individuals, rather than the δ¹⁵N showing variations in weaning ages.

There is no evidence from the Lukin Street and Kilkenny Union workhouse individuals for different socio-economic status between the flat dentine profile and variable profile individuals, so this cannot be tested using the data from this study.

**7.9.6 A new interpretation of Fuller et al. 2003**

The study by Fuller et al. (2003) in combination with the paper by Richards et al. (2002) was the first to use incremental sections of dentine from individuals from medieval Wharram Percy, England to achieve temporal resolution, and, in combination with bone collagen, produce “lifeways” to investigate breastfeeding and weaning. Fuller et al. (2003) showed that there was a trend for the δ¹⁵N and δ¹³C to reduce from crown dentine to cervical root dentine and to reduce again to apical root dentine. In juveniles, the tooth used was the DM2, and for adults the permanent canine (C) and M3. In all cases rib bone collagen was measured, and compared with the dentine values. Although Fuller et al. comment that the isotope values of some individuals did not follow this pattern, more weight was given to the mean values from the population than to individual profiles (Fuller et al. 2003).

For this study profiles have been produced using the data from Fuller et al. (2003) and approximate ages for the mid-point of each dentine section using AlQahtani et al. (2010) (table A.11, Appendix 1). When the Wharram Percy data is analysed, it can be seen that for 5/21 of the DM2’s, the crown and cervical dentine δ¹⁵N values are either within 0.2‰ (which is the quoted analytical error) or the crown dentine has a lower δ¹⁵N value than the cervical dentine. For these individuals there is no isotopic evidence for breastfeeding in the crown dentine of the DM2. For 6/9 of those individuals who died before the age of 3.5 years (i.e. before the completion of the DM2) (figures 7.47-7.57) the δ¹⁵N and δ¹³C values of the rib collagen are lower than those of the latest-forming dentine. In five of these, the presence of cervical or apical root dentine suggests an older actual age than that given in the study. This mismatch between skeletal and dental age could suggest that there is some element of delayed skeletal development, or stunting (Cardoso 2007; Conceição and Cardoso 2011), which could explain why the δ¹⁵N and δ¹³C values in the bone are lower than the dentine. The isotopic differences are
consistent with the pattern of differences between bone collagen and dentine collagen seen in this study (section 7.8.1).

If the $\delta^{15}N$ values are combined with the $\delta^{13}C$, different patterns are seen in the profiles (figure 7.47-7.67).

Figure 7.47 $\delta^{13}C$ and $\delta^{15}N$ values of dentine sections and bone collagen for individual G5229 from Wharram Percy (data from Fuller et al. 2003)

Figure 7.48 $\delta^{13}C$ and $\delta^{15}N$ values of dentine sections and bone collagen for individual NA37 from Wharram Percy (data from Fuller et al. 2003)
Figure 7.49 \( \delta^{13}C \) and \( \delta^{15}N \) values of dentine sections and bone collagen for individual G327 from Wharram Percy (data from Fuller et al. 2003)

Figure 7.50 \( \delta^{13}C \) and \( \delta^{15}N \) values of dentine sections and bone collagen for individual NA28 from Wharram Percy (data from Fuller et al. 2003)

Figure 7.51 \( \delta^{13}C \) and \( \delta^{15}N \) values of dentine sections and bone collagen for individual G430 from Wharram Percy (data from Fuller et al. 2003)
Figure 7.52 δ¹³C and δ¹⁵N values of dentine sections and bone collagen for individual WC072 from Wharram Percy (data from Fuller et al. 2003)

Figure 7.53 δ¹³C and δ¹⁵N values of dentine sections and bone collagen for individual G339 from Wharram Percy (data from Fuller et al. 2003)

Figure 7.54 δ¹³C and δ¹⁵N values of dentine sections and bone collagen for individual G363 from Wharram Percy (data from Fuller et al. 2003)
Figure 7.5 δ\textsubscript{13}C and δ\textsubscript{15}N values of dentine sections and bone collagen for individual NA79 from Wharram Percy (data from Fuller \textit{et al.} 2003)

Figure 7.6 δ\textsubscript{13}C and δ\textsubscript{15}N values of dentine sections and bone collagen for individual G576 from Wharram Percy (data from Fuller \textit{et al.} 2003)

Figure 7.7 δ\textsubscript{13}C and δ\textsubscript{15}N values of dentine sections and bone collagen for individual WC097 from Wharram Percy (data from Fuller \textit{et al.} 2003)
Figure 7.58 δ¹³C and δ¹⁵N values of dentine sections and bone collagen for individual G614 from Wharram Percy (data from Fuller et al. 2003)

Figure 7.59 δ¹³C and δ¹⁵N values of dentine sections and bone collagen for individual NA30 from Wharram Percy (data from Fuller et al. 2003)

Figure 7.60 δ¹³C and δ¹⁵N values of dentine sections and bone collagen for individual G424 from Wharram Percy (data from Fuller et al. 2003)
Figure 7.6 δ^{13}C and δ^{15}N values of dentine sections and bone collagen for individual NA23 from Wharram Percy (data from Fuller et al. 2003)

Figure 7.6 δ^{13}C and δ^{15}N values of dentine sections and bone collagen for individual EE65 from Wharram Percy (data from Fuller et al. 2003)

Figure 7.6 δ^{13}C and δ^{15}N values of dentine sections and bone collagen for individual EE66 from Wharram Percy (data from Fuller et al. 2003)
Figure 7.64 $\delta^{13}C$ and $\delta^{15}N$ values of dentine sections and bone collagen for individual WC0141 from Wharram Percy (data from Fuller et al. 2003)

Figure 7.65 $\delta^{13}C$ and $\delta^{15}N$ values of dentine sections and bone collagen for individual G500 from Wharram Percy (data from Fuller et al. 2003)

Figure 7.66 $\delta^{13}C$ and $\delta^{15}N$ values of dentine sections and bone collagen for individual EE72 from Wharram Percy (data from Fuller et al. 2003)
Figure 7.67 $\delta^{13}$C and $\delta^{15}$N values of dentine sections and bone collagen for individual G568 from Wharram Percy (data from Fuller et al. 2003)

The effects of physiological stress on the $\delta^{15}$N values as seen in dentine collagen profiles from the Kilkenny juveniles have demonstrated that where the $\delta^{13}$C collagen values are flat or contrary to the direction taken by the $\delta^{15}$N, then stress and not dietary change can be inferred from higher $\delta^{15}$N values.

In three juveniles from Wharram Percy (NA79, G327 and NA23) the $\delta^{13}$C profiles are flat although large peaks in $\delta^{15}$N occur, suggesting that these individuals may be showing physiological stress while the composition of the diet is unchanged. For others the $\delta^{15}$N and $\delta^{13}$C profiles co-vary, suggesting any changes to be related to the diet. For G658, the wide variations in the $\delta^{15}$N and $\delta^{13}$C values suggest dietary changes which may demonstrate some marine input to the diet.

The samples analysed from the eight Wharram Percy adults provide an opportunity to produce profiles similar to those in this study (figure 7.68-7.75). Fuller et al. (2003) interpret the profiles as showing evidence for breastfeeding due to the higher $\delta^{15}$N values in the canine crown dentine formed at approximately 0.5 to 6 years of age, which would include tissue formed during breastfeeding. However, 2/8 of these individuals (EE67 and CN28) have lower $\delta^{15}$N values in the crown dentine than the cervical dentine, which suggests that these two have no isotopic evidence for breastfeeding.
Figure 7.68 $\delta^{13}$C and $\delta^{15}$N values of dentine sections and bone collagen for individual EE36 from Wharram Percy (data from Fuller et al. 2003)

Figure 7.69 $\delta^{13}$C and $\delta^{15}$N values of dentine sections and bone collagen for individual CN28 from Wharram Percy (data from Fuller et al. 2003)

Figure 7.70 $\delta^{13}$C and $\delta^{15}$N values of dentine sections and bone collagen for individual G597 from Wharram Percy (data from Fuller et al. 2003)
Figure 7.7 $\delta^{13}$C and $\delta^{15}$N values of dentine sections and bone collagen for individual CN2 from Wharram Percy (data from Fuller et al. 2003)

Figure 7.72 $\delta^{13}$C and $\delta^{15}$N values of dentine sections and bone collagen for individual EE3 from Wharram Percy (data from Fuller et al. 2003)

Figure 7.73 $\delta^{13}$C and $\delta^{15}$N values of dentine sections and bone collagen for individual NA59 from Wharram Percy (data from Fuller et al. 2003)
Combining $\delta^{15}$N and $\delta^{13}$C to produce profiles for the eight Wharram Percy adults shows that individual interpretations can be made about their diet and physiology (figures 7.68-7.75. For example, EE67 and CN28 show a gradual co-varying rise in both isotope values throughout childhood and adolescence towards a higher rib collagen value as an adult. For G597, because the $\delta^{13}$C profile is flat, the high $\delta^{15}$N of the crown dentine is probably physiological rather than dietary. For CN2, EE3 and G746, the $\delta^{15}$N and $\delta^{13}$C values move in opposite directions, which could not be the case during breastfeeding. For NA59, there is a good correlation between the changes in the $\delta^{15}$N and $\delta^{13}$C dentine profiles from the canine: this could provide evidence for the effects of prolonged...
breastfeeding as suggested by the historical evidence for this medieval population (Richards et al. 2002).

7.9.7 Evaluating the new interpretation

From the observed variations, it appears that there are individuals (both juveniles and adults) in the Wharram Percy study who do not show isotopic evidence for breastfeeding in their collagen. However, some of the $\delta^{15}N$ and $\delta^{13}C$ profiles from Wharram Percy individuals are consistent with the current breastfeeding model. It is also possible that the whole medieval population in Wharram Percy had a higher level of stresses in infancy than the 19th-century Londoners or Irish, which can be seen in the dentine collagen $\delta^{15}N$ values of both victims and survivors.

Taking the Fuller et al. (2003) data into consideration with the data from this study, it is possible that profiles obtained from deciduous teeth can show some evidence for breastfeeding when both $\delta^{15}N$ and $\delta^{13}C$ dentine collagen profiles for infancy and early childhood co-vary. This effect may be of a short duration, and may not be visible in some individuals because the actual rise in values is small. Fuller et al. (2006a) report a range of 1.7-2.8‰ in $\delta^{15}N$ differences between modern mother/infant fingernail during breastfeeding. The isotopic values will be averaged over the approximately 4.5 months it takes for the formation of the first 1mm of dentine in deciduous teeth. The effect of averaging would be greater in the approximately 9 months represented by the first 1mm dentine section from the M1. Where there is a combination of effects from both diet and physiology the rise in $\delta^{15}N$ in the collagen could be much higher than the expected trophic level effect.

Higher $\delta^{15}N$ and $\delta^{13}C$ values measured in the final section of dentine collagen than the rib collagen which is forming at the same age in juveniles were observed in both studies. This confirms that bone collagen is not the best tissue to represent diet or physiology at the approximate time of death as there appears to be some mechanism during periods of stress (nutritional, growth or disease) that allows dentine to continue to grow while it appears that new bone is not forming, and thus not recording the isotopic changes.

The conclusion from the evidence from the two published studies (Fuller et al. 2003; Eerkens et al. 2011) and the data from this study must be that pre-natal maternal isotope
ratios, diet (breastfeeding or not) and physiological stress can all affect the final collagen values which are measured, and so must be taken into consideration when interpreting collagen data from the perinatal and infant period of life. The use of incremental dentine allows the comparison of victims and survivors of childhood at the same age. Different populations can be compared in terms of their maternal and infant health: those with a higher proportion of profiles with raised non-dietary δ¹⁵N may be experiencing more stress during these critical periods of life.

7.10 Migration: the importance of time resolution.

The analysis of the dentine profiles for the individuals from Lukin Street and Kilkenny Union workhouse have shown how wide a variation there can be in the collagen δ¹⁵N and δ¹³C in different areas of the root of a tooth, and how different this can be from the bone collagen values. In past studies (e.g. Müldner et al. 2011) bulk values have been obtained from dentine and compared to the values in the bone, discovering differences that can be interpreted as migration since the age at which the dentine was formed. In the case of LUK 1567 (figure 6.7) where the dentine collagen δ¹⁵N and δ¹³C at the end of the root is a close match to the bone collagen values, the changes in dietary values from the crown dentine would not have been discovered if the root tips had been measured as a bulk sample. Where migration between habitats with different diets during childhood or adolescence is suspected, this is now an action that could be identified, and given an age range, using this technique.
CHAPTER EIGHT

CONCLUSIONS AND SUGGESTIONS FOR FURTHER WORK

8.1 Introduction

In this chapter an evaluation is made of the success of the study in addressing the research aims and objectives stated in section 1.3. The benefit of measuring isotope ratios in a range of different tissues in the same individual is discussed.

Suggestions are given for future work which could be undertaken on the two study populations to improve and enhance the information related to migration, to improve the methodology for the analysis of dentine increments and to refine the interpretations of $\delta^{15}N$ and $\delta^{13}C$. Suggestions are made for further work to investigate the findings of this study.

8.2 Addressing the research aims

8.2.1 Characterizing the dietary regimes in mid-19th-century London and Ireland, and identifying Irish Famine survivors where no other evidence is available.

Using a combination of documentary evidence for diet and the $\delta^{13}C$ and $\delta^{15}N$ of bone collagen, it is possible to detect different dietary regimes within the two cemetery populations. The combined $\delta^{13}C$ and $\delta^{15}N$ data from all tissues can identify potential immigrants to London buried in Lukin Street. The immigrants identified are not just from Ireland, but also from other areas with a dietary regime which differs isotopically from the 19th-century London diet identified in this study. In searching for four dietary regimes (section 3.10.1, figure 3.6), it has been possible to identify local $\delta^{15}N$ and $\delta^{13}C$ values for the majority of the Lukin Street individuals, consistent with other contemporary London populations (dietary regime 1). Dietary regime 2 was identified within the majority of the individuals from Kilkenny Union Workhouse but where bone turnover was rapid, dietary regime 3 was detected in some juveniles. A combination of dentine and bone collagen $\delta^{13}C$ and $\delta^{15}N$ identified some adults where dietary regime 3 was suggested. It was not possible to identify dietary regime 4 within the two populations using bone collagen, although it is possible that the elevated $\delta^{15}N$ values of Lukin Street infants could reflect perimortem physiological and nutritional stress. The unexpected appearance of individuals with $\delta^{15}N$ and $\delta^{13}C$ values consistent with a
marine protein diet (LUK 755 and LUK 1348, Miguel Pineda) underlines the potential for paleodietary reconstruction to identify migrants within a cemetery population.

It is important, however, to note that the presence of good archaeological and historical context was of great benefit in the interpretation of the results.

8.2.2 Improving temporal resolution for dietary changes using carbon and nitrogen isotope analysis of recovered skeletal tissues

The bone collagen data obtained from individuals from the Kilkenny Union Workhouse cemetery which identifies the presence of C$_4$ maize in the diet, although a short-term change, underlines the need to take into account the age-related changes in physiology and bone turnover and its consequent effects on the speed and magnitude of changes in the isotope values within the bone when interpreting results. Adults in the Lukin Street cemetery with a value for bone collagen $\delta^{15}$N of $\leq$10‰, identifying them as having a plant-based diet, could be Irish migrants to London, as their bone collagen turnover rate means that it will take a long period of time before the diet in their new home can change the isotope ratios. Conversely, children will assimilate the new $\delta^{15}$N and $\delta^{13}$C values from the diet much more quickly, and those who migrate as juveniles may appear, from their bone collagen, to be local after a period of time.

The M2 dentine profile of LUK 1567 shows that, although her bone collagen isotope ratios would suggest she is a Londoner, she has probably moved during childhood from an area where the diet was different. Similarly, LUK 1348 (Miguel Pineda) has adult bone collagen which suggests a high marine input to the diet, but the PM2 dentine profiles shows that this could not have been the case before the age of about 15 years. Comparing the bone collagen and bulk dentine isotope values showed that the adult LUK 1129 and juvenile LUK 316 may have experienced a change in diet with a C$_4$ input which suggests they are also recent migrants from Ireland to London. Given the small number of adults within the population whose dentine increments were sampled, it is possible that other childhood migrants are present, and could be identified with further dentine sampling.
8.2.3 Investigating whether nitrogen isotopes in incremental dentine sections can identify physiological changes such as nutritional stress in children living through the Famine period

Slow bone turnover in adults may explain why elevated δ¹⁵N values (dietary regime 4) are not found in the bone collagen of the known Famine victims in the cemetery of the Kilkenny Union workhouse. However, the rapid bone turnover of juveniles has made it possible to identify the short-term consumption of maize as a radically different diet from potatoes in bone collagen δ¹³C values. The successful development of a technique to analyse collagen from incremental dentine sections, and assign an estimated age to each section, has allowed the interpretation of carbon and nitrogen isotopes in these individuals in terms not only of diet, but also physiological changes during childhood and adolescence. The dentine profiles of the juveniles from Kilkenny who show the short-term change to a C₄-based diet also show a variety of patterns within the δ¹⁵N profiles. Assuming that the diet of the individuals did not incorporate a sudden shift towards a high trophic level dietary input it would appear that these δ¹⁵N profiles are reflecting the ability of the individual to maintain homeostasis, and where there are changes, these could be the result of catabolic or anabolic processes. In one individual, KUW 4 (figure 6.12) the short-term rise in δ¹⁵N appears to coincide with the introduction of the maize: this could be a marker for the point in time that the individual was so nutritionally distressed that they had to seek relief food, and once the calorie intake improved, so did nitrogen balance with a corresponding fall in δ¹⁵N. Figure 6.11, KUW 14, displays a flat δ¹⁵N profile while the δ¹³C indicates the introduction of maize: this demonstrates a lack of connection between the δ¹³C and δ¹⁵N. Similarly, in the dentine profiles of juveniles from both populations, where rises in δ¹⁵N cannot be explained by dietary changes because the δ¹³C values do not show a corresponding trophic level change, it could be interpreted as a failure of homeostasis, especially where δ¹³C falls as δ¹⁵N rises, as seen in the hair studies by Neuberger (in press) and Mekota (2006) and interpreted as the catabolism of body fat which has δ¹³C values which are 3‰ lower than other body tissues such as muscle. The differences in complete and incomplete M1 δ¹⁵N dentine appear to show that flat profiles for isotope values are a good predictor of survival (figure 7.3), although this seems to go against the acknowledged importance to infant health of breastfeeding, as there is no evidence for
the expected trophic level shifts from breastfeeding in the diet of the survivors. It may be that the wide variations (and here the Famine victims can be excluded) seen in the M1 and deciduous molar dentine profiles of children who died prematurely reflect widely varying diets, or changes in stress levels (which may be the result of dietary changes) or both. Research from clinical studies would suggest that stress from nutritional deprivation (Fuller et al. 2004; Hatch et al. 2006; Mekota et al. 2006; Duška et al. 2007) or repeated infections (Floud et al. 1990, 250f; Powanda and Beisel 2003) or both can cause wide variation in nitrogen balance. Bone collagen only provides a single blurred value for $\delta^{15}$N and $\delta^{13}$C (Hedges et al. 2007), which in light of the differences between dentine collagen and bone collagen in the dead juveniles in this study may not reflect the true nutritional status. Segmental hair analysis provides a short-term set of values which may reflect changes in $\delta^{15}$N up to six weeks earlier than $\delta^{13}$C (Petzke and Lemke 2009), so it may be that dentine, with a medium-term averaging of $\delta^{15}$N and $\delta^{13}$C, is revealing features of physiological stress which have not been identifiable until now. Those studies of weaning through the analysis of $\delta^{15}$N in bone collagen which have ignored (or not reported) $\delta^{13}$C may be missing vital information about the causes of the raised $\delta^{15}$N of the infants in the population. $\delta^{13}$C of collagen seems to mainly reflect the diet, perhaps because the trophic level effect from catabolism is much smaller, or perhaps because the body pool of available carbon is greater than that of nitrogen from dietary protein; furthermore, it appears that major dietary change may appear in the isotope values of bone collagen more rapidly than is currently accepted (section 7.7.4, adults with raised $\delta^{13}$C bone collagen). At times of undernutrition the energy demands of the citric acid cycle in mitochondria have precedence over all other body requirements for protein (Owen et al. 1998) which may help to explain the rises in $\delta^{15}$N collagen. If $\delta^{15}$N collagen represents diet plus the effect of loss of homeostasis this could explain variations in population bone collagen datasets which are not easy to interpret in dietary terms alone.

8.3 Combining body tissues

The “lifeways” produced for the individuals in section 7.7 are an illustration of the detail which can be gleaned from analysing different body tissues from the same individual. While it is of great value to estimate the diet of a population from the $\delta^{15}$N and $\delta^{13}$C, human bone collagen datasets always exhibit a range of isotope ratios. If
available, the data from other tissues, especially of outliers, may enhance the interpretation, and identify reasons for their unusual values. The analysis of dentine can give juvenile values for the adults in the population which can be compared not only to their own adult bone collagen, but also with the juveniles who died, and at the same age. The comparison of those who survived and those who died would provide information on the health of juveniles, and the perinatal values may shed light on health during pregnancy and infancy. Even when the skeletal assemblage is fragmentary, the analysis of developing and complete teeth can provide a comparison between deceased and survivors, and with population means for bone collagen.

8.4 Future work on samples from Kilkenny Union workhouse and Lukin Street

8.4.1 Incremental dentine analysis

Because of the costs involved in time and analysis, only a small number of the available teeth from the two sites have been sampled. The remaining ten teeth from Kilkenny would be a priority for further analysis: the historical evidence suggests that there was a devastating famine event in Ireland in 1816 and several of the adults are in an age group that may have lived through that event. Dentine analysis may reveal profiles for these individuals showing changes in δ¹⁵N and δ¹³C consistent with a short-term stress event.

Because of the Lukin Street demography, juveniles age 0-5 years were a large group, and there are still a considerable number of juveniles whose teeth have not been sampled. Further data from these would be very helpful to add to the library of dentine profiles for each age group and aid the interpretation of the perinatal samples for those who died prematurely.

8.4.2 Other elements and isotopes

As discussed in section 3.6, the isotopic value of δ¹³C in collagen represents the protein element of the diet, while the isotope value of δ¹³C in carbonate from bone, dentine or enamel represents the whole diet: the proportion of dietary foodstuffs can be determined and a more detailed assessment of diet made using both values (Froehle et al. 2012). The comparison of bone carbonate with bone collagen, or enamel carbonate with co-genetic crown dentine collagen would add to the interpretations given above.

The analysis of dental enamel carbonate would also give values for δ¹⁸O. Studies have shown that this is related to the δ¹⁸O of drinking water ingested, and thus the climatic
zone inhabited during the formation of the tissue (Fricke et al. 1995; Ehleringer et al. 2008). As a tool to address the identification of migrants during childhood, the enamel carbonate $\delta^{18}O$ of the Kilkenny and Lukin Street individuals would be an interesting study. Although the putative difference in rainwater values between the west coast of Ireland and south-eastern England is small (Darling et al. 2003; Diefendorf and Patterson 2005), as one of a suite of values, there may be more subtle interpretations to be made for the potential Irish migrants to Lukin Street identified through their bone collagen $\delta^{15}N$. Dentine from archaeological sites can be subject to diagenetic contamination, but it may be possible to use phosphate oxygen from incremental samples to seek temporal resolution for $\delta^{18}O$.

Migration has been inferred from the isotope ratios of strontium measured in human dental enamel. The strontium values originate from the rock that produces the soil on which crops are grown, and will be incorporated in the food chain (Bentley 2006; Montgomery 2010). The geology of the British Isles is complicated, but it is possible that migrants will have lived in areas of Ireland which have strontium isotope ratios which differ from those in London. It would be particularly interesting to measure the strontium isotope ratios of the two outliers with marine dietary input.

During the historical research undertaken for this study, it became apparent that the living conditions of the urban poor exposed them to a number of dangers not evident in rural Ireland. The deliberate contamination of foodstuffs with lead compounds to provide colour and sweetness, the high levels of airborne pollution from London smog, and the possibility of lead ingested from pottery glazes, lead piping and lead paint and even lead nipple-shields (Gordon and Whitehead 1949) suggest that there may be high cumulative lead burden in the body tissues of Londoners. In rural Ireland, drinking water would not be piped to homes, the potato-based diet would be free of any contaminations, and the lack of any heavy industry would suggest a low level of exposure to bio-available lead. The concentration of lead in dental enamel has been used as a measure of exposure in modern and archaeological studies (Ericson 2001; Arora et al. 2006; Montgomery et al. 2010). As a potential addition to the evidence for rural, rather than a London, origin, the measurement of enamel lead concentration would be a useful tool.
The unexpected outcomes of this study have included potential for identifying a link between the osteological evidence for chronic undernutrition in juveniles and the isotopic information contained in the teeth. Lead is a cumulative poison which can cause short and long-term effects on the individual and has been linked to rickets (Caffey 1938; Gordon and Whitehead 1949; Vico and Dessy 1988) and long-term neurological damage, including delinquent behaviour (Byers and Lord 1943; Gulson et al. 1998; Needleman et al. 2002; Bower et al. 2007). As a follow-up study, the measured lead concentrations from the dental enamel could be compared to the osteological evidence and the incremental dentine $\delta^{15}N$ profiles, to evaluate any correlations.

8.5 Further work

Because the number of teeth sampled by dental incremental collagen analysis in this study was small and limited to two 19th-century sites, and there is only one other published study with similar time resolution (Eerkens et al. 2011), and one about to be published (Montgomery et al. in press) the next step should be to carry out more analysis to refine the methods and increase the range of samples from different geographical areas and time periods.

8.5.1 Methodological development

There is potential for the methods used in this study to be refined in order to improve the temporal resolution, and evaluate the effect of secondary and tertiary dentine on the isotopic values.

During the study, increments of differing sizes were produced, and a 1mm increment appeared to give a reliable collagen yield sufficient for measurement, in duplicate, at all levels of the root. As shown in section 5.5 (figures 4.3 and 5.12) cutting the root at $90^\circ$ to the surface will result in averaging across the incrementally forming layers of dentine. Because of this, reducing the section size will eventually reach a stage at which the ability to discriminate between one averaged section and the next will be lost, as a low yield would entail combining two or more adjacent sections to have enough material for analysis. A study designed to find the best balance between resolution and yield would be of benefit. The use of microscopy to identify the incremental structures in a slice of dentine, especially the neonatal line in teeth which start to form before
birth, would facilitate sectioning the teeth respecting these landmarks and allow
resolution of pre- and post-natal values. It would also be useful to work with other teeth:
upper incisors have a similar developmental age to M1, and upper canines which have a
similar developmental age to M2. Both may offer better resolution because of the length
of the roots, allowing more sections to be taken.

Because primary dentine does not remodel, it is a reliable source of temporally-
constrained isotopic information (see section 4.4). Cementum is easily removed in the
process of cleaning the tooth by air abrasion. However, secondary dentine continues to
form at the internal surface of the pulp chamber, and although slow to develop, will be
recording new isotopic values as it is laid down which may not match the underlying
dentine. Tertiary dentine (which is produced as a response by the dentinoblasts to an
insult such as carious invasion or wear on the outer surface of the dentine) may also be
present in a tooth and may be incorporating elements with new isotope ratios. In older
individuals, there is also a progressive calcification of the dentinal tubules from the root
tip upwards.

In order to quantify the effect of these tissues, a pilot study needs to be carried out using
teeth which have these later forming layers present. The layers of secondary and tertiary
dentine are visibly different to the original dentine, and so roots could be divided
longitudinally, the newer layers removed from one half, and then matched incremental
sections made of each half: the collagen isotope ratios from each section could then be
compared. If a large amount of any of these tissues is recovered, it may be possible to
produce collagen from these and measure the isotopic value obtained. The translucent
areas in the root are caused by calcification of the tubules: these areas do not contain
much organic material, so will not affect the collagen values (Nanci 2003b).

8.5.2 Modern samples
Modern samples of teeth which have never been buried, from individuals about whom
some health and life history is available, would form the ideal proxy for testing some of
the new interpretations of $\delta^{15}N$ proposed in chapter seven.

It would be necessary to exclude anyone with a history of prolonged undernutrition or
disease, but a well-nourished modern individual should be able to maintain homeostasis
throughout childhood, and provide a “control” population. Sex of the tooth donor would
be ascertained and the δ^{15}N profiles compared to the WHO growth charts to evaluate any changes which appear to be associated with the major growth spurts post-natally, at age 4-6 and at puberty, and if male and female δ^{15}N patterns around the time of the pubertal growth spurt are different. For donors of teeth forming around birth, information could be gathered about the length of the period of exclusive breastfeeding the individual had as a child. This information could then be matched to the δ^{15}N and δ^{13}C dentine collagen profiles to establish how breastfeeding appears in this tissue.

As can be seen from the recent paper by Neuberger et al. (in press) there is interest in the application of isotopic information from segmental hair analysis within a forensic setting to assess dietary deprivation. Dentine incremental analysis could also be applied to the cases where hair may not be available, or go far enough back in time to cover a period of suspected malnutrition.

### 8.5.3 Ancient populations

In ancient populations, the same incremental dentine analysis can reveal whether the patterns seen in this study are period specific, or due to human physiology. To test the current and new interpretations of juvenile bone collagen in relation to breastfeeding and stress, it would be useful to have access to individuals from sites where the bone collagen has been evaluated and a weaning pattern suggested. Teeth would be selected from both juveniles and adults, whose bone collagen has already been measured, to test the δ^{15}N and δ^{13}C dentine collagen profiles for survivors and non-survivors of childhood and establish whether the same flat profiles are prevalent in survivors but not in juveniles.

Targeting individuals within a population who show osteological evidence for stress, such as enamel hypoplasia, Harris lines, diseases associated with malnutrition such as scurvy and rickets, or who are small for age (stunted), and comparing them with individuals who have no sign of chronic disease, would give the opportunity to investigate links between nutritional status and stress events. The events which cause enamel hypoplasia (e.g. malnutrition, febrile illnesses) affect the ameloblasts during production of the enamel matrix, which returns to normal after the event, and so are temporally discrete: the change in the morphology is “fossilised” by the subsequent waves of enamel mineralization (Reid and Dean 2000). Thus, enamel hypoplasia,
especially if repeated at regular intervals in the same tooth, can be directly associated with the dentine forming at the same time and investigated using isotopic analysis.

Dentine collagen increments would seem to offer a way of investigating the dietary patterns of outliers in a bone collagen dataset, particularly if the individual is a juvenile or early adult where any unusual $\delta^{15}N$ and $\delta^{13}C$ dentine collagen profiles could give information about dietary/physiological changes which have been incorporated into the average values seen in the bone collagen.

**8.5.4 Individual amino acid studies**

Amino acids which are essential or conditionally essential must be obtained from dietary proteins (see section 3.6), and where this is not possible, they will be recycled by the body (catabolism), which causes a trophic level rise in the $\delta^{15}N$. The recycling of these amino acids will also cause a trophic level effect on the $\delta^{13}C$ contained within them, but it is of a much smaller magnitude. Recent research using hydrolysis of proteins (collagen and keratin) and chromatography to separate the individual amino acids has allowed measurement by mass spectrometry of the $\delta^{13}C$ of individual amino acids (Smith et al. 2009; Raghavan et al. 2010). It is possible that there will be a measurable change within the $\delta^{13}C$ of the essential amino acids when compared with the non-essential amino acids, but that this will be masked in a bulk collagen sample because of the large differences in the proportion of some amino acids compared to others. In effect, the averaging of $\delta^{13}C$ of the protein as a whole will reduce any trophic level effect on the individual amino acids.

Liquid chromatography/mass spectrometry (LC-MS) of amino acids may offer a way to investigate the more variable dentine collagen profiles. If samples are taken from the collagen at points in the $\delta^{13}C$ profile with differing isotope ratios, it may be possible to see how $\delta^{13}C$ of each amino acid changes: if all are rising or falling at the same rate, then there would be no discernible difference between the essential and non-essential amino acids. However, if essential and non–essential show different changes in $\delta^{13}C$, it may be an indication that there is recycling taking place in some amino acids and not others which, when combined, is not affecting the bulk (whole collagen) values. It is also possible that differences between essential and non-essential amino acid $\delta^{13}C$ may offer a diagnostic tool for scurvy. The body cannot produce the amino acid hydroxyproline from proline when the body is deficient in vitamin C. Hydroxyproline is
important to maintain the structure of collagen, and when missing from the protein results in the growth of connective tissues which are defective, causing the characteristic symptoms of scurvy. If it is possible to identify recycling of hydroxyproline by changes in $\delta^{13}$C this may indicate the presence of scurvy when it is still subclinical (i.e. the characteristic bony changes have not appeared on the skeleton) in the case of dentine collagen, temporal resolution may be possible for an episode at a time in childhood when subsequent bony healing has taken place and the disease is no longer visible osteologically.

8.6 Conclusions

This study has shown the value of carbon and nitrogen isotope analysis as a tool in the investigation of migration. As a relatively inexpensive analytical procedure when compared to strontium, lead and phosphate oxygen isotope analysis, it can be employed where there is a suspected difference in the diet in the place of origin and burial.

The development of a method to improve temporal resolution for carbon and nitrogen isotopes during the period of tooth growth (i.e. perinatal to age 23-24 years of age) has allowed the identification of migration between geographical places with differing diets during childhood and adolescence. This study has shown that the current model for breastfeeding and weaning by comparing isotope values from the bone collagen of juveniles with the mean from the bone collagen of adult females in a burial population can no longer be considered to be a valid method. Incremental dentine analysis appears to offer a chance to investigate developmental milestones within the juvenile years of individuals such as weaning and puberty, although further work is essential before the reproducibility of these patterns within the profiles of this small sample can be confirmed. Combining co-genetic tissues and tissues formed at different periods of life offers an opportunity to examine the turnover rates of these tissues, and their sensitivity to stress.

The benefit of using an historical period population has been seen in the detailed analysis of the pathways of migration from Ireland to London, the availability of detailed dietary information, information about health and disease in mid-19th-century Britain and Ireland, and the particular socio-economic groups from which the cemetery populations came. Context is the key to understanding the isotopic results which were obtained. The icing on the cake is the few epigraphic details which were available and
enhanced the overall interpretation of the lives of these individuals. In a small way this study (in combination with the work of the archaeologists, osteologists and historians) has allowed the “invisible” members of society in these cemeteries, who left behind very little in the way of documentary evidence, to tell something of their life histories.
Bibliography


Dickson, RW (1822-1824) *An Improved system of Management of Livestock and Cattle*.


Fuller, BT, Molleson, TI, Harris, DA, Gilmour, LT & Hedges, REb (2006b) Isotopic evidence for breastfeeding and possible adult dietary differences from Late/Sub-Roman Britain. *American Journal of Physical Anthropology* 129: 45-54.


Gaskell, P (1833) *The manufacturing population of England*. London:


Gustafson, G (1950) Age determination on teeth. *Journal of the American Dental Association* 41: 45-54


Neuberger, FM, Jopp, E, Graw, M, Püschel, K & Grupe, G (in press) Signs of malnutrition and starvation: Reconstruction of nutritional life histories by serial isotopic analyses of hair. *Forensic Science International* (0)


Various (1838-1856) Annual Reports of the Registrar General of England. London:


227


Wright, LE (2012) Examining childhood diets at Kaminaljuyu, Guatemala, through stable isotope analysis of sequential enamel microsamples. *Archaeometry*


