ASSESSING ARCTICA ISLANDICA AS A PROXY FOR SCOTTISH MARINE CLIMATE CHANGE

Keziah Jane Stott

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Assessing Arctica islandica as a proxy for Scottish marine climate change

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March 2014

A thesis submitted to the University of St Andrews for the Degree of Doctor of Philosophy

School of Geography and Geosciences

University of St Andrews

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I, Keziah Jane Stott, hereby certify that this thesis, which is approximately 50,015 words in length, has been written by me, that it is a record of work carried out by me and that it has not been submitted in any previous application for a higher degree.

I was admitted as a research student in October 2007 and as a candidate for the degree of PhD in Geography and Geosciences (Science) in October 2007; the higher study for which this is a record was carried out in the University of St Andrews between 2007 and 2013.

I, Keziah Jane Stott, received assistance in the writing of this thesis in respect of spelling, language, grammar and syntax, which was provided by Mrs Lesley Stott, Mr David Gelder, Dr Nigel Simmons, Dr Alix Cage and Mr Alisdair Cain.

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Abstract

This thesis investigates the potential of the bivalve *Arctica islandica* (Linnaeus, 1767) from fjordic sites in NW Scotland for reconstructing past marine environmental /climatic variability. Using dendrochronological and sclerochronological techniques, six master chronologies were created which when compared show little common variability between the sites, indicating no common response to regional scale forcing. The chronologies were compared to local and regional scale SST and land based datasets, with no significant, time stable responses to climate found. It is clear the growth/climate response of *A. islandica* from these sites is complex, potentially due to the shallow nature of the sample sites, direct local drivers such as food availability and, potentially, anthropogenic activity in the region.

Geochemical analyses of the shell material were undertaken to examine the timing and magnitude of the radiocarbon bomb-peak and the stable carbon isotope signature of the oceanic Suess Effect. The timing of the radiocarbon bomb-peak in Loch Etive does not appear to match previously published results from other marine locations and are a potentially serious challenge to the assumption that *A. islandica* GI are always annual features. Results comparing $\delta^{13}C$ values and the age of the specimen when these values are incorporated into the shell material strongly indicate an ontogenetic control over $\delta^{13}C$, meaning the Suess Effect could not be effectively investigated. To take these ontogenetic influences into account it is suggested that any data from the juvenile period of shell life is not used.

Analysis of shell biometrics and morphology indicate significant relationships between shell age and height and age and weight, however the errors for these are large (±78 years and ±80 years respectively). These results indicate that despite large errors shell height, as a predictor of age, has the potential to be used for *in situ* population studies.

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1 Introduction

1.1 Project Rationale

Possibly one of the most sensitive locations to study past climate variability in the North Atlantic is the west coast of Scotland which is ideally located, in close proximity to the North Atlantic Current, to capture the strong regional influence of North Atlantic water masses and their variability through time. The North Atlantic Ocean in particular plays an important role in regional European climate processes mainly because of the influence of the North Atlantic Current/Gulf Stream, the North Atlantic Oscillation (NAO), the Atlantic Multidecadal Oscillation (AMO) and, indirectly, the North Atlantic Meridional Overturning Circulation (AMOC).

The variability of the NAO is examined by the differences between air pressure in the Azores High and the Iceland Low (Hurrell, 1995; Wanner et al., 2003) and influences the transportation of heat/moisture around the Atlantic (Hurrell et al., 2003) (Figure 1.1). NAO variations have been shown to influence NW European climate, e.g. during positive NAO phases NW Europe experiences warmer and wetter winters (Trouet et al., 2009).

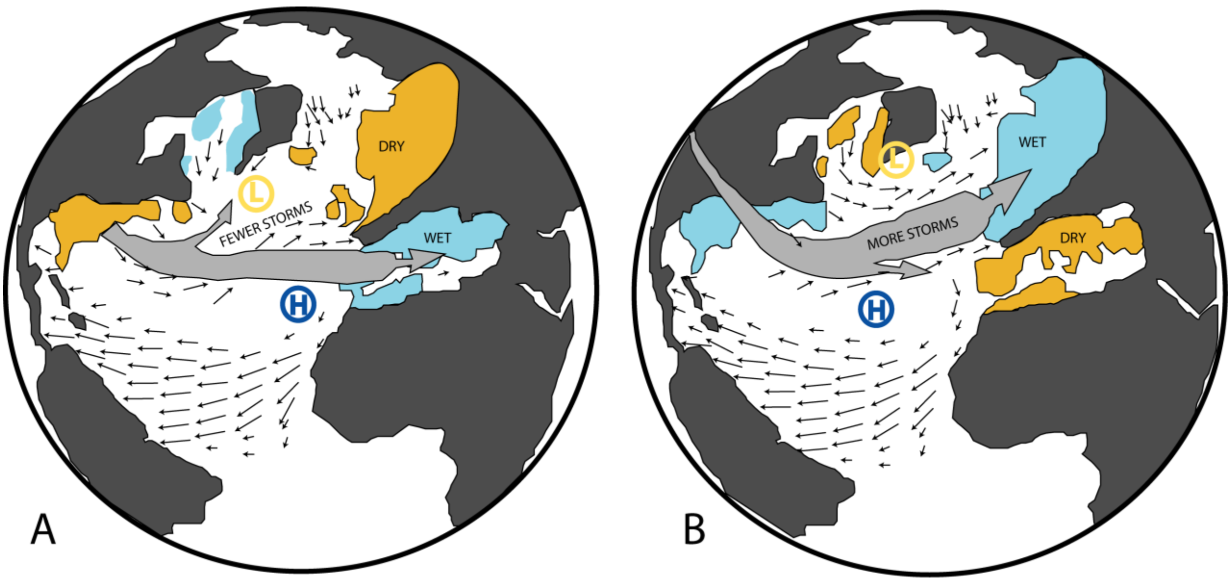


Figure 1.1: Schematic figure of the winter North Atlantic Oscillation (NAO) illustrating both phases. A) The NAO in negative phase, resulting in a colder and drier NW European climate, B) The NAO in a positive phase with a warmer and wetter NW European climate. Adapted from Bell and Visbeck (2012).

In addition to atmospheric forcing and NAO variability, NW Scotland is also influenced by the North Atlantic Current/Gulf Stream, which transports warm, tropical waters to the North Atlantic as part of a global thermohaline circulation (THC) system (Figure 1.2). This process ensures that European climates are generally milder than those at the same latitude elsewhere in the northern hemisphere, and it has been suggested that the rate of THC reduced in the past causing, for example, the Younger Dryas (YD – circa 11-10 ka BP; Gordon, 1997) cooling event (Teller et al., 2002). Teller et al. (2002), for example, suggested that during the Younger Dryas an outburst of freshwater into the North Atlantic Ocean, caused changes to circulation patterns in the THC. To better understand the palaeoclimate history of Scotland, proxy records which are sensitive to climatic variability must be developed that extend our knowledge beyond the instrumental data available, the focus of this research will be the marine environment as there is currently little information available for this region.

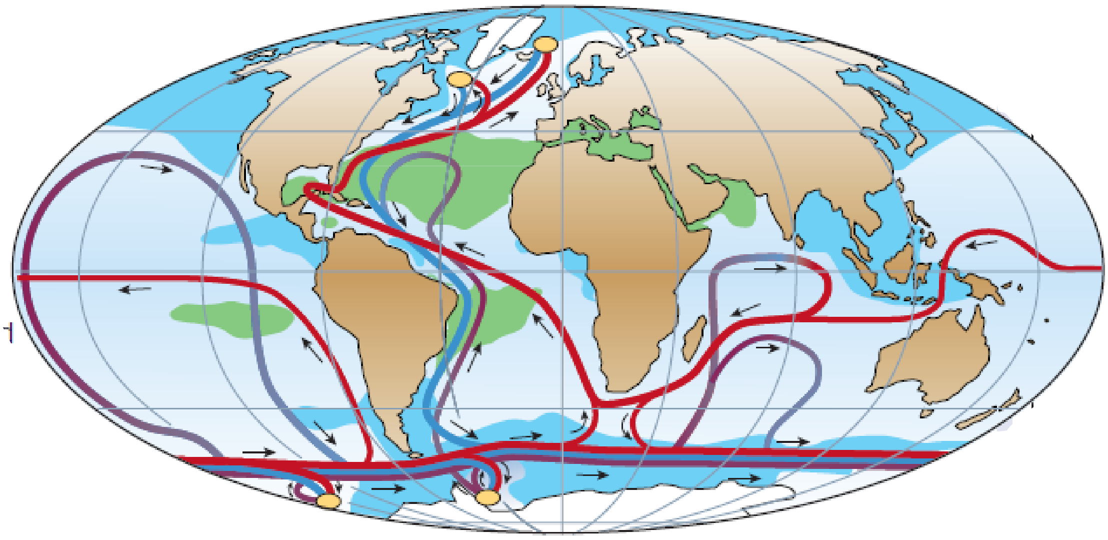


Figure 1.2: Schematic figure of the THC from Rahmstorf (2002; 208). The yellow dots indicate the location of deep water formation, red lines are near surface waters, the blue and purple lines represent deep and bottom currents respectively. Areas shaded in green are reported as having salinity greater than 36, and the blue shading represents salinity levels below 36.

There is currently a distinct lack of high-resolution marine and terrestrial palaeoclimate records suitable for such analyses. In this thesis, a high-resolution proxy is defined as having annual to decadal resolution. For NW Scotland, Proctor et al. (2000; 2002) produced speleothem records in excess of 1000 years, which have been used to investigate precipitation/NAO and temperature/precipitation/SST/NAO respectively using changes in stalagmite growth rate. Proctor et al. (2000) also used their record to investigate the winter NAO. Trouet et al. (2009) used the speleothem record from Proctor et al. (2000) (AD 900-1993), along with a Moroccan tree record (Esper et al., 2007), as a proxy for NAO variability. There is also a move to increase the number of dendrochronological records available for Scotland to create longer term interannual summer temperature reconstructions (Wilson et al., 2012). Previous work elsewhere has already shown the potential to derive a reconstruction of sea surface temperatures (SSTs) from tree ring records, either using them to reconstruct coastal water changes or to investigate larger-scale climate events such as El Niño Southern Oscillation (ENSO) (e.g. D'Arrigo et al., 1996; D'Arrigo et al., 1999; D'Arrigo et al., 2005; D'Arrigo et al., 2006; Wilson et al., 2010). Corals also have huge potential for marine palaeoclimate research e.g. research into ENSO (Wilson et al., 2010). However, there are currently no published coral records for the coast of Scotland to produce annually-resolved climate proxy records. There is also the potential to use coralline algae, which have annual to sub-annual banding (Burdett et al., 2011). Kamenos (2010) published a bi-weekly shallow water temperature record, for the period 1353 to 2006, using Loch Sween coralline algae which highlighted the potential of this emerging research field. There is still a lack of high-resolution marine records for Scotland as the only available records do not capture high resolution climate information well e.g. marine/fjord sediment core records (e.g. Cage 2005; Cage and Austin, 2010; Hibbert et al., 2010; Hibbert, 2011).

In recent years the coastal fjords of NW Scotland have begun to be seen as potentially important locations for palaeoclimatic research. Gillibrand et al. (2005) have shown the sensitivity of Scottish west coast fjords to NAO forcing, while Cage and Austin (2010) have shown their potential as recorders of past climate, such as the local timing of the Little Ice Age and an abrupt warming circa. AD 1540. To address the lack of high-resolution (i.e. annually to sub-decadally resolved) marine records for NW Scotland, the annually-resolved growth records of the marine bivalve *A. islandica* for six fjordic sites along the west coast of Scotland were explored in this study. The advantage of using a species such as *A. islandica* as a climate proxy is its wide geographical distribution (see Section 1.4) around the North Atlantic, allowing the development of a network of chronologies to investigate basin-wide responses to climate and study the response of this species to different environmental conditions.

1.2 Fjords

Fjords, sometimes referred to as sea lochs, are flooded coastal valleys formed by glacial activity (either in the past, or still ongoing in the present day). There are two fjord classifications in common use; glaciated (i.e. those in Arctic regions where glacial activity still occurs) and non-glaciated fjords (i.e. those around the Scottish coast where glaciers are no longer present) (Howe et al., 2010). The two lochs being studied here (Lochs Creran and Etive) are non-glaciated fjords. Fjords are complex systems (Figure 1.3) which has led to many publications on the processes acting within them (e.g. Gage, 1972a; Gage, 1972b; Edwards and Edelsten, 1977; Aarseth, 1997; Allen and Simpson, 1998; Dix and Duck, 2000; Howe et al., 2001; Austin and Inall, 2002; Howe et al., 2002;Nordberg, 2002; Murray et al., 2003; Filipsson and Nordberg, 2004; Lyså et al., 2004; Gillibrand et al., 2005; Nørgaard-Pedersen et al., 2006; Leonov and Kaswase, 2008; Hjelstuen et al., 2009). There has also been a recent increase in publications studying the potential of fjords as recorders of past climate variability (e.g. Nordberg et al., 2002; Mikalsen et al., 2001; Nordberg et al., 2001; Austin and Inall, 2002; Murray et al., 2003; Gillibrand et al., 2005; Cage and Austin, 2010). The majority of these have focused on either sediment records or the use of foraminifera changes/geochemistry. It is also possible to use other fauna e.g. molluscs, living in fjords to investigate palaeoclimatic variability (e.g. Stott et al., 2010) which is the focus of this research. Fjord hydrography is outlined in more detail in Section 2.1.1.1.

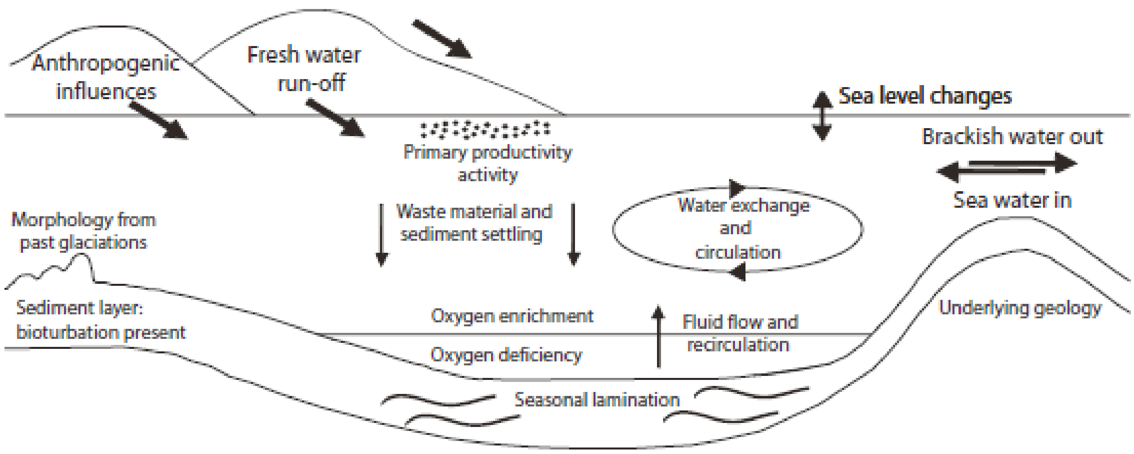


Figure 1.3: Main processes acting in a non-glaciated fjord (Adapted from Howe et al., 2010).

1.2.1 Potential of Fjords as Palaeoclimate Archives

As has already been mentioned, it is only recently that the potential of investigating palaeoclimate proxies from fjords has begun to be fully investigated, with the focus being on sediment and foraminifera records. Nordberg et al. (2000 – in Sweden), Nordberg et al. (2001 – in Sweden), and Gillibrand et al. (2005 – for Scotland) all found evidence that NAO variability can be studied in fjordic settings using a variety of techniques including the use of benthic foraminifera analysis (Nordberg et al., 2000) and sediment core analysis (Nordberg et al., 2001). Mikalsen et al. (2001) and Kristensen et al. (2004) also found NE Atlantic circulation influences in the fjords they studied from the west coast of Norway. Cage (2005) suggested that it is generally fjords with shallower sills that are able to record NAO forcing (e.g. Nordberg et al., 2000; Nordberg et al., 2001). If this is the case then sill depth should be considered as an important variable if the intent is to use fjords for NAO reconstructions. However, location and orientation of the fjord is also very important as it must be within the geographical area influenced by the NAO (Figure 1.1). It may also be expected that sample sites further into a fjord would show a dampened NAO signal compared to those nearer the mouth.

In the Scottish context Gillibrand et al. (2005) showed the potential of a NAO signal being recorded in changes in renewal events/basin water salinity in Loch Sunart, while Dix and Duck (2000) and Howe et al. (2002) have investigated the late glacial – Holocene transition period recorded using seismic stratigraphy analysis and sediment analysis respectively. However, few projects have investigated Holocene records in Scottish fjords (Murray et al., 2003; Cage and Austin, 2010). Murray et al. (2003) did not develop a palaeoclimate reconstruction, but they did determine that high sedimentation rates in Loch Etive (0.5 cm a year; sedimentation rates reported by Cage and Austin(2010) for Loch Sunart are ~1 cm a year for 0-50 cm and 4-5 cm year for 50-300 cm), along with evidence of fauna responding to past climate variability means there is potential to provide high resolution climate records for the overlap between the sediment core record and the *A. islandica c*hronology.

1.3 Potential proxy records

There are multiple archives with the potential to create proxy climate records of varying resolution. These include; historical records (e.g. Brázdil et al 2005;Dobrovolný et al., 2008; Dobrovolný et al., 2010) , marine sediment core analysis (e.g. Oliver et al., 2010; Cage and Austin, 2010), speleothem analysis (e.g. Fairchild et al., 2001; Baker et al., 2002), ice cores (e.g. Francey et al., 1999; Steffensen et al., 2008; Berggren et al., 2009; Vinther et al., 2006; Vinther et al., 2010), lake sediments (e.g. Bjune et al., 2005), dendrochronology (e.g. Douglass, 1914; Blasing and Fritts, 1976) and sclerochronology (e.g. Marchitto et al., 2000; Schöne et al., 2004; Kamenos, 2010). Historical record analysis involves using a variety of records including diaries and port records as means of reconstructing past climate and can be used to produce both temperature and precipitation records (Brázdil et al., 2005). Ice core records can use $\delta^{18}O$ variations to provide seasonally resolved temperature records (Vinther et al., 2010), while lake sediment records have previously been used for a variety of purposes including temperature and precipitation for July and the winter respectively (Bjune et al., 2005).Marine sediment cores (either from deep-water or coastal locations) can be used to investigate palaeoclimate using variables such as foraminifera stable isotope records (e.g. Cage and Austin, 2010) and pollen analysis (Mokeddem et al., 2010). Speleothem analysis involves the study of annual increments in speleothems (e.g. Fairchild et al., 2006) and through the measurement of stable isotopes within the stalagmites (e.g. Baker et al., 2011), while with dendrochronology, tree-ring analysis can be used to provide climate proxies (e.g. Fritts, 1976; Speer, 2010). Sclerochronology uses a variety of proxies including corals (Hudson et al., 1976), otoliths (inner ear bones e.g. Surge and Walker, 2005), sclerosponges (sponges with a hard skeleton), coralline algae (Kamenos et al., 2008; Kamenos, 2010), bones and shells (e.g. Schöne et al., 2005a). Marine sediment cores, speleology, dendrochronology and sclerochronology are all described in more detail later in this chapter.

When selecting any proxy for climate reconstruction, it is important to choose one which responds to one dominant climate variable in their surroundings e.g. temperature. If they record multiple variables then they are less than ideal, resulting in the fact that a reconstruction of one climatic factor would not be possible. Equation 1.1 below is a model which can be used to conceptualise the factors influencing growth. Here it focuses on its application to dendrochronology and sclerochronology (Cook, 1985a):

$G = C + A + D1 + D2 + E$ Equation 1.1

Where G is recorded growth

C is the climate signal in the individual series making up the master chronology

A is the growth trend related to age (known as the ontogenetic growth trend in sclerochronology)

D1 is a factor influencing growth rates of individuals (e.g. death of an individual specimen)

D2 is a common influence to all individuals at a location (site-specific disturbances e.g. pollution and trawlers)

E represents random variability within growth.

1.3.1 Marine Sediment Core Analysis

Marine sediment cores, (e.g. van Kreveld et al., 2000; Oliver et al., 2010; Hibbert et al., 2010), have the potential to provide a wealth of palaeoclimatic information including; ice sheet dynamics (Hibbert et al., 2010), links between ice sheets and marine processes (e.g. D-O cycles in van Kreveld et al., 2000), temperature (e.g. Cage and Austin, 2010) and sea circulation changes from $\delta^{13}C$ measurements in foraminifera (e.g. Oliver et al., 2010). Unless sampled in environments with high sediment deposition (e.g. fjords), marine sediment core proxy reconstructions have a low-resolution (defined as proxies with a sample resolution of at least one record every 50 years based on work by Cunningham et al., 2013). By sampling in fjordic environments with their high sedimentation rates (Howe et al., 2010) the resolution of records produced can be decadal or better. There are a variety of variables that can then be studied to investigate climate changes recorded in the fjordic environment including foraminifera analysis (Cage and Austin, 2010) and changes in sedimentation patterns (Hass et al., 2010).

For Scottish fjords, Cage and Austin (2010) and Mokeddem et al. (2010) have reconstructed past climate change events using a variety of methods between them, both producing climate records for Loch Sunart. Cage and Austin (2010) used oxygen isotope records from benthic foraminifera to reconstruct past summer temperature, while Mokeddem et al. (2010) used a combination of pollen analysis, grain size variations and benthic foraminifera assemblages to reconstruct climate variations such as the timing of the Last Glacial Maximum (LGM). Nørgaard-Pedersen et al. (2006) studied sediment records from Loch Etive to investigate changes in relative sea-level (RSL) and past variability in deep water renewal events. However, the low number of fjordic palaeoclimate records for the region means that it is difficult to replicate findings and validate results. The use of additional proxies is therefore required for validation purposes. In Cunningham et al. (2013) the Loch Sunart record of Cage and Austin (2010) is compared to other marine records from across the North Atlantic. Findings indicate that the Loch Sunart results do not fit with those from other records from the NE Atlantic. Therefore, to determine why this is the case, it would be advantageous to find alternative climate records from the region to verify such results. Another problem with fjord sediments is that although they have the potential to provide high-resolution records, they are not annually-resolved, making validation with instrumental data difficult. The goal is to produce annually-resolved records which can be used to validate the decadal trends from sediment core results which reconstruct marine temperature and atmospheric process variability.

1.3.2 Dendrochronology

Dendrochronology involves the study of annually-resolved tree-rings and is perhaps one of the best known annually-resolved proxy archives with its long history (e.g. Douglass, 1914; Douglass, 1920; Douglass, 1929; Blasing and Fritts, 1976) and is widely used as the main constituent in large-scale multi-proxy studies (e.g. Mann et al., 1998; Newkom et al., 2010). Dendrochronology has wide coverage, and because of good site control there is good knowledge concerning what different sites will offer a situation that is lacking in many other disciplines. Tree-ring research is also important in archaeological work (e.g. Baillie, 1982; Bannister and Robinson, 1975; Eckstein et al., 1986) and as a tool for calibration of ^{14}C atmospheric curves for ^{14}C dating (e.g. Becker, 1993). Dendroclimatology as the investigation of changes in annual ring widths as a means of reconstructing past climate (e.g. Fritts, 1976), has multiple sub-disciplines. These include the increasing trend in analysing isotopes in trees as climate proxies (e.g. Libby and Pandoffi, 1974; Lipp et al., 1991; Loader and Switsur, 1996; McCarroll and Loader, 2005; Loader et al., 2007; Treydte et al., 2007; Loader et al., 2008;

Robertson et al., 2008), blue intensity investigation (e.g. Campbell et al., 2007; Wilson et al., 2012) and maximum density analysis (e.g. Polge, 1970; Jones and Parker, 1970; Parker and Henoch, 1971; Schweingruber et al., 1978; Briffa et al., 2002a; 2002b; Wilson and Luckman, 2003). Although trees have been used to indirectly reconstruct SSTs (e.g. Wilson et al., 2010) they are not ideal for providing deeper marine climate proxy record as they are incapable of providing bottom water data.

There are several key dendrochronological methods which must be outlined as they are relevant for sclerochronology. These are crossdating and detrending of raw growth data. Crossdating (see Figure 1.4) is the most important dendrochronological technique as it helps ensure correct dating control of the final chronology through the identification of common wide and narrow rings between tree-ring series (Stokes and Smiley, 1968; Yamaguchi, 1991). This technique not only provides a calendar age to each tree-ring, but also helps to identify growth series with either missing or false bands. The importance of crossdating for constructing robust, correctly dated dendrochronological records has recently begun to be recognised in sclerochronology, with researchers beginning to apply the technique (e.g. Black et al., 2008; Butler et al., 2010: Stott et al., 2010).Detrending of raw growth rate data is necessary due to the presence of a biological trend (known as the ontogenetic growth trend in sclerochronology), expressed as higher growth rates in the younger growth rings, relative to later on. Without the removal of this trend there would be a bias in the final chronology towards the periods where younger tree records are present. The application of both techniques will be further described in the context of this research in Chapter 4.

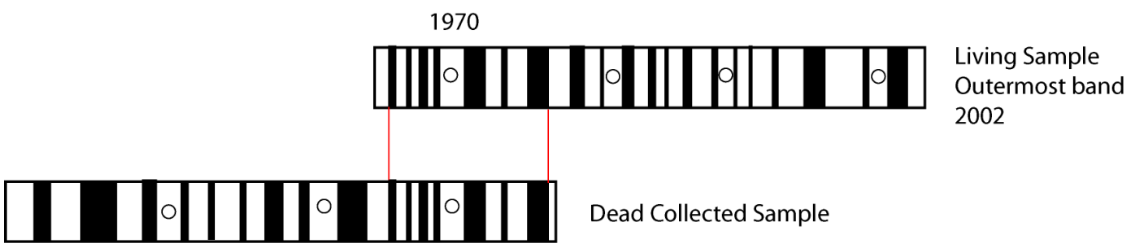


Figure 1.4: Principle of crossdating. The top sample was live collected with a known date for the outermost ring. By matching the patterns in the ring widths a date can be applied to the dead collected sample below. This methodology is also applied to multiple live-collected samples to ensure dating control between samples.

1.3.3 Sclerochronology

Sclerochronology focuses on the investigation of the accreted hard parts of organisms such as shells, corals and fish otoliths, to examine how variables such as growth rates and chemical composition change during the life-time of the organism (Jones et al., 2007). In the marine environment these techniques have been applied to shells (e.g. Schöne et al., 2005a), corals (e.g. Hudson et al., 1976) and sclerosponges (e.g. Swart et al., 1998; Hughes and Thayer, 2001). Due to the common techniques utilised in both dendrochronology and sclerochronology, the former is often considered to be the forbearer of sclerochronological research. Although sclerochronology is a relatively new field of research, having only been active since the 1960s/1970s, there is great potential to use it to develop annually-resolved records that reflect marine environmental change.

As with dendrochronology, sclerochronology has multiple sub-disciplines and applications. The primary discipline is scleroclimatology which focuses on creating growth chronologies for the purpose of climate research (e.g. palaeoclimatic reconstruction); however, sclerochemistry is the application of geochemical analyses to either the hard part of the organism or its soft tissue. Gröcke and Gillikin (2008) suggested the use of the term sclerochemistry in the literature where geochemical techniques are used; the application of sclerochemistry can be used to investigate ^{14}C variations (e.g. Weidman and Jones, 1993) which can be used to investigate the difference in the timing of the bomb-peak in the atmospheric and marine records, and temperature changes (e.g. Buchardt and Simonarson, 2003).Researching the ^{14}C signal in the marine environment is important for a variety of reasons including understanding CO_2 gas exchanges between the ocean and atmosphere and circulation in water masses (Broecker et al., 1980; Weidman, 1988; Scourse et al., 2012; Wanamaker et al., 2012).

If scleroclimatological or sclerochemical techniques are utilised for the purposes of providing annually-resolved climate records then it is necessary to ensure the species fits certain criteria:

1) There must be evidence of annually deposited growth increments (GIs) in the hard part of the organism that can be used to age/date specimens, e.g. GIs of an annual nature in the mollusc *A. islandica* (Schöne et al., 2005b)
2) They must have a common variance and common response to factors influencing their growth allowing crossdating of any internal growth increments to be undertaken

3) Variations in their GI widths/geochemical variations in the hard part of the organism must have the potential to be used to investigate changes in variables such as temperature, salinity, food supply and pollution. However, it is important to note that if a specimen is influenced by too many variables it can be difficult, and sometimes even impossible, to use the record to reconstruct changes in a single variable e.g. climate (see Equation 1.1). If there is a mixed signal concerning the variables influencing growth increment widths/geochemistry then it needs to be feasible to determine how each variable is influencing the measured proxy, otherwise the species is of no use as a palaeoclimatic proxy.

For the west coast of Scotland there are three main species of marine bivalve that could potentially be used for such research. They are *Glossus humanus*, *Glycymeris glycymeris* and *A. islandica.* However, at the time of starting this research little was known about the potential of *Glossus humanus*, and *Glycymeris glycymeris* as palaeoclimatic archives, particularly for Scottish sites (this has since been studied in Reynolds, 2011; Brocas, 2013; Reynolds et al., 2013). As a result the marine bivalve *A. islandica* was chosen for analysis. The species is described in more detail in Section 1.4 and has been studied over the last ~15 years as a proxy record for climate variability (e.g. Witbaard, 1996; Witbaard, 1997; Schöne et al., 2003a). The work of Brocas (2013) focused on using *Glycymeris glycymeris* from the Irish Sea to create annually-resolved archives and found a significant, positive correlation between shell GIs and the winter NAO. Reynolds et al. (2013) were able to use a crossdated growth increment chronology from *Glycymeris glycymeris* to create a multi-proxy record (this included the shell growth increment variability and a foraminifera record from a fjordic sediment core) which correlated with SST data. These studies indicate that *Glycymeris glycymeris* has the potential to be used as an annually resolved proxy for reconstructing past climate change. To date no peer-reviewed papers have been published regarding the use of *Glossus humanus*, however it has been studied with some promising results for providing palaeoclimatic reconstructions in the future (e.g. Reynolds et al., 2009).

As already mentioned species can react to multiple variables (Equation 1.1) and if the climate signal is not the dominant influence over growth rates because of additional influence from site specific factors (Equation 1.1), then it may not be possible to use the record as a climate proxy.

1.3.3.1 History of sclerochronology

Since the publication of perhaps the first paper concerning sclerochronological research on shells by Davenport (1938) who investigated the timing of GI deposition in the mollusc *Pecten irradians*, research has been carried out on shells for palaeoclimatic and palaeoenvironmental proxies. Table 1.1 summarises some of the key past sclerochronological and sclerochemistry research (focusing on mollusc and *A. islandica* based work). The field has changed greatly over recent years. Initial research did not use dendrochronological techniques such as crossdating until the 2000s (e.g. Schöne et al., 2003a). Since then its application has become standard within the field, thus helping introduce improved dating control in chronologies. From Table 1.1 it is notable that there has been little published research undertaken in fjords and in shallow water sites.

Year	Author(s)	Application	Geographical location of study	Site water depth: Shallow <30 m, Medium 99 – 31 m, Deep >100 m.	Crossdating applied?
1938	Davenport	The first paper on sclerochronology in shells	Cold Spring Harbour (Long Island)	Not mentioned	Not applicable – not necessary in study
1953	Loosanoff	Work into *A. islandica* reproduction	Rhode Island	Medium	Not applicable – not necessary in study
1969	Merrill and Ropes	*A. islandica* distribution researched	Continental shelf – Gulf of Maine and Middle Atlantic Bight	Not mentioned	Not applicable – not necessary in study
1976	Taylor (1976a, b)	Two papers researching shell biology in *A. islandica*	Not applicable – laboratory based study	Not applicable - methods paper	Not applicable – not necessary in study
1976	Bearse	Looked at how environmental factors influence density and distribution of *A. islandica* in Rhode Island	Rhode Island	Not mentioned	Not applicable – not necessary in study
1979	Murawski and Serchuk	Investigated the morphology of *A. islandica*	Middle Atlantic Shelf	Ranges from shallow to medium	Not applicable – not necessary in study
1980	Jones	Paper on annual cycles of GI formation		Not applicable - methods paper	Not applicable – not necessary in study
1980	Thompson et al.	Looked for synchronisation in *A. islandica* shell growth rates from a single population for verification of annual nature of GIs	Middle Atlantic Bight	Not mentioned	Did not use crossdating, but do look for synchronous growth rate patterns
1982	Murawski et al.	Investigating *A. islandica* growth. Used mark and recapture of shell samples	Middle Atlantic Bight	Medium	Not mentioned
1982	Turekian et al.	Researched GIs – helped to prove their annual nature		Medium	Not mentioned
1983	Jones	Possibly the first paper discussing the need for standardised growth rates	Not applicable - methods paper	Not applicable - methods paper	Not mentioned
1987	Ropes	Paper on acetate peel preparation for ageing *A. islandica*	Not applicable – techniques paper	Not applicable - methods paper	Not mentioned
1990	Brey et al.	Ecological importance and growth of *A. islandica* in Kiel Bay	Kiel Bay, Western Baltic Sea	Not mentioned	Not applicable – not necessary in study
1994	Swaileh and Adelung	Investigated trace metal levels in *A. islandica*	Kiel Bay, Western Baltic Sea	Not mentioned	Not applicable – not necessary in study
1996	Swaileh	Investigated trace metal levels in *A. islandica*	Kiel Bay, Western Baltic Sea	Not mentioned	Not applicable – not necessary in study

1997	Witbaard and et al. (a)	Research into juvenile *A. islandica* growth	Kiel Bay (Baltic Sea)	Not mentioned	Not applicable – not necessary in study
1999	Cargnelli et al.	Researched *A. islandica* habitats	Not applicable	Not applicable - methods paper	Not applicable – not necessary in study
2000	Marchitto et al.	Correlated *A. islandica* chronologies but didn't call it crossdating	Georges Bank, Nantucket Shoals and Iceland	Not mentioned	Successfully used crossdating
2000	Dahlgren et al.	Distribution and genetics of *A. islandica* studied	Global locations involved	Not mentioned	Not applicable – not necessary in study
2000	Todland et al.	Applications of laser ablation ICP-MS for sclerochronology	Cardigan Bay, Wales	Not mentioned	Not applicable – not necessary in study
2001	Lewis et al.	Population recruitment of *A. islandica* on Georges Bank investigated	Georges Bank	Not mentioned	No crossdating to support sample age data
2003	Schöne et al. (a)	First real mention of crossdating in sclerochronological literature	North Sea and Norwegian Sea	Not mentioned	Crossdating undertaken
2005	Liehr et al.	Used *A. islandica* to investigate sediment contamination	Mecklenburgh Bight (western Baltic Sea)	Not mentioned	Crossdating not mentioned
2006	Scourse et al.	Produced a floating chronology using *A. islandica* for the Mediaeval period	North Sea – water	Deep	Yes, crossdated dead samples to create a floating chronology
2007	Helama et al.	Investigated response of bivalve (*A. islandica*) and tree increments to climate change	Tromsø region – exact location unknown	Not mentioned	Crossdating undertaken for chronology construction
2008	Harding et al.	Investigated how age structure and recruitment in *A. islandica* can be influenced by water temperature	Mid-Atlantic Bight (North America)	Not mentioned	Not applicable – not necessary in study
2008	Wanamaker et al.	Long lived non-colonial animal found – an *A. islandica* specimen aged 405 years old	Icelandic shelf	Not mentioned	Potential/concepts of crossdating mentioned
2010	Begum et al.	Allometry/morphology of *A. islandica* studied	Norwegian coast, Kattegat, Kiel Bay, White Sea, German Bight, northeast Iceland.	Not mentioned	No – not the aim of the research.
2010	Stott et al.	Investigation of *A. islandica* growth in a Scottish fjord	Scottish fjords	Shallow	Yes, but with low inter series correlation
2010	Butler et al.	Construction of the longest sclerochronological *A. islandica record*	Irish Sea	Medium	Crossdating was successfully undertaken

		for the UK			
2011	Ridgway et al.	Investigated how shell size, growth rates and maturity are correlated with mollusc longevity	Not clearly stated	Not stated	Not applicable – not necessary in study
2011	Morton	Studied *A. islandica* biology	Not applicable	Not applicable - methods paper	Not applicable - methods paper
2011	Matras	Investigated *A. islandica* shell growth rates in several Faeroese locations	Several locations including one loch	Not mentioned	Not mentioned
2011	Hiebenthal et al.	Studied effect of seawater pCO_2 and temperature on *A. islandica* and *Mytilus edulis* shell stability	Western Baltic Sea	Shallow	Not applicable – not necessary in study
2012	Scourse et al.	Used *A. islandica* growth increments and ^{14}C measurements to study the timing of the bomb peak	Temperate North Atlantic: Georges Bank, Sable Bank, Icelandic Shelf, Tromsø, German Bight, Oyster Ground	Shallow	Only shells from the Icelandic Shelf were crossdated. For some sites only one shell made up the chronology used to study the bomb peak
2013	Brocas et al.	Used growth rates in the shell of *Glycymeris glycymeris* to investigate its potential as a palaeoclimatic proxy	Irish Sea	Medium	Crossdating successfully undertaken
2013	Butler et al.	Studied climate change on the North Icelandic Shelf using *A. islandica*	North Icelandic Shelf, close to the North Atlantic Polar Front	Medium	Crossdating undertaken successfully
2013	Munro et al	Studied aging of *A. islandica*	Not applicable		N/A
2013	Reynolds et al.	Used *Glycymeris glycymeris* growth rate variability from the west coast of Scotland, along with a foraminiferal record to create a multi-proxy climate record	West coast of Scotland (Tiree Passage).	Shallow to medium	Crossdating undertaken

Table 1.1: Key dates in sclerochronology – focusing on its application to the marine bivalve *A. islandica.* Also indicated is the environmental context in which the studies were undertaken and whether any crossdating was applied to samples. Also included is information regarding whether crossdating was undertaken on samples and the location from which samples were collected.

1.4 *Arctica islandica*

A. islandica was chosen as the focus for this study as a proxy for environmental change due to (1) its well-documented longevity – Wanamaker et al. (2008) report a specimen in excess of 400 years old, (2) there are a number of variables that can be studied from the shell for palaeoclimate investigations including GI width variations and changes in shell geochemistry including $\delta^{18}O$ (Weidman et al., 1994) and ^{14}C changes (Witbaard et al., 1994), (3) cross matching of shell GI widths from a site can be undertaken, indicating growth driven by a common response to local variables including such as the climate (Wanamaker et al., 2008), (4) it is possible to crossdate fossil shells to create floating chronologies (Scourse et al., 2006), and (5) dead-collected samples can be cross dated with live-collected specimens to extend the period of analysis (Marchitto et al., 2000).

1.4.1 Species identification

A. islandica is a sub-littoral, infaunal marine bivalve mollusc (Witbaard, 1997). The main identifying features of this species are the periostracum, which is brown for juveniles and black in adulthood (Figure 1.5), and the presence of annually-resolved GIs within the shell. Records documenting the age to which specimens live commonly exceed 200 years (Witbaard, 1997). However, a live-collected sample from the North Icelandic coast (recovered in 2006) was determined to have been just over 400 years old when captured (Wanamaker et al., 2008).

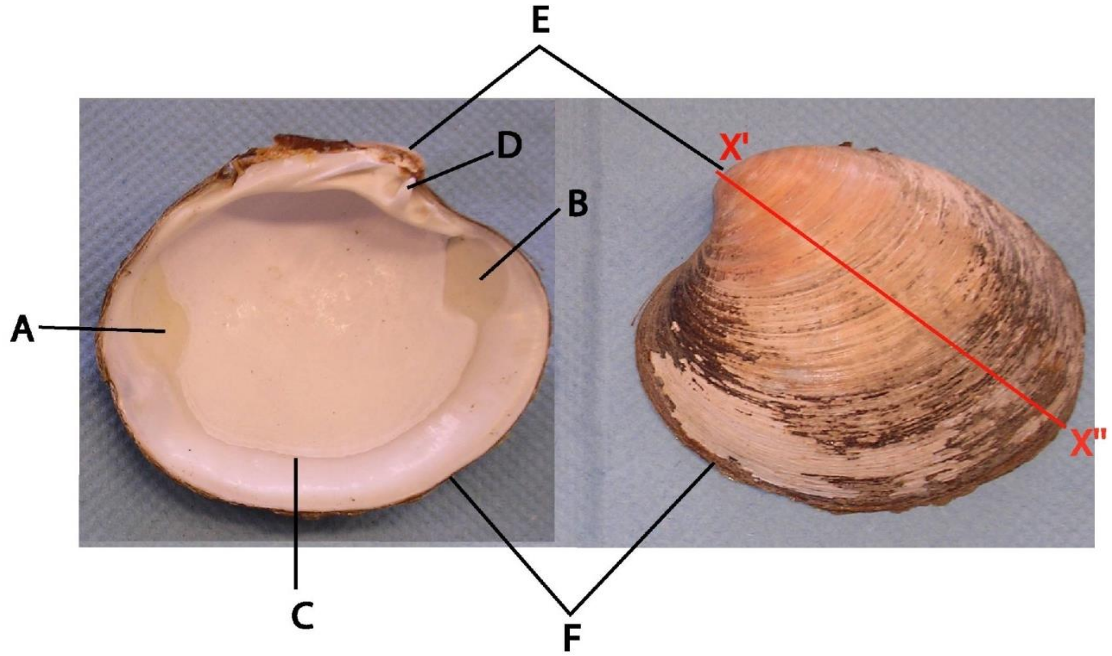


Figure 1.5: Main features of an *Arctica islandica* shell (Left hand valve interior view on left and exterior view on right – height of shell is 93 mm). Labelled are the: (A) posterior muscle scar; (B) anterior muscle scar; (C) pallial line; (D) hinge tooth; (E) umbo; and (F) the periostracum. The red line on the exterior picture is the line of section and is also the line used to work out specimen height. Note that the periostracum (F) is brown in smaller shells, but due to iron deposition is black in larger shells (Brey et al., 1990).

1.4.2 Shell Growth

A. islandica shells have two valves, which join in the umbo region of the shell (Figure 1.5) via a hinge ligament (Ruppert and Barnes, 1994). The shells themselves have three aragonitic layers: an outer prismatic layer, a thin myostracum and an inner layer (Witbaard, 1997). All parts of the shell have different micro-structures (Witbaard, 1997), these include:

- Growth increment boundary/growth increment line (Figure 1.7) – “irregular, simple prisms” (Witbaard, 1997; 16)

- Growth increment (Figure 1.7) – “homogenous structure, which consists of irregular complex crossed lamellar and crossed acicular-crossed lamellar microstructures” (Witbaard, 1997; 16).

The aragonite is deposited as calcium carbonate inside a protein framework (Moore, 2001) and covered by the periostracum (Figure 1.5) which is also made of protein (Moore, 2001). The periostracum is important in the shell secretion process and is laid down at the periostacal groove (Ruppert and Barnes, 1994), and supports the growth of new aragonite layers (Marin and Luquet, 2004). Extrapallial fluid, which is present between the mantle and the shell, is where the aragonite and organic material from which the shell is constructed is secreted and then deposited (Ruppert and Barnes, 1994). Without the periostracum the surrounding sea water would be able to interact with the extrapallial fluid, it prevents this by acting as a seal between the two reservoirs at the periostacal groove (Ruppert and Barnes, 1994).

1.4.3 Biology and Ecology

A. islandica favours sandy mud/mud (Liehr et al., 2005) and medium to fine grained sand (Thórarindóttir et al., 2008) sediments, and can regularly be found in water depths ranging from 10 to 280 metres, although they can live outside these depths (Thompson et al., 1980). They are generally found in water temperatures between 0 and 20^{o}C (Nicol, 1951 in Witbaard, 1997). The presence of only a short siphon (Figure 1.6), which is used to pump water containing the phytoplankton on which it feeds into its body (Cargnelli et al., 1999) (so called filter-feeding), means they are only shallow burrowers (Saleuddin, 1964). However, during the summer it is possible to sometimes see specimens on the sea bed itself (Buchardt and Simonarson, 2003).

Figure 1.6: Photograph of a buried *A. islandica* specimen with its siphons open. Image courtesy of M. Sayer (NFSD). Shell is approximately 12 cm at the widest point.

Temperature has been shown to play an important role in the development of specimens from one stage of growth to another. There are three biologically distinct stages of specimen growth (Cargnelli et al., 1999):

1) Planktonic egg/larvae
2) Juveniles
3) Adulthood.

The larval stage is sub-divided into three developmental periods which rely on temperature to allow progression. They are (Cargnelli et al., 1999):

1) Eggs hatch into planktonic larvae
2) Larvae develop a shell - this is the first stage where the bivalve shell is present
3) Larvae become capable of swimming and a burrowing foot develops.

Once larval development is complete and the specimen enters the juvenile stage, relatively fast expansion is observed in sample GIs, which then tapers off as individuals reach adulthood and is known as an ontogenetic growth effect in most sclerochronological literature (see Figure 1.7 for an illustration of this in cross section). This must be accounted for when GI measurements are detrended for chronology construction (see Chapters 1 and 4 for further discussion). Sexual maturity is sometimes not reached until the age of 13 years old; however it is variable depending on site location and specimen sex (Cargnelli et al., 1999). The ontogenetic growth trend can be present in samples until they have reached an age of 30. This ontogenetic growth is common in molluscs; as the extent of the ventral margin increases and the surface area over which new material is added, the extension rate and hence GI width decreases.

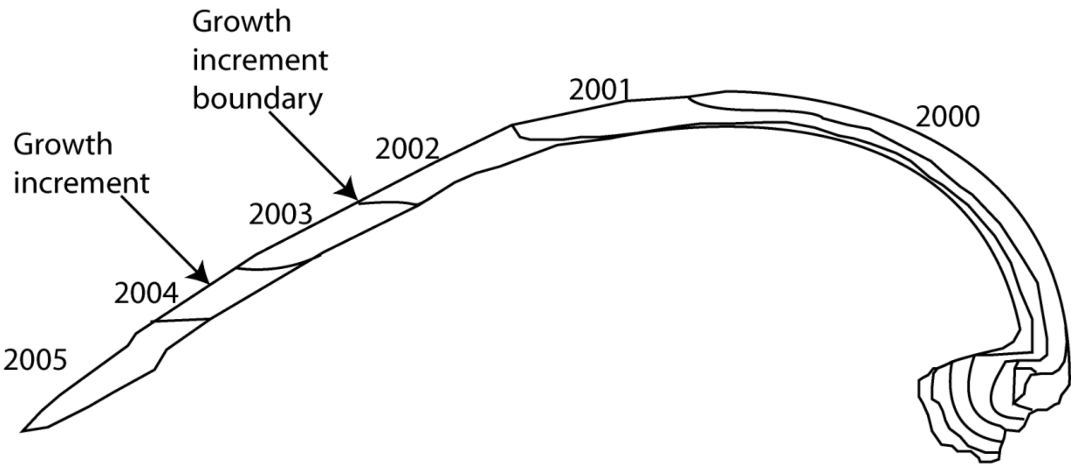


Figure 1.7: Cross-section of an *Arctica islandica* shell. NB. Wider GIs near the umbo, decreasing in size moving towards the ventral margin. (Image adapted from Witbaard, 1997).

Currently, the timing of the growing season for *A. islandica* remains uncertain. Schöne et al. (2003a) postulated that in the North Atlantic the aragonite in the shell is accreted between January/February to August. In Schöne et al. (2004) and Schöne et al. (2005b), the growing season of specimens from the North Sea and Iceland respectively was determined to be February to September. Weidman et al. (1994 – in Marchitto et al. (2000)) proposed that on Georges Bank (America – approximate location 41°N, 66°W), specimens cease to grow during the coldest months (January to April). While Witbaard (1997) suggested that they do not grow during the winter months because the spring phytoplankton, on which they depend for their main food source, is not present before March. Different growing seasons may be observed as a result of differences in locations from which the studied samples are taken. This would support the observations of Witbaard (1997) that growth starts and ends at different bottom temperatures, and fits with evidence from other organisms; the growth season of trees have been shown to vary for different species and locations(Wilson et al., 2007). A further complexity is the suggestion that the growth period may not remain the same throughout the lifetime of the animal; Schöne et al. (2005b) demonstrated that for the first 39 years of growth specimens had the same growth period. If this is the case then it has important implications for isotope studies carried out on shells, this is because of the pronounced changes in bottom water temperature throughout the seasonal cycle (Austin et al., 2006).

Temperature is important in determining the rate of *A. islandica* shell growth, although food supply is also likely to be a vital controlling factor. Without food, growth could not occur (Witbaard, 1996). Indeed it was proposed by Witbaard (1996) that food availability is more likely to influence GI growth rates than any other variable. *A. islandica* feeds through filtration via its siphon when on the sea bed (Witbaard, 1997), but when below the surface of the sediment it switches to anaerobic metabolism (Witbaard, 1997). Through the use of laboratory experiments, Witbaard (1996) proposed that food availability for *A. islandica* is determined by sedimentation rates, upper water column production rates and phytoplankton quantity, which is related to copepod abundance further down the water column (Witbaard et al., 2003) and, indirectly, to temperature, light and nutrient levels. Given the importance of food as a controlling factor on growth, the question remains whether or not growth increment data can be used to reliably predict temperature.

1.4.4 Distribution

An understanding of the distribution of *A. islandica* is of interest for a variety of reasons.

1) In Canada and America much work has focused on this subject due to the commercial value of the species within the food industry (e.g. Kilada et al., 2007). Knowledge of population distribution and numbers is important to prevent depletion of species numbers.
2) The focus in Europe has been to map the distribution of *A. islandica* to discover where it can be used as a proxy for past climate, as well as a tool for investigating past anthropogenic influences over the marine environment. As *A. islandica* originated in the Cretaceous period (Witbaard and Bergman, 2003), the investigation of how the

distribution of the species has changed within the fossil record may be used to make inferences concerning past global climate change on a broad scale.

3) Continued study of population distribution into the future will also allow changes in population locations to be used to make inferences concerning site specific changes e.g. temperature, sediment conditions, food availability, and predation.

Figure 1.8 illustrates the past and present day distribution patterns of *A. islandica*. Currently *A. islandica* is found widely distributed in the North Sea north of 53°30'N (Witbaard and Bergman, 2003), while to the south and east of the North Sea it is found only in water exceeding 30 metres depth (Witbaard and Bergman, 2003). Within the North Atlantic Ocean it is confined to the boreal waters of Europe including the Bay of Cadiz (north of Iceland), the Scandinavian coast, the White Sea, and the Faroe Islands (Thompson et al., 1980). It is also found between the Canadian Arctic and Cape Hatteras (North Carolina) (Kilada et al., 2007).

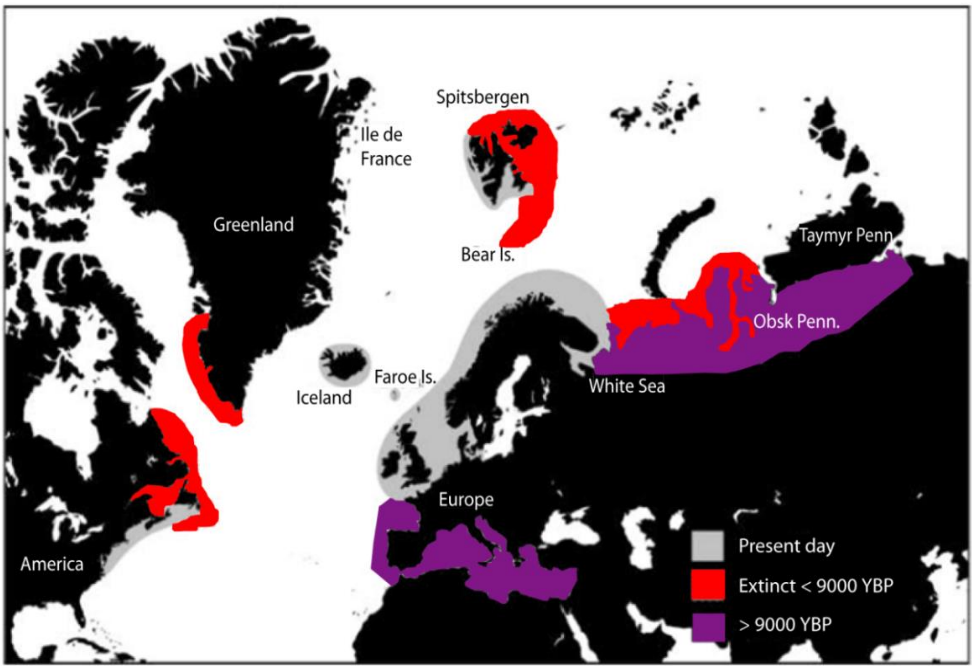


Figure 1.8: Distribution of *Arctica islandica.* Grey: Indicates locations where *A. islandica* are found at present day. Red: Sites where *A. islandica* is now extinct but was found < 9000 YBP. Purple: Sites where there is evidence of the species from > 9000 YBP. Adapted from Dahlgren et al. (2000; 488).

1.4.5 Growth increments

A. islandica deposit distinct GIs every year in the shell (see Section 1.4.5.1). When counted (ideally after crossdating) these GIs can be used to determine the age of a specimen (e.g. Jones, 1980; Schöne et al., 2003a), thus allowing the longevity of the species to be determined. Figure 1.7 is a cross-section of an *A. islandica* shell illustrating how GIs look when a shell is sectioned. The figure also highlights that the outermost GI represents the last year of growth before death (Witbaard, 1997). Therefore, if a specimen is live-collected then this outermost GI represents the year of collection and provides a chronological tie-point when constructing a GI chronology for the sample. However this may not always be the case because the outermost GI may not be fully developed when sampled or, when a peel is taken, the small difference in relief between the shell and resin in the polished section can cause the outermost increment on the peel to be unclear and, on some occasions, it may be missing altogether. Finally, it is also possible that there has been surface erosion and damage to the shell, often including the final bands.

Sclerochronology has much in common with dendrochronology (Section 1.3.2), the main similarities are that like trees most shells exhibit an age-related growth trend (Figure 1.7) which must be accounted for using detrending methods. Many other methodologies are shared between the two disciplines, including crossdating of the detrended data, the creation of master chronologies using software such as ARSTAN and the ability to relate changes in annual growth rates to climate variability (Stott et al., 2010). There are, however, some differences between the two research areas which mainly relate to the terminology used. For example, in dendrochronology, trees are said to deposit annual rings, while shells deposit annual growth increments (GIs) (Figures 1.4 and 1.7 respectively); in dendrochronology the age-related growth trend is referred to as the age trend, while in sclerochronology it is called an ontogenetic trend.

1.4.5.1 Verification of the annual nature of GIs

Several approaches have been adopted to demonstrate the annual nature of the banding in *A. islandica*. Thompson et al. (1980) carried out a study that determined that the GI width variations in multiple shells from the same populations were synchronous. The synchronisation of GIs from within the same sample population indicates that the periodicity with which they are deposited is the same between samples. This methodology did not prove definitively that GIs in *A. islandica* are annual; it does however provide strong evidence of the potential to see a synchronous response to external factors (such as climate) in the GIs of shells from a given population. Ropes (1988; in Scourse et al., 2006) carried out a series of mark and recapture experiments on live shells. Between the marking and recapture events the number of GIs deposited was the same as the number of years that had lagged between the two events. Work by Weidman et al. (1994) looked at variations in the $\delta^{18}O$ signal recorded within single GIs to prove they are annual because of the seasonal $\delta^{18}O$ pattern present. Another tool used to determine that GIs are annual is the use of time-dependent, natural (Smith et al., 1991 in Witbaard et al., 1994) or anthropogenic radionuclides, signals which are taken up from the surrounding water by organisms (e.g. Turekian et al., 1982). Finally, the increasing number of publications presenting crossdated *A. islandica* chronologies (e.g. Schöne et al., 2003; Scourse et al., 2006; Witbaard et al., 2005; Butler et al., 2009a; Butler et al., 2009b; Schöne and Fiebig, 2009; Stott et al., 2010) support the annual nature of GI deposition.

1.4.6 Potential of *Arctica islandica* in palaeoclimate and anthropogenic impact research

A. islandica has a history of being used successfully to provide sea temperature records. Buchardt and Simonarson (2003), Dunca et al. (2006) and Schöne et al. (2004) all used $\delta^{18}O$ records from shell samples to investigate past sea temperature records. This is possible as the shell incorporates $\delta^{18}O$ in equilibrium with the surrounding sea water as it grows (Weidman et al., 1994). Such research is only viable because species growth is influenced by changes in sea water (and by extension air) temperature, amongst other factors including food supply (Witbaard, 1996). However, this relationship is not always a straightforward one. For example Witbaard et al. (2003) found organisms (e.g., copepod) higher in the water column could disrupt the supply of food to the sea bed, thus inhibiting shell GI growth rates. As stated earlier food supply has also been shown by Witbaard (1996) and Schöne et al. (2005c) to influence annual shell growth rates in *A. islandica*. The species also has the potential to provide an NAO phase proxy record (Schöne et al., 2003; Schöne et al., 2005b; Stott, 2006; Helama et al., 2007). It was proposed by Schöne et al. (2003) that this may be partly due to the resuspension of sediment containing food suitable for consumption by *A. islandica* during positive Winter North Atlantic Oscillation (WNAO) phases as a result of wind-driven mixing of water masses.

The variation in ^{14}C between shell GIs has been used in *A. islandica* for a variety of purposes; Weidman and Jones (1993) used ^{14}C records from *A. islandica* shells to provide information concerning palaeo-currents for Georges Bank (USA). ^{14}C has also been used to investigate anthropogenic activity as a tracer of atmospheric-marine exchanges. This is achievable due to the release of ^{14}C into the atmosphere during the 1950s/1960s during the nuclear bomb testing period, which led to a ^{14}C 'bomb-peak' in the atmosphere circa. 1963 (Goslar et al., 2005). The difference in the timing of the bomb-peak in marine records can be compared to that in the atmosphere to provide an insight into gas exchanges between the ocean and atmosphere. Research into ^{14}C variations can also be used to investigate the marine ^{14}C radiocarbon reservoir (e.g. Butler et al., 2009a). $\delta^{13}C$ records in shells can also be used in a similar manner due to their ability to act as recorders of the timing of the anthropogenic $\delta^{13}C$ Suess Effect in the marine environment (Butler et al., 2009a; Daniels, 2010). Where the $\delta^{13}C$ Suess Effect is a change in $\delta^{13}C$ values of both the atmosphere and marine environment due to CO_2 released from fossil fuel combustion (Bacastow et al., 1996), initiated during the Industrial Revolution (Baxter and Walton, 1970). Such findings can then be compared to atmospheric records to look at the timing/magnitude differences. The use of both $\delta^{13}C$ and ^{14}C variability in the shells of *A. islandica* to investigate the timing of the ocean $\delta^{13}C$ Suess Effect and the bomb-peak is discussed further in Chapter 6.

Geochemical analyses of the shell using laser ablation ICP-MS (LA-ICP-MS) can be used to ascertain the prevailing environmental conditions at the time of GI deposition including; temperature, salinity, seasonality and productivity (Todland et al., 2010). Liehr et al. (2005) carried out LA-ICP-MS measurements on *A. islandica* shells and atomic absorption spectrometry (AAS) on the soft tissue. Their work illustrated the length of time *A. islandica* soft tissue contaminated with Cu, Pb and Zn takes to recover from pollution events (Liehr et al., 2005). Geochemical analyses have also been carried out by Foster et al. (2009) to determine what influences Sr level change in the shell of *A. islandica* and by Swaileh and Adelung (1994) to investigate trace metal levels and how the body size influences content/concentrations. Geochemical analyses are valuable for demonstrating the timing of anthropogenic activity impacting on the marine environment. It can also help provide a chronology for other marine records where gaining a chronological framework is not always achievable at the annual resolution (i.e. sediment cores).

1.5 Aims and objectives

The previous section highlighted several issues that require investigation to further our understanding of the use of *A. islandica* as a marine palaeoenvironmental proxy. As a result of these identified issues there are three main aims of this thesis.

1.5.1 To undertake an investigation into of the potential of Scottish *A. islandica* to provide reliable climate proxy records

There is a lack of investigations into *A. islandica* shells as palaeoenvironmental proxies for Scotland (Foster, 2007; Stott et al., 2010; Reynolds, 2011). Six sites were sampled in two Scottish fjords and investigated using dendrochronological methods to determine if climate is the dominant driver of growth rates. Building up a network of six sites should allow the effect of site-specific factors such as sediment grain size to also be considered. This research may help indicate whether using *A. islandica* from Scottish fjords is a viable avenue for future research, or whether the signal is too diluted by other factors. If *A. islandica* is proved to be a reliable proxy record for climate change in the field area then it is aimed that it will be used to address the lack of proxy data for the marine realm.

1.5.2 Testing whether height and/or weight can be used to predict age

The ability to predict ages either in situ using height, or in the laboratory using height/weight with minimum sectioning would be of great benefit. This would not only help to reduce the impact on populations through the reduction of sample removal (in the case of in situ measurements) and also reduce sampling time in the laboratory. Currently, such analysis can only be undertaken on an individual site level; however by testing the relationship between the variables for all the sites combined will also provide an insight into how shells from a larger area may be able to use either variable to predict age.

1.5.3 Geochemical analyses to investigate the timing of the ocean $\delta^{13}C$ Suess Effect and radiocarbon bomb peak in fjordic settings

Geochemical variations in ^{14}C will be measured to investigate the marine ^{14}C reservoir age effect in Loch Etive and the effect of the Sellafield reprocessing plant on local ^{14}C values. These will help provide a better understanding of localised variations in the marine ^{14}C reservoir age effect using data from Cage et al. (2005). The impact of Sellafield discharge on fjordic sites is important to help track how aqueous waste from the plant impacts on marine flora and fauna. Analysis of $\delta^{13}C$ changes will also be undertaken to investigate the timing/magnitude of the ocean $\delta^{13}C$ Suess Effect at the sites, these results will be compared to other marine records (e.g. Butler et al., 2009a) and the atmospheric record (Francey et al., 1999). $\delta^{13}C$ values will also be used to investigate whether there is an ontogenetic influence on $\delta^{13}C$ values as has been observed elsewhere as this has a potential impact on the period of shell growth from which material can be sampled.

1.6 Overview of thesis research

This thesis is split into seven chapters to address the aims and objectives outlined above. Chapters 2 to 6 are outlined below, the final chapter is an overall discussion for the entire thesis, and the final chapter deals with the conclusion and future directions. Parts of this thesis has been written up and published in Stott et al. (2010); however the paper does not make up an entire chapter, rather the work is present, as in the paper, in many of the chapters because of the structure of the thesis. This paper was written along with five other co-authors, however I was the primary author on the paper, and the level of input from the co-authors was on a par with that received from supervisors on the thesis. The only exception to this is where data was provided by co-authors for the paper (the ^{14}C analysis shells – the Loch Creran data was provided by Cage, and the North Sea data by Weidman). Extracts from the paper appear in this thesis as in the publication (including in this chapter); for those chapters where this is the case a note has been made in the chapter outline below. Secondary data is also used in Chapter 6 for the $\delta^{13}C$ investigation of the ocean $\delta^{13}C$ Suess Effect. This data comes from an undergraduate dissertation project by Daniels (2010) which was carried out with assistance from the author.

Chapter 2 – Field Area and Site Analysis: focuses on introducing the field area and the analysis of sediments collected from the field area as part of the thesis in order to determine how sediment grain size, sediment water content and organic carbon content at each site differs. These results are used later in Chapter 7 to look for patterns between results generated in Chapters 2, 4, 5 and 6. Parts of this chapter have been taken from Stott et al. (2010).

Chapter 3 – Instrumental Data: in order to fully analyse the chronologies constructed in Chapter 4 for their potential as climate proxies, it is important to first gain an understanding of instrumental data available for the region. This is achieved through comparing local, regional and gridded sea and air temperature datasets to look for a common pattern between these series and therefore determine if the longer, gridded sea and air temperature records can be used where the local/regional data are too short in length to be of any real use in Chapter 4.

Chapter 4 – Chronology Construction and Response Function Analysis: this chapter introduces the methodology behind constructing *A. islandica* growth chronologies and how they are analysed to determine if they record a climate signal in their growth increment variations. A growth chronology is constructed for each of the six sites (introduced in Chapter 2), and these are compared to see if there is a common signal between the series. All six chronologies are compared to the instrumental datasets selected for analysis in Chapter 3 to look for a climate signal in the shell growth records. Parts of the chapter are from Stott et al. (2010).

Chapter 5 – Shell Biometrics and Morphology: in order to determine if there are any morphological differences between shells from different sites, analysis of shell width, height, length and weight are undertaken and the results compared. In addition, the relationship between shell age and weight/height are investigated to determine if either weight or height can be used as predictors of age, something which would be of benefit for analysing population age structures without sampling as many shells. The population age structures of the six field sites are investigated to determine whether populations are starting to age, or show signs of recent recruitment. Parts of the methodology, along with some results, are from Stott et al. (2010). Some of the biometrics data (height, weight etc.) were collected by Ms Helen Beddow-Twigg, Ms Jodi Old, Ms Liz Daniels and Mr Campbell Dowell, as part of either undergraduate dissertation work, or in the case of Campbell during work on a Nuffield Summer internship in the department.

Chapter 6 – Geochemical Analysis: analysis of variations in $\delta^{13}C$ and ^{14}C are undertaken to investigate the ocean $\delta^{13}C$ Suess Effect and the timing of the radiocarbon bomb-peak in the field site respectively. Unlike the rest of the analyses, these are undertaken on material from the outer shell as there is more material available from this part of the shell. Results are compared to those collected by other researchers from elsewhere in the UK, as well as slightly further afield. Some of the ^{14}C results and methodology presented here are from Stott et al. (2010), while stable isotope results from 1 site come from work undertaken by Ms Liz Daniels as part of her undergraduate dissertation (Daniels, 2010).

2 Field Area and Site Analysis

2.1 Field Area

This chapter describes the field area and the six sample locations which were chosen to capture different environmental gradients. These are placed into their wider oceanographic context, and the different site conditions are investigated to determine how sediment grain size, sediment water content and organic carbon (OC) content varies between the six sample sites. Understanding these site characteristics may help explain differences in growth rates and climate response between the shell growth records.

2.1.1 Field area setting

2.1.1.1 Fjord hydrography

As already mentioned in Chapter 1, all the sample sites are located within fjords on the west coast of Scotland (Figure 2.1). Therefore, it is important to consider how the hydrography of fjords may vary and how this may have a bearing on processes influencing shell growth at these sites. The main features of fjords (Figure 2.1) are a glacially over-deepened basin, and a sill at the fjord entrance which separates the fjord from the adjacent water body, thus limiting water circulation and oxygen renewal in the fjordic waters (Howe et al., 2010). Fjords also have a high freshwater input from the surrounding area, most of which is river-derived, mainly from the river at the fjord head (Inall and Gillibrand, 2010). In some cases, such as Loch Etive, the level of freshwater input leads to stratification of the water column in the area surrounding the river mouths (Howe et al., 2010). This freshwater input means that fjords have a lower salinity than the adjoining coastal water (Howe et al., 2010). Within modern non-glaciated fjords in the temperate/mid-latitudes, rivers play an important role. Not only do they contribute to the carbon supplied to the fjord (along with runoff and primary production (PP)), but they are also attributed as one of the controlling factors over fjordic sediment supply (Howe et al., 2010).

Figure 2.1A: Location of the field area in the context of the United Kingdom and Ireland. Also shown is the location of Kentra (red circle) which is relevant for the material discussed in Figure 2.3

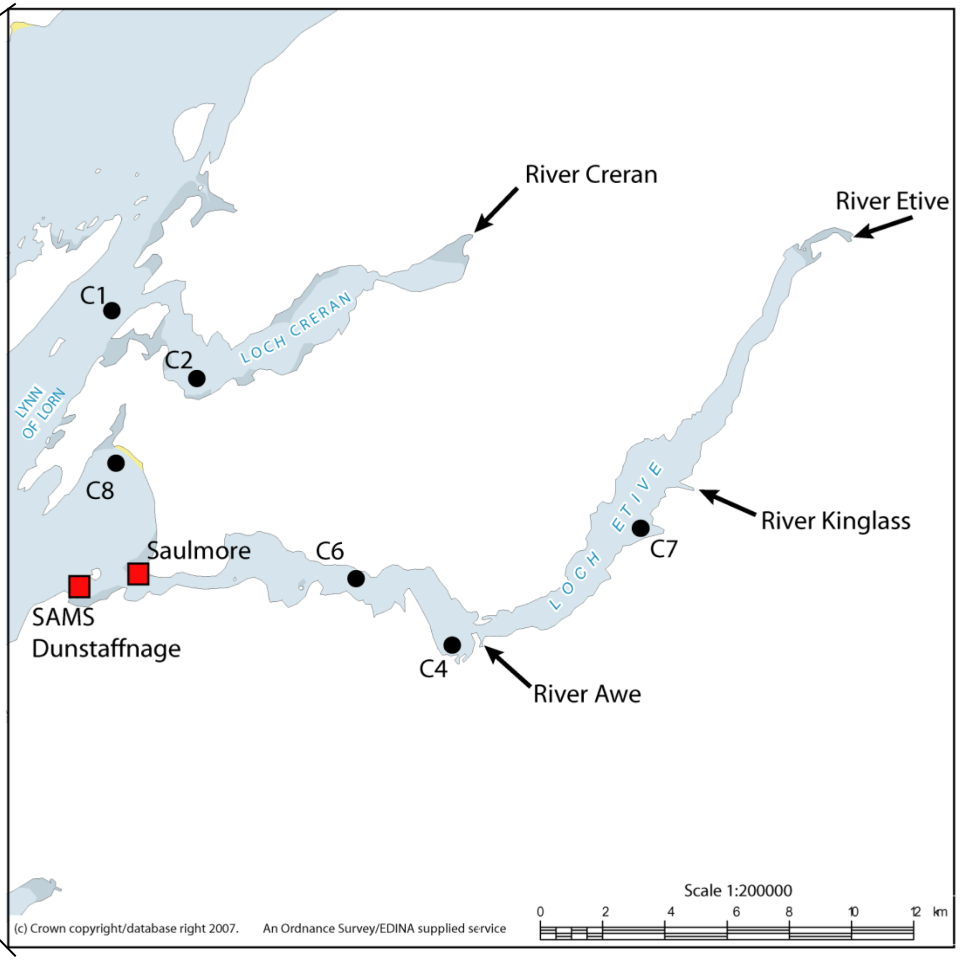


Figure 2.1B: Location of the six sample sites in relation to the local instrumental datasets; see Table 2.1 for location names. Also indicated is the location of the SAMS research station and the two fjordic instrumental datasets (Dunstaffnage and Saulmore)

Table 2.1: Field site names and depth

Site	Name	Depth
C1	Lynn of Lorn	11 to 17 m
C2	Loch Creran	20 m
C4	Airds Bay	14 to 18 m
C6	Ardchatten Priory	12 to 18 m
C7	Seal Rocks	16 to 24 m
C8	Ardmucknish Bay	18 m

The water column configuration present in fjords differs from coastal waters due to different stratification processes (see Figure 2.2). In coastal waters, stratification is generally driven by seasonal thermal changes. This is not the case in fjords where a combination of high freshwater inputs and restricted flow of water leads to density driven stratification which has no clear seasonality (Inall and Gillibrand, 2010). In many fjords, deep isolated basins also create a very distinct water pattern. These basins are often sinks of older water, which is only refreshed by newer water which occurs over timeframes from weeks to years (Inall and Gillibrand, 2010). Deep water renewal events rely on denser, external water entering the fjord and crossing over internal sills to force deeper water in the basin upwards due to density differences, therefore causing a renewal of the deep water in the basin (Inall and Gillibrand, 2010). These deep water renewal events affect bottom water currents, creating maximum currents of 0.1 to 0.4 m. s^{-1}, which in turn causes resuspension of sediment and organic material from the fjord bed (Inall and Gillibrand, 2010). They also have the potential to cause deoxygenated water to move upwards in the water column, this may lead to biodegradation and even fish death events (Inall and Gillibrand, 2010). It is important to fully understand such events because they have the potential to greatly influence fjordic ecosystems.

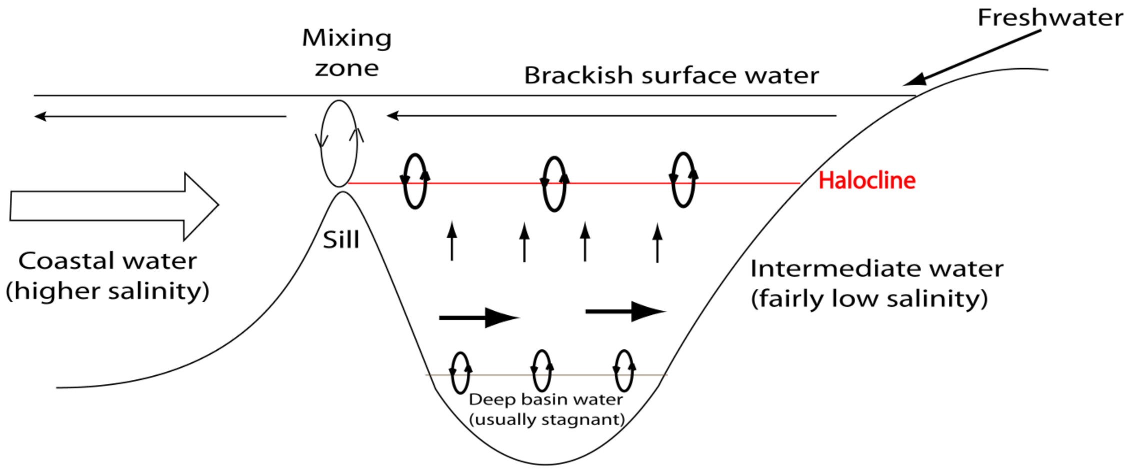


Figure 2.2: Fjordic water column structure. The arrows indicate water transport/mixing. (Adapted from Cage, 2005).

2.1.1.2 Geological setting

The field area is underlain by rocks from the Dalradian Supergroup (a range of rocks including quartz- and mica-rich metamorphic, fine-grained metamorphosed sedimentary rocks, limestones and metamorphose basalt). There are also some Caledonian granites and gabbros (igneous) and Devonian volcanic (igneous) rocks in the local area (Mitchell, 1997). The region is bound by the Highland Boundary Fault to the south and the Great Glen Fault to the north (Mitchell, 1997).

Over the last 500ka multiple glaciations have affected the area (Stoker et al., 2006). These events have greatly influenced the local landscape; glacial activity created over-deepened, coastal basins, and when the ice retreated they filled with water, creating the fjords present along the west coast of Scotland. Other local glacial features include; raised shorelines (a glacio-isostatic rebound feature), moraines and glaciofluvial sediments deposited in the area as a result of glacial activity. It is possible to use the raised features resulting from deglaciation after the Last Glacial Maximum (LGM) to interpret past changes in relative sea level (RSL) as a result of glacio-isostatic uplift (e.g. Shennan et al., 2000; Shennan et al., 2012). These are outlined in the next section where their implications for fjord and coastal water exchanges will be briefly summarised.

2.1.1.3 Relative Sea Level Change

Relative sea level (RSL) refers to the sea-level in relation to land (Pethick, 1984); a positive RSL change reflects either an increase in sea-level or a decrease in land-levels, while the opposite is the case for negative RSL changes (Pethick, 1984). There are two main reasons for RSL changes:

1) Eustatic,
2) Local/regional tectonic activity or isostatic movement.

In NW Scotland, RSL changes caused by isostatic movements as a result of local/regional glacial activity are of particular interest. During the LGM the weight of the ice mass on Scotland caused depression of the Earth’s crust. Once the ice melted the land began to recover and undergo a process known as isostatic rebound (Pethick, 1984). Isostatic rebound is not uniform across Scotland and actually continues today. Coupled with global eustatic sea-level changes (i.e. those caused by changes in ocean volume due to the flux of global ice sheet/glacier ice into/out of the ocean), RSL has changed over time as the interaction between isostatic rebound and eustatic sea-level have changed (Pethick, 1984).

During periods where RSL has fallen, due to isostatic rebound exceeding changes in eustatic sea-level, features such as raised beaches and isolation basins form (Sissons et al., 1966; Pethick, 1984; Smith et al., 2003; Shennan et al., 2005; Shennan et al., 2006). These geomorphological features can be used to interpret past changes in sea-level, and therefore provide a potential constraint on the interactions between coastal and fjordic waters over time (i.e. RSL will influence fjord sill depth and therefore exchange). Outer Loch Etive for example has raised shorelines dating to the early Holocene at 14m Ordnance Datum (Gray, 1974 in Nørgaard-Pedersen et al., 2006).

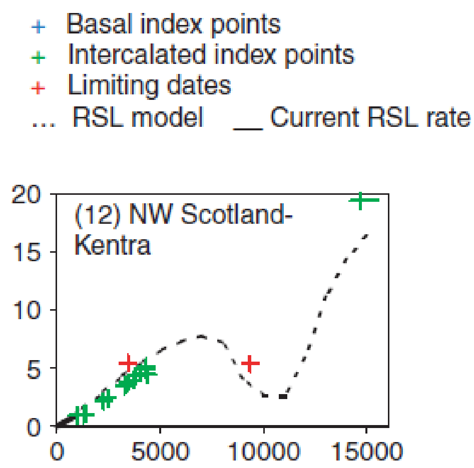


Figure 2.3: Relative sea-level (RSL) change for Kentra, Scotland relative to present day sea-level (m), the x-axis is measured in years BP. The solid line is a best estimate of RSL change in the late Holocene (see Shennan and Horton, 2002). The dashed line comes from work by Shennan et al. (2002a in Shennan and Horton, 2002) and illustrate predicted past RSL changes (image from Shennan and Horton, 2002; 515). The location of Kentra is illustrated in Figure 2.1a.

The exchange of water between the fjords and coastal waters varies between fjords (depending on season, tide, freshwater input and sill depth at the fjord entrance (Howe et al., 2010)), but also over time due to changes in RSL. Since deglaciation after the LGM (c. 20 ka.), Scotland has experienced isostatic uplift (see Figure 2.3), leading to the creation of raised beaches around the Scottish coast (Sisson et al., 1966; McIntyre and Howe, 2010). Shennan et al. (2000) and Lambeck (1995) have carried out research into these features as measures of past sea-level changes as a response to glacio-isostatic uplift after deglaciation. Such research has indicated that over the Holocene, sea-level changes have fluctuated, thus influencing the exchange rates between the fjordic and coastal waters; this not only affects fjord water salinity, but also circulation and deep water renewal events (Nørgaard-Pedersen et al., 2006). For the time scales investigated in this thesis, such events have no direct impact on the research. However, if longer (i.e. Holocene) chronologies were ever developed using fossil shell material, then these issues may become important given the late Holocene tendency for RSL fall and hence shoaling around entrance sills.

2.1.1.4 Climate

The predominant influence on local climate for the field area is the North Atlantic, in particular the North Atlantic Current/Gulf Stream which is responsible for providing the region with moisture and heat from the tropical Atlantic (Met Office, 2012a). Coastal air temperatures for the west of Scotland have mean annual values between 4-13°C (max daily temperatures) and

0-8°C (min daily temperatures) (Met Office, 2012b), with the warmest months tending to be July and August, while January/February are normally the coldest months (Met Office, 2012a). Rainfall varies between its highest in October to January, and its lowest in May/June (Met Office, 2012a), with an annual average of 180 to 270 days of rain ≥1.0 mm (Met Office, 2012b).

2.1.2 Regional oceanography

The fjordic region of Scotland is important in the North Atlantic climate context due to its oceanographic setting. The area is influenced by the relatively warm, saline waters of the North Atlantic Current (Ellett, 1979) and thus is indirectly affected by the North Atlantic Meridional Overturning Circulation (AMOC). It is possible that external forcing (e.g. solar and volcanic activity) may have influenced the strength of AMOC (Stenchikov et al., 2009), which has been shown to have influenced past abrupt climate events during the last glaciations (Hofer et al., 2011) and events such as the Little Ice Age. Therefore AMOC has been, and remains, an important factor in NW European climate systems (Cage and Austin, 2010). As changes in the AMOC can be climatically important, identifying sites which can record past variations over time are key. Fjords on the west coast of Scotland are influenced by AMOC and westerly air stream changes and therefore are useful for investigating climate variability for NW Europe (Austin and Inall, 2002).

Much work has been carried out studying the currents, salinity and temperature properties of the waters off the west coast of Scotland (McKay et al., 1986; Holliday et al., 2000; Inall et al., 2009). This has been done using a variety of methods such as Conductivity-Temperature-Depth (CTD) casts to investigate salinity, and the tracking of radioactive isotopes from the Sellafield nuclear reprocessing plant to look at current flows (McKay et al., 1986). Previous research indicates there are two main water masses influencing the west coast of Scotland; Atlantic waters and the Irish Sea (McKay et al., 1986). The main water bodies present along the west coast of Scotland are the Scottish Coastal Current (SCC), the North Atlantic Current, the North Atlantic Slope Current (see Figure 2.3 for the location of these three currents), and in the Rockall Trough (RT), the Eastern North Atlantic Water (ENAW) and Labrador Sea Water (LSW) (Holliday et al., 2000).

The SCC (Figure 2.4), a combination of water from the Irish Sea and the Clyde Sea moves northwards along the coast of Scotland (Inall et al., 2009) and is the predominant current along the west coast of Scotland. The ratio of freshwater, Irish Sea and Clyde Sea water which constitutes the SCC is seasonally dependent, as is the mixing that occurs between the water masses (Ellet, 1979); the Clyde Sea contribution to the SCC freshens the water mass, as do some land-based run-off water sources (McKay et al., 1986). However, the contribution from the land is minimal, meaning that the SCC gets diluted by less than 1% by volume (Inall et al., 2009). Another inshore current influencing the oceanography off the west coast of Scotland is the European Slope Current (ESC), which like the SCC, is a north flowing current and has its southern limit at the Goban Spur and a northern extent in the Shetland Islands (Inall et al., 2009). The RT is one of the ways in which North Atlantic waters reach the Norwegian Sea and comprises two main water masses; the ENAW in the upper water column and below 1200m LSW re-circulates in the basin due to shallower topography in the north meaning that it is unable to escape (Holliday et al., 2000).

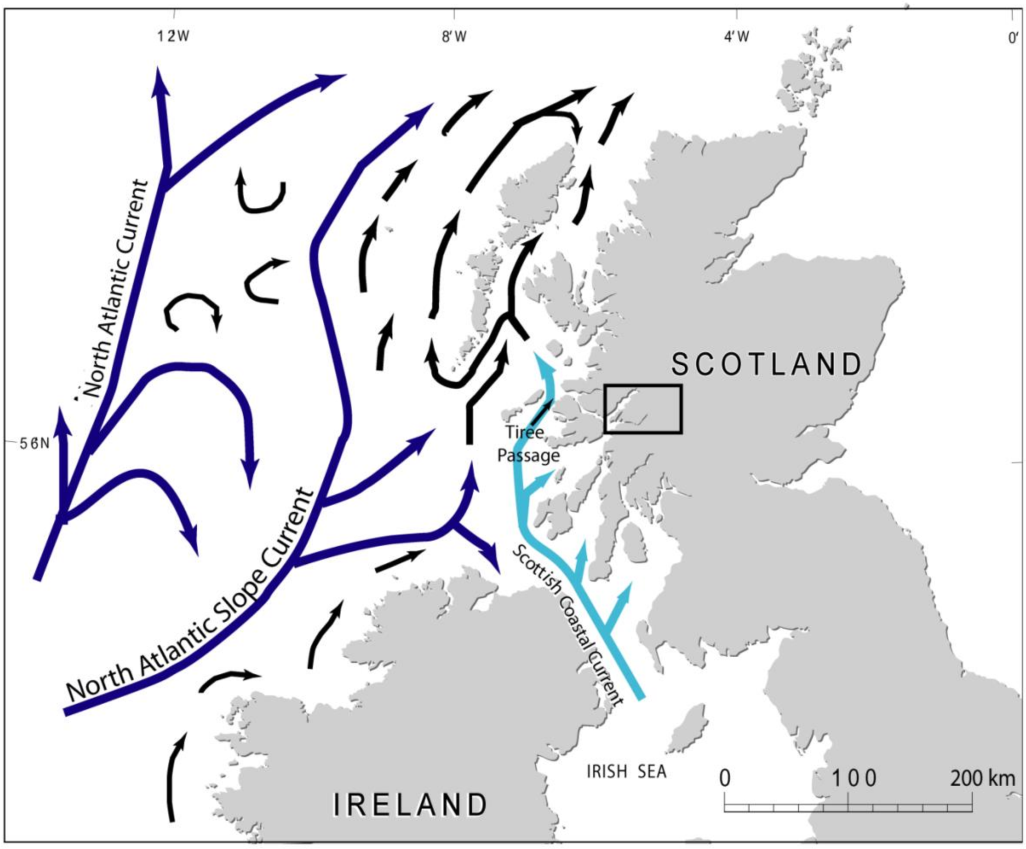


Figure 2.4: Main currents off the west coast of Scotland (Adapted from Cage and Austin, 2010). The black box indicates the location of the field area; for a more detailed map of the sampling sites see Figure 2.1B.

2.2 Sample Sites

All six sites (Figure 2.1B) have several common features; over the 20th century all sites have seen some form of anthropogenic activity in the area (which will be discussed in more detail in Section 4.3.1). The timing of the phytoplankton bloom is similar between the sites around mid-March (200mg C. m^{-3}) and levels in the summer are also comparable between sites at approximately 50mg C. m^{-3} (Ross et al., 1994). These factors theoretically mean that *A. islandica* at each location should have similar food availability levels, and therefore this should not have a large influence on inter-site growth differences. As a result potential common response to climate variability between the sites should be maximised.

2.2.1 Lynn of Lorn (Site C1)

The Lynn of Lorn is a well-mixed coastal site at the entrance to Loch Linnhe, with water depths at the point of collection ranging from 11 to 17 m. Sediment here has been previously described in Collier and Brown (2005) as consisting of silty mud with variable amounts of silt and gravel present. Samples at this site were collected close to sampling site V18 of Brown and Collier (2008) – which they classified as habitat type SS.SMu.VirOphPmax (based on the classification scheme of Connor et al., 2004, see Appendix 1 for more information), meaning the site is classified as having salinity levels between 30-35. In addition, this site is moderately exposed to waves with weak tidal streams (Connor et al., 2004). Annual seawater temperatures in the area ranged from 5.6°C (January to March), to 15.1°C (August to September) (generated from daily average of 240 measurements, August 1995 to March 2009; M.D.J. Sayer, unpublished data). Salinity averages range from 33.3 to 34.1 (estimated from Firth of Lorne from Heath, 1995).

2.2.2 Loch Creran (Site C2)

Loch Creran is well-stratified (Ross et al., 1994) with an overall flushing time (the time it takes for water to leave the sea loch system) of 6 to 7 days (Tett, 1973 in Ross et al., 1994) and consists of four basins which, according to temperature and density data, are strongly coupled (Ross et al., 1994). The different sediment types found in each of these basins is outlined in Table 2.2. Loch Creran opens into the Lynn of Lorn (Section 2.3.1) at the narrows near the Isle of Eriska (Donovan, 2006) at which point the sill depth (7m deep; Black et al. (2000)) is fairly shallow and unobstructed (Ross et al., 1994). Loch Creran has a catchment area of 167 km^2 (Ansell, 1974), and is much smaller than that for Loch Etive.

Salinity in Loch Creran is comparable to that in the Lynn of Lorn, with variation being less than 1 at any one time and a range of 2 near the loch bottom (Gage, 1972b). At the surface, however, there are indications of fresh water; Gage (1972a) recorded a lowest salinity of 24.6 which is more than 8 less than the value at the loch bottom at the same time. The only seasonal pattern in salinity recorded at the surface is due to periods of increased freshwater runoff after heavy rainfall (Gage, 1972a). Temperatures recorded by Gage (1972a) are also fairly similar to those in the Lynn of Lorn, with an annual range of approximately 7 to 9°C, the lowest value being in February/March (6°C) and the highest in August/September (13 to 15°C). Freshwater inputs for Loch Creran come from River Creran at the head of the loch as well as from several other rivers (Figure 2.1). River Creran is an important source of terrestrial material to the loch (Loh et al., 2008), the mean input of freshwater in Loch Creran in $286x10^6$ $m^3.y^{-1}$ (Edwards and Sharples, 1983 in Loh et al., 2008).

Table 2.2: Sediment types present in each of the basins in Loch Creran (Figure 2.1), according to Black et al. (2000). These results are generalised for each basin, but do indicate changes between the basins.

Basin	Sediment type present	Sample sites present
Basin 1 (lower basin)	Coarse sediments	N/A
Basin 2	West end: Coarse sediments East end: Soft, enriched, muddy sediments	C2
Basin 3	Muddy sediments	N/A
Basin 4	Deep sections have a similar biotope present to basin 3	N/A

Site C2 was selected because it was investigated by Gage (1972a; 1972b) (site C5 in these papers) when live specimens were collected from the site. Once a robust chronology has been constructed for this site it may be possible to crossdate these older samples into the chronology, thus extending the record back further in time. The site has a depth of 20m with muddy sediments present on the loch floor (Gage and Tett, 1973).

2.2.3 Loch Etive (Sites C4, C6, C7 and C8)

Loch Etive opens into the Lynn of Lorn at the Falls of Lora, which is a narrow opening causing turbulent rapids to flow there during the end of the ebb tide (Ross et al., 1994). It also has a high ratio of freshwater discharge to tidal flow (Edwards and Sharples, 1986). Loch Etive is 28km long (Ridgway and Price, 1987) and has two basins (within which are assorted smaller basins (Howe et al., 2002)), which are weakly coupled (Ross et al., 1994). The overall flushing time for Loch Etive is 12 days, although this is increased somewhat due to the large depth of the upper basin of approximately 150m (Ross et al., 1994). The outer basin is ~60m deep (Ridgway and Price, 1987). This flushing time can be broken down into 3-4 days for the lower basin and an exchange time between the two basins of 10 to 14 days (Ross et al., 1994). Loch Etive has a catchment area of 1300km^2 (Ridgway and Price, 1987), a mean freshwater input value of 3037.5 x10^6.m^3. yr^{-1} (Edwards and Price, 1986, in Loh et al., 2008), a total surface area of approximately 28km^2 (Ridgway and Price, 1987) and high levels of freshwater input – which comes from rainfall and also the Rivers Etive, Awe and Kinglass (Howe et al., 2002) which are also important sources of terrestrial material to Loch Etive (Loh et al., 2008, Howe et al., 2002). This means that there can be prolonged periods of water stratification in the loch (Loh et al., 2008). Salinity levels in Loch Etive have previously been shown to range from a maximum of ~30, while it can reach lows of ~5 (Ansell, 1974), values that are much lower than those seen in Loch Creran.

Deep water renewal (see Section 1.4.1 for definition) in Loch Etive occurs due to low freshwater runoff and can be considered aperiodic; average timing of renewal is $1^1/_3$years (Edwards and Edelsten, 1977). Such long periods between water renewal events in Loch Etive causes stagnation of bottom water which causes a second pycnocline (present at depths between 30-100 m), below which there are slow variations in salinity and temperature recorded (Edwards and Edelsten, 1977).

The upper section of Loch Etive is within an igneous-metamorphic mixture, with the outer portion, to the west of Bonawe (Figure 2.1), having a geological setting of andesitic and acidic lavas and tuffs of Old Red Sandstone age (Howe et al., 2001). Between these two geologically different areas there is an outcrop of phyllites and slates of Dalradian age (Howe et al., 2001).

Bottom water sediment conditions have different characteristics between the two Loch Etive basins; in the upper basin oxidation only occurs to a depth of ~1cm, below which the sediment present is dark-grey to black (Ridgway and Price, 1987); in this environment there is little biological activity – *A. islandica* can be found and the tube worm *Spirochaetopterus typicus* is present (Ridgway and Price, 1987). It is a different matter in the lower basin, where two tube worm species dominate the upper sediment layers; *Capitella capitati* and *Nepthys hombergi* along with many other macrofaunal species (Ridgway and Price, 1987). The sediments in which these fauna live are generally red-brown in colour and oxidation of sediment occurs to a depth of ~5cm, below this the colour changes to a green-grey (Ridgway and Price, 1987). The four Loch Etive sites are summarised in Table 2.3.

Table 2.3: Site properties, starting with site C7 at the head of the loch moving down to site C8 at the loch mouth; all site locations are illustrated in Figure 2.1.

Site	Site Description
C7	Also known as Seal Rocks, site C7 is located in the upper basin of Loch Etive, therefore the flushing time here is longer than for sites C4, C6 and C8 (Ross et al. (1994) quote a flushing period for the whole loch of 12 days, 3-4 days for the lower basin and an exchange time of water between the two basins of 10-14 days). Site collection depths range from 16 to 24 m. Sediment at this site is visually very different to the other Loch Etive collection sites; it is almost liquid/fine mud-very fine silt (Sayer pers. comm., 2009). Halocline depth is at ~20 m (Gage, 1972 in Murray et al., 2003). Temperature at the loch bottom ranges from ~8 to 10°C (Gage, 1972 in Murray et al., 2003).
C4	The Airds Bay site is within the lower Loch Etive basin (Figure 2.1) and is relatively well sheltered. Shells collected at this site come from water depths ranging from 14 to 18 m, where the sediment is visually described as being soft but firm (compact) mud sand (Sayer pers. comm., 2009).
C6	Site C6 (near Ardchatten Priory) like site C4 is also in the lower basin of Loch Etive, but it is closer to the loch mouth and is less sheltered than Airds Bay. The site is 12 to 18m deep and has sediment present which is visually described as soft but firm (compact) mud sand (Sayer pers. comm., 2009).
C8	Site C8 is in Ardmucknish Bay is located just outside the mouth of Loch Etive, and has a site depth of 18m. The site is visually described as having a muddy substratum mixed with shell, sand and gravel (Sayer pers. comm., 2009).

2.3 Site Analysis

To better understand the conditions in which *A. islandica* are found, as well as to further investigate inter-site variability, the following environmental variables were analysed; grain size, sediment water content, and organic carbon (OC) content. These variables were analysed for several reasons. Characterisation of grain size data/sediment types in which other *A. islandica* populations have been found has already been undertaken in Iceland (Thórarindóttir et al. (2009) and in the western Baltic Sea (Liehr et al., 2005). Such research has indicated that this species favours sandy mud/mud (Liehr et al., 2005) and medium to fine grained sand (Thórarindóttir et al., 2009). Therefore, by carrying out similar work for the field area it is possible to see how the grain size at the Scottish sites studied here differs to that in which other populations are found. OC content was chosen for analysis as no previous research into the OC content of sediment in which *A. islandica* is found has been published. If all the sites have similar OC content values this may suggest that the species favours sites with a certain OC level. This information could help identify whether changes/differences in OC content at the site influences the response of *A. islandica* to climate. The sediment water content values are being studied in an attempt to discover whether this influences where shells are found, something which has yet to be studied in the literature in any detail to date.

2.3.1 Methods

All three variables were measured using samples from sediment cores collected by the National Facility for Scientific Diving (NFSD). At each site six push-cores (Wilding and Sayer, 2002) were collected and subdivided into three equal sections (0-4 cm, 4-8 cm and 8-12 cm). The notation for each core section is as follows; (i) site ID, (ii) core number, (iii) sample depth (lower depth recorded). For example, core C1 1-4 is core number one from depth 0-4 cm, collected at site C1. For some analyses undertaken sample sizes are small due to restricted material availability e.g. sediment grain size data, this must therefore be considered when choosing analysis methods and undertaking normality tests.

To analyse sediment water content, samples were freeze-dried and weights from before and after recorded. The difference between the two weights can then be used to work out water content using Equation 2.1:

$$Percent\ water\ content = \left(\frac{wet\ weight\ (g) - dry\ weight\ (g)}{wet\ weight(g)}\right) x\ 100 \quad \text{Equation 2.1}$$

After freeze-drying, samples for grain size analysis were run through a Coulter Counter, with each sample processed three times (with sonification between each step to break apart any cohesive sediment particles). For each sample run, the three outputs were averaged together, meaning only one dataset per sample was later analysed. The analyses carried out on the grain size series were threefold; (i) visual comparisons between the data using a combination of stack plots (ii) ternary diagrams, and (iii) correlation between the histograms. However, for the correlation work it is necessary to take into account potential autocorrelation (AC) of the data which can artificially inflate the confidence in the correlation results between series recorded. Equation 2.2 was used to calculate the actual degrees of freedom (df) to gain a 'true' p-value for each correlation carried out. Using Equation 2.3 and the n-value gained from Equation 2.2 the 'true't-value can be calculated, which along with correlation t-tables can be used to see if the correlations are significant.

$$N' = N\frac{(1-r_{1x}r_{1y})}{(1+r_{1x}r_{1y})}$$ Equation 2.2

Where r_{1x} and r_{1y} are the first order AC values for samples x and y,

N' is the adjusted degrees of freedom (n-value),

N is the original n-value.

$$t = \frac{r}{\sqrt{[\frac{1-r^2}{N'-2}]}}$$ Equation 2.3

Where N' is the value gained from Equation 2.2

r is the correlation coefficient value between the two series being investigated.

For each site, two sediment grain size datasets were generated for analysis. Initial work was undertaken on a single core at each site with one sample from each depth analysed. This is done to investigate the homogeneity of sediment grain size down core. However, due to the life position of *A. islandica* (see Figure 4.3) it is mainly the top section (near surface) of the cores that is of interest. The results for the grain size analysis are presented on a site basis, and then all the site data are compared. For the ternary diagrams, the Wentworth (1922) class terms for sediments are used to determine the percentage of clay, silt and sand in each sample. The three sediment types are defined according to the following sizes:

Clay <4 µm

Silt 4 to 63 µm

Sand >63 µm

OC content analysis was carried out on the same cores chosen for the down core grain size work. Samples of a known weight were analysed using Loss on Ignition (LOI) in a furnace at 450°C. Weights prior to and after LOI analysis are recorded and the difference in values used to work out the OC content of the samples as a weight percentage.

2.3.2 Results

2.3.2.1 Sediment water content

The sediment water content values (median and inter-quartile range (IQR)) for the six sites are summarised in Figure 2.5. These results show that at site C7 all the depths analysed have higher water content values compared to the same depth at the other five sites. It is only at C1, C6 and C7 where all values from the three depths are significantly different (Figure 2.5). There are no patterns of decreasing values for C8, and at C4 there is an overall increase in values moving down core, however these are not significantly different (at the 95% confidence level)[1]. Whether the higher water content values at site C7 have a bearing on various growth factors in *A. islandica* will be investigated in Chapter 7.

To quantify the relationships present between the data shown in Figure 2.5, Kruskal-Wallis tests were undertaken for the site data to test for intra-site differences, and for inter-site differences for each depth analysed (0 to 4, 4 to 8 and 8 to 12 cm) (Table 2.4). These indicate that at sites C2, C4 and C8 there are no significant intra-site differences in sediment water content. For sites C1, C6 and C7 there is at least one significantly different inter-site value. From the depth data groups it is only C7 that is statistically different from all the other site values. The Kruskal-Wallis results (Table 2.4) confirm the visualisation of the data in Figure 2.5.

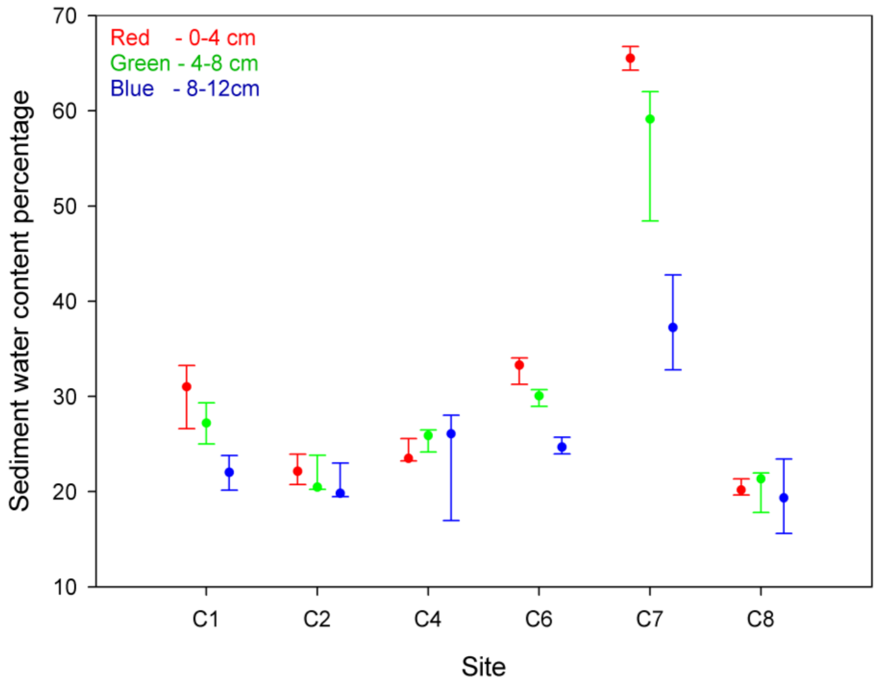


Figure 2.5: Sediment water content data for the six sites, the mid-point represents the median and the measure of the variance of the data the IQR. Mean and standard deviation were not used due to the skewed nature of the data (see Appendix 2). Significance level used : 95%

[1]All tests using significance levels are carried out at the 95% significance level unless otherwise stated

Analysis Group	H-value	p-value
Site C1	10.84	0.004
Site C2	2.74	0.254
SiteC4	0.67	0.714
Site C6	13.43	0.010
Site C7	14.75	0.001
Site C8	0.79	0.672
Depth 0-4cm	29.96	0.000
Depth 4-8cm	30.26	0.000
Depth 8-12cm	19.93	0.000

Table 2.4: Kruskal-WallisH test results on data in Figure 2.5 comparing intra-site differences in sediment water content (rows 2 to 6) and inter-site differences at the three depths (rows 7 to 9)

2.3.2.2 Sediment grain size

The down core sediment grain size distribution data for the six sites (Figure 2.6) show that the predominant sediment type is either sand or silty sand, which broadly agrees with previous work characterising the sediment type in which *A. islandica* occurs (Liehr et al.,2005; Thórarindóttir et al., 2008). At sites C1, C4 and C7 data from all three depths plot within the same sediment type which are silty sands (C1 and C7) and sand (C4); for the other sites there are some down core differences in sediment type observed. For example, at site C8 two of the data points are in the silty sand section of the diagram, while the other plots in the sand portion. This difference in sediment type with depth is clearly seen in the stack plot of the data (shown in Figure 2.7 as an example of an alternative way to present the data – the stack plots for the remaining sites are presented in Appendix 3).

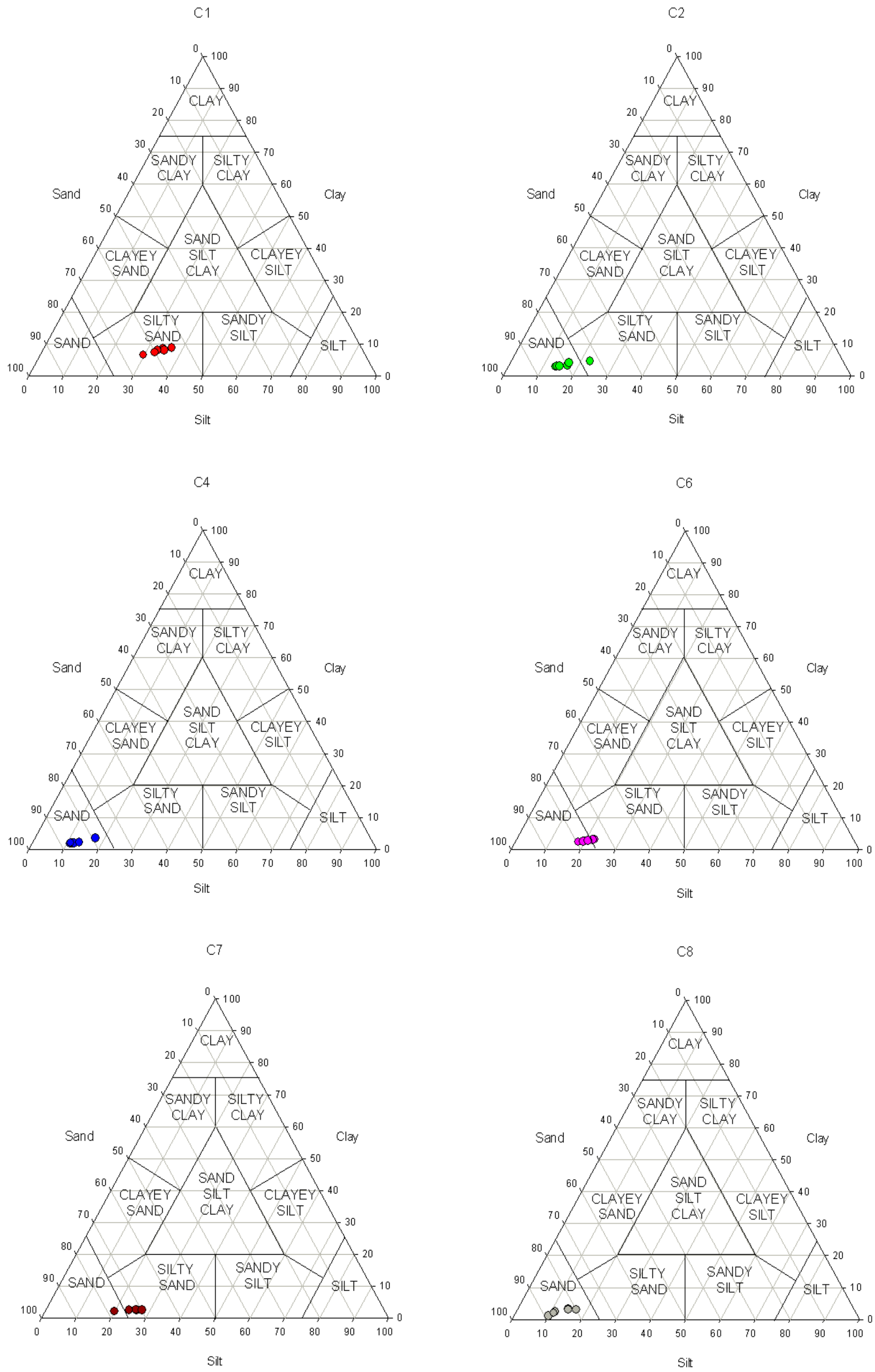


Figure 2.6: Ternary diagrams for each site for the three down core sections analysed to indicate sediment type (as volume percentage) present at the six sites. Stack plots for the grain size distribution results for each site are illustrated in Appendix 3. Cores analysed here are as follows: C1 – core 5; C2 – core 5; C4 – core 5; C6 – core 4; C7 – core 5: C8 – core 1.

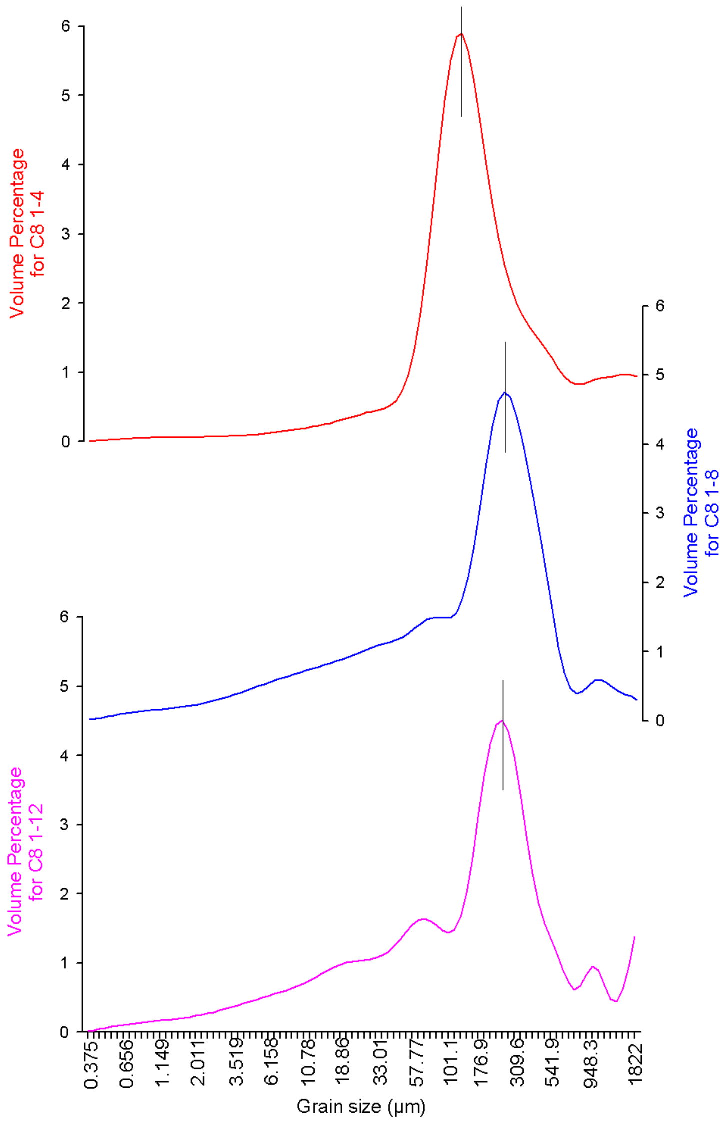


Figure 2.7: Example of a stack plot of grain size distribution – in this instance for site C8, core 1 (down core analysis). All the other stack plots are in Appendix 3 0-4 cm in red, 4-8 cm in blue and 8-12 cm in pink.

The ternary diagram plots of the core surface sediment (Figure 2.8) support the findings in Figure 2.6 i.e. that the predominant sediment type at all six sites is sand/silty sand. As with the down core data, there are still some differences between the sites but they all suggest generally consistent sand to silty sand habitat preference.

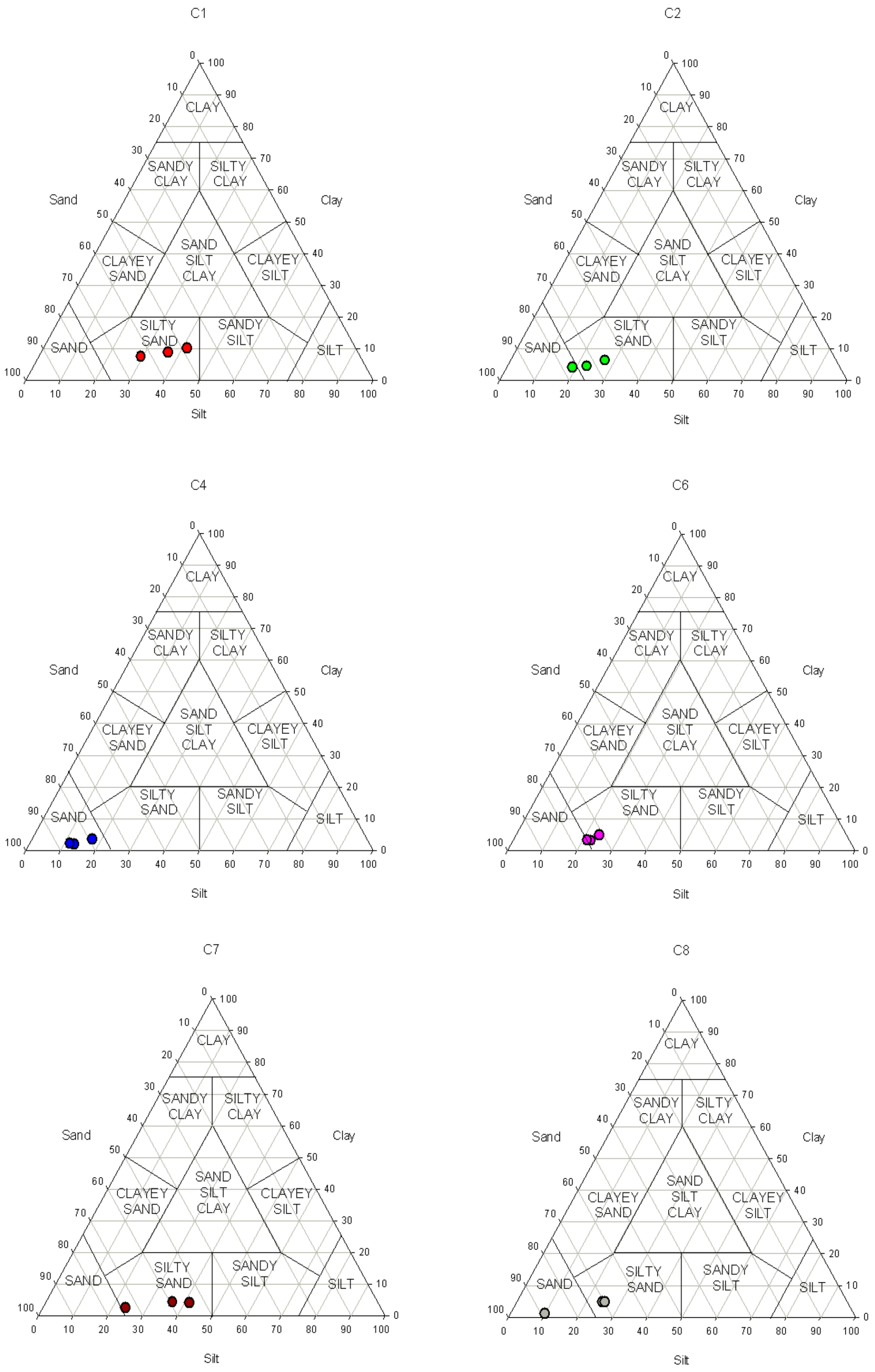


Figure 2.8: Ternary diagrams (volume percentage) illustrating sediment type present in the six core surface samples analysed at each site. The stack plots of the data used to generate these results are in Appendix 3.

To acquire a better understanding of how the grain size at each site differs, distribution data were plotted and correlated (see Appendix 3) to test for a common sediment matrix distribution both down core and for the surface sediment series. From the example stack plot in Figure 2.7 it is possible to see that there is a visual coherence present with a slight shift in the mode of the C8 1-4 sample towards finer grain sizes and a low df (degrees of freedom). To ensure that the low df did not bias the correlation analyses, the AC corrections outlined in Equations 2.2 and 2.3 were undertaken on all data sets; analysis was not feasible where N' was lower than 3. At sites C4, C7 and C8 all the results had N'<3 and therefore correlations could not be robustly performed for these examples. Site C1 was the only site where all N' values were greater than 3, however all these correlations were non-significant. It was only for site C2 where any of the correlations were statistically significant (Table 2.5). All the correlation results are presented in Appendix 4. Ultimately due to the low sample numbers this proved an inconclusive and poor approach to the analyses and therefore an alternative method was chosen for use – chi-squared.

Table 2.5: Significant correlations between grain size distribution series after correcting for the AC present in the grain size distribution series as illustrated in Figure 2.7. All the other correlation results are in Appendix 4.

Site	Core sections	r	p-value
C2	5-4 and 5-8	0.965	<0.05
	5-8 and 5-12	0.943	<0.05

The chi-squared test was used to look for significance between the modes of the data distributions. The Chi-squared test is also appropriate as it can be used on small data-sets (i.e. when df is low, where df is defined as degrees of freedom) and standard normality tests cannot be performed (see Appendix 5 for normality test results). The chi-squared analysis was carried out for both the down core and sediment surface data; the results are summarised in Table 2.6 and indicate five significantly different results; at site C8 the significantly different results are likely due to the shift in the mode of sample 1-4 towards the finer grain size fraction (Appendix 3K). For site C1 there are several peaks which deviate from the average mode for the surface analyses producing the significantly different results, while at site C2 the mode of the surface sample analysed in the down core analysis is shifted towards the finer grained sediments compared to the other two results (Appendix 3). Finally, for site C7 the surface sample has a mode which is further towards the coarser grained sediment fractions than the two lower core samples. These results support the visual differences inferred from both the ternary diagrams (Figures 2.6 and 2.8) and Appendix 3. However, this is not unexpected, and simply indicates that the sediments within a single collection site are not completely homogenous. Of greater interest is whether or not any of the sites are characterised by sediment types which differ from those found by Liehr et al. (2005) and Thórarindóttir et al. (2008), which would suggest the ability of *A. islandica* to inhabit a wider range of sediment habitat types.

Table 2.6: Results of chi-squared analyses of the sediment grain size data (modes – as illustrated in Appendix 3), down core n = 3, surface n = 6

Site	Series Analysed	Chi-squared$_{calc}$ value	Chi-squared$_{tab}$ value	Significance
C1	Down core	1.59	5.99	Not significantly different
	Surface	22.49	11.07	Significantly different
C2	Down core	9.69	5.99	Significantly different
	Surface	8.141	11.07	Not significantly different
C4	Down core	0.68	5.99	Not significantly different
	Surface	0.968	11.07	Not significantly different
C6	Down core	0	5.99	Not significantly different
	Surface	0	11.07	Not significantly different
C7	Down core	14.99	5.99	Significantly different
	Surface	0.86	11.07	Not significantly different
C8	Down core	42.75	5.99	Significantly different
	Surface	60.44	11.07	Significantly different

When all of the data from the sites are compared on two ternary diagrams (Figure 2.9) it can be seen that all the sites have broadly similar sedimentary characteristics. The surface sediment ternary diagram in Figure 2.9 shows that out of the six sites, C1 has the most distinct sediment type (silty sand). In Figure 2.10 the grain size data from both down core and core surface samples for each site have been averaged to generate an overall indication of average sand, silt and clay content. The data are used later in Chapter 7 for comparison with other site variables and shell growth data.

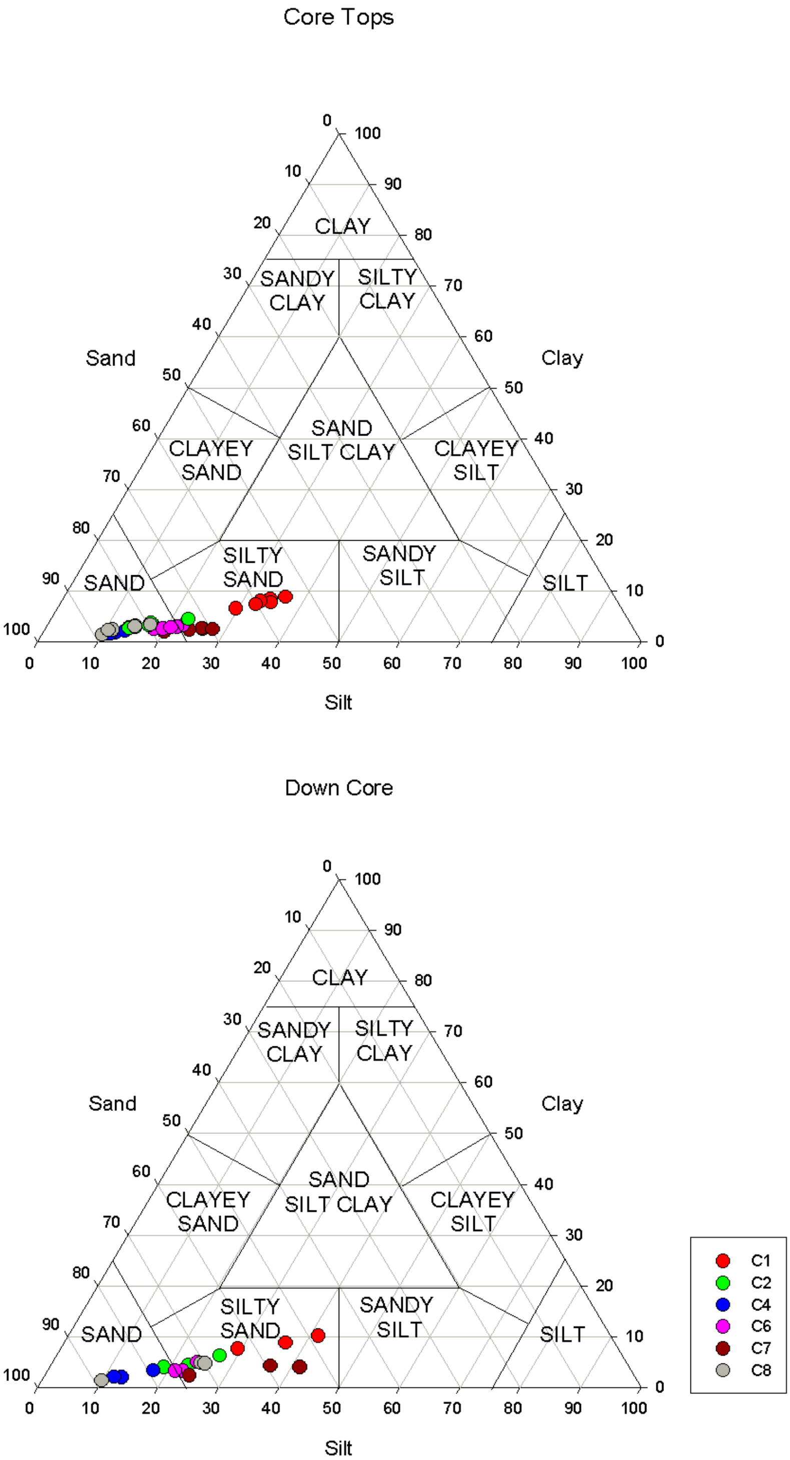


Figure 2.9: Ternary diagrams for all of the sites. The top diagram illustrates the sediment type present in the core top samples, while the bottom diagram is the sediment type present in the down core samples from the six sites (0-4, 4-8 and 8-12 cm).

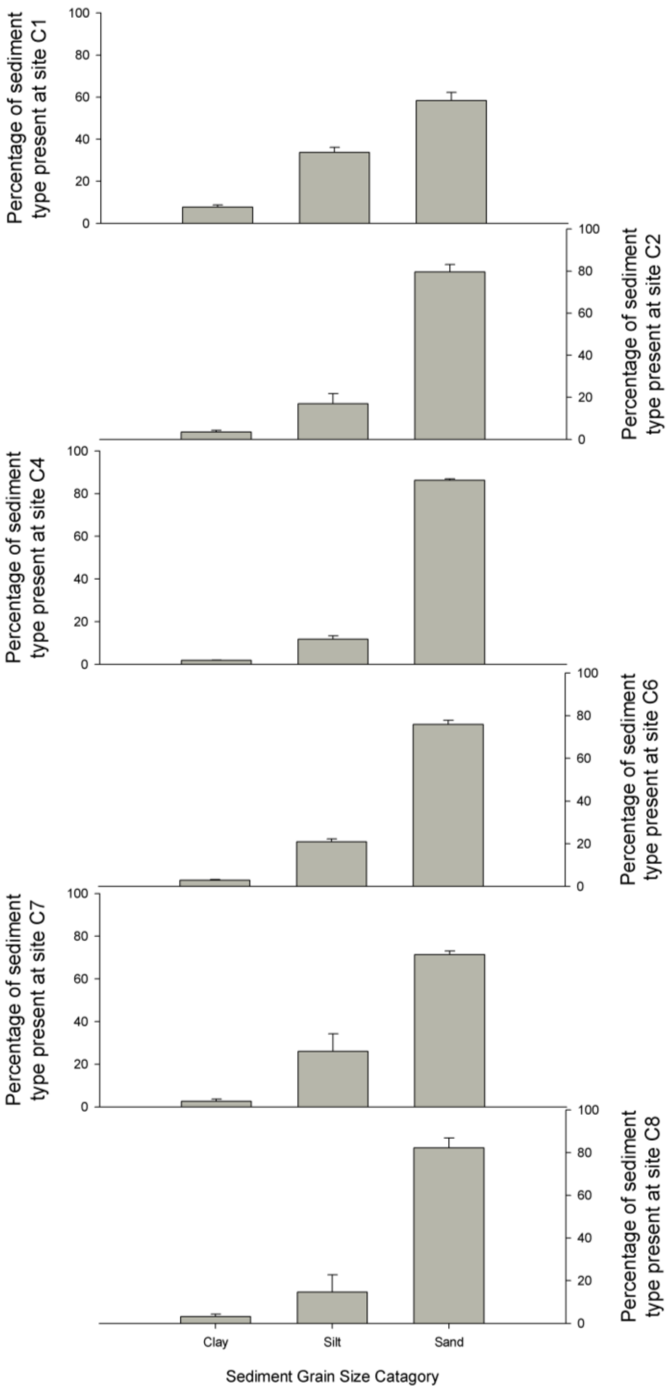


Figure 2.10: Bar charts illustrating how the percentage of the three sediment types (clay, silt and sand) vary between the six sites (as not all the data are normally distributed this is calculated using the median and the errors are the IQR.

When the sediment type distributions in Figure 2.10 are considered there appears to be a clear preference for silty-sand among all the *A. islandica* sampled within Lochs Etive and Creran.

However, when the average mode values for each site are considered (Figure 2.11) it is clear that grain size increases moving down Loch Etive from a mode of 103.71 ± 6.1 µm at site C7 to 228.61 ± 15.8µm at site C8. A down-fjord increase in grain size was also recorded by Gage (1972b) in both Lochs Etive and Creran. Gage (1972b) found a relationship between grain size and water depth, smaller grain sizes were typically found in deeper water, becoming coarser moving towards the shallower waters near the entrance (Gage, 1972b). Gage (1972b) suggested that this pattern is likely due to differences in tidal currents within the fjords, affecting bottom conditions of sediment entrainment and deposition. Gage (1972b) also showed biological community gradients changing in conjunction with grain size data. It is likely that fjord hydrography plays an important role in defining these spatial patterns and hence the distribution of benthic communities, including *A. islandica*.

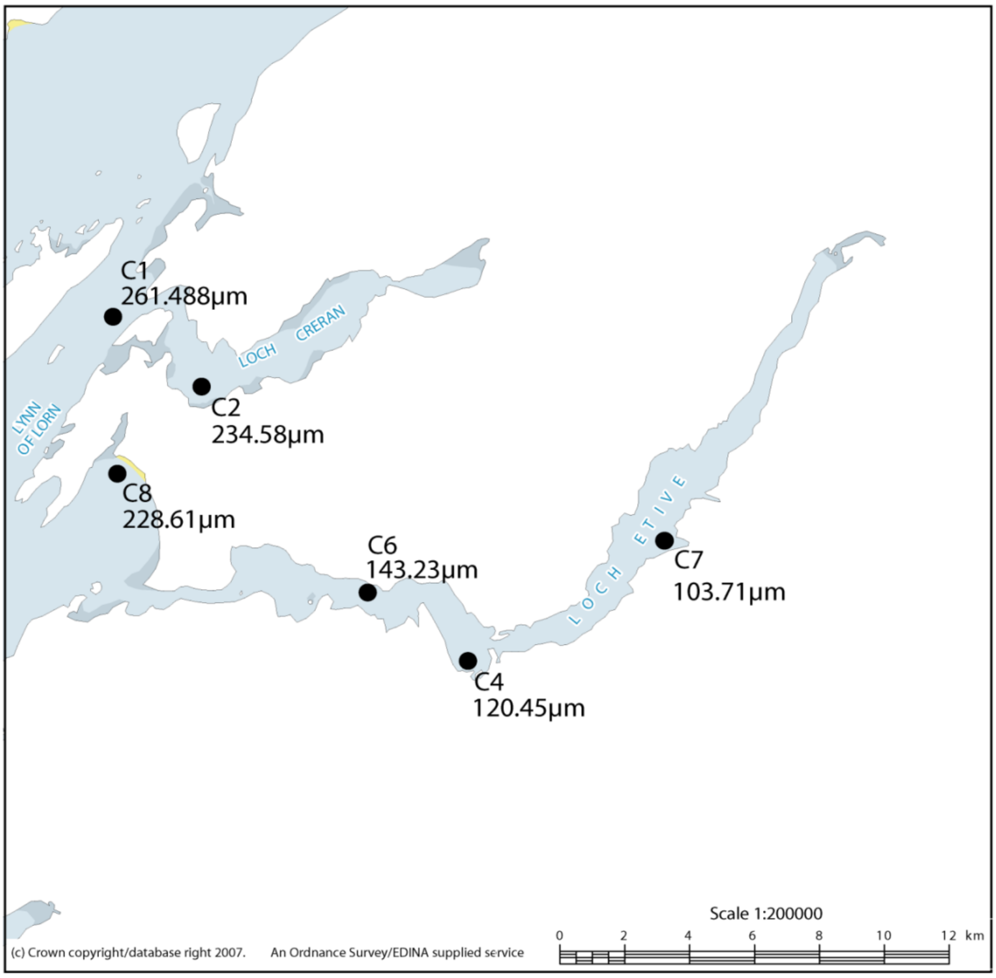


Figure 2.11: Map illustrating the grain size average mode values for the six study sites.

The grain size data indicate that all six sites are dominated by either sand or silty sand sediment (Figures 2.6 and 2.8). These results broadly match earlier findings by Liehr et al. (2005) and Thórarindóttir et al. (2008) concerning the sediment types favoured by *A. islandica*. These authors described the species as favouring sandy mud/mud, and medium to fine grained sands respectively. Within a fjordic environment, grain size is known to vary greatly and reflect hydrographic conditions (Gage, 1972b). As hydrography also impacts food supply (Witbaard, 1996; 1997) it is entirely likely that all these factors determine the distribution of *A. islandica* (see Figure 2.12).

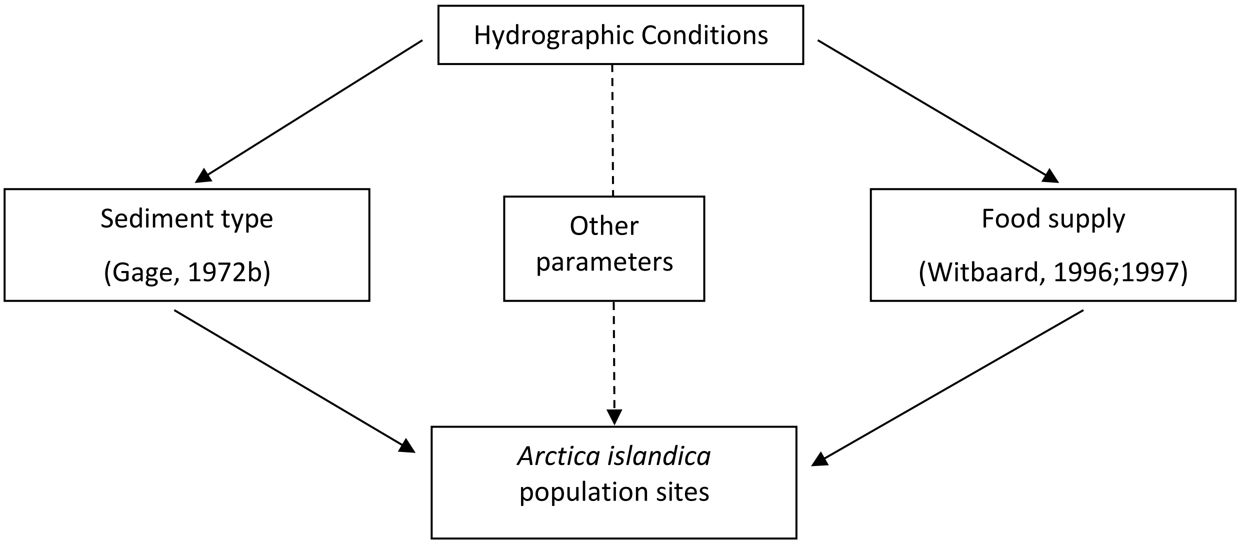


Figure 2.12: How hydrographic conditions can impact on *Arctica islandica* distribution via both sediment type and food supply. The other parameters concerns factors which modulate species response to hydrographic condition changes e.g. pollution and climate.

That all the *A. islandica* populations studied here were found within a well-defined sediment type range, along with the fact that Liehr et al. (2005) and Thórarindóttir et al. (2008) found populations in similar sediments may be of use in the future in using initial bottom surveys of sediment type to target potential *A. islandica* sampling sites. Out of the six sites, C1 has the most distinct sediment type (Figures 2.6 and 2.8), while site C7 has the smallest average mode grain size. Therefore, molluscs from these sites may exhibit distinct responses to environmental conditions.

2.3.2.3 Organic carbon content

In Loch Creran, Loh et al. (2010) found a pattern of OC content values decreasing from the head of the loch to its entrance (Figure 2.13). A similar pattern is found in the Loch Etive results presented here (Figure 2.14), with an overall decrease in OC content values from site C7 to C8. The values for C4 and C6 do not fit into this overall trend, although as the 2SE (where SE stands for Standard Error) bars for these two sites overlap the data are not significantly different at the 95% confidence limit.

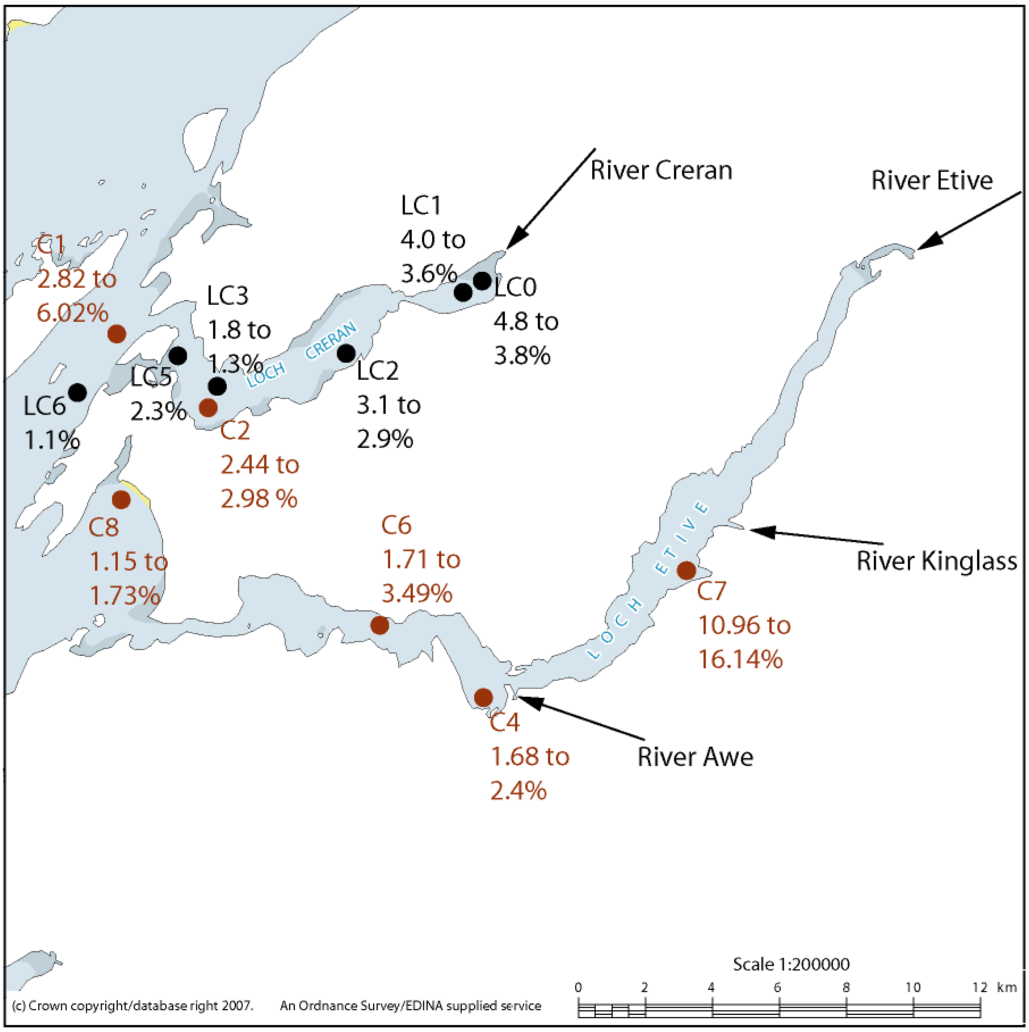


Figure 2.13: Organic Carbon content values from Loch Creran by Loh et al. (2010) in black (Adapted from Loh et al., 2010) also shown are the OC values from this study in brown.

Research by Ansell (1974) and Nørgaard-Pedersen et al. (2006) indicated that riverine inputs were important in supplying suspended material and sediment into Loch Etive, including OC. For example Ansell (1974) found that in a period of just over a year the River Awe was contributing between 8.93 mg/l and 0.116 µg/l of suspended material to the loch per day. It is, of course, possible that the size of the particles being introduced to the loch is such that they remain in suspension, and that the proximity of any given site to riverine input is not significant in determining sediment OC content (Figure 2.14). However another, even larger, source of suspended material to Loch Etive is the River Etive at the loch head (Figure 2.1). Ansell (1974) recorded daily suspended sediment loadings of between 29.73 mg/l and 0.153 µg/l. Such a large input of suspended sediment very likely contributes to the high OC content values at site C7, together with the other notable organic sources including phytoplankton cells, decomposition of macro-algae and phytoplankton production (Ansell, 1974). These sources coupled with the poor exchange of water between the upper basin in which site C7 is located and the lower basin (Ross et al., 1994) are most likely the reason for the C7 OC content values also being significantly different from those at the other Loch Etive sites. The OC input into the upper basin is less likely to reach the lower basin, especially when the long time-frames over which deep water renewal can occur are considered (mean renewal rate of $1\,{}^{1}/_{3}$ years in Loch Etive, (Edwards and Edelstein, 1977)).

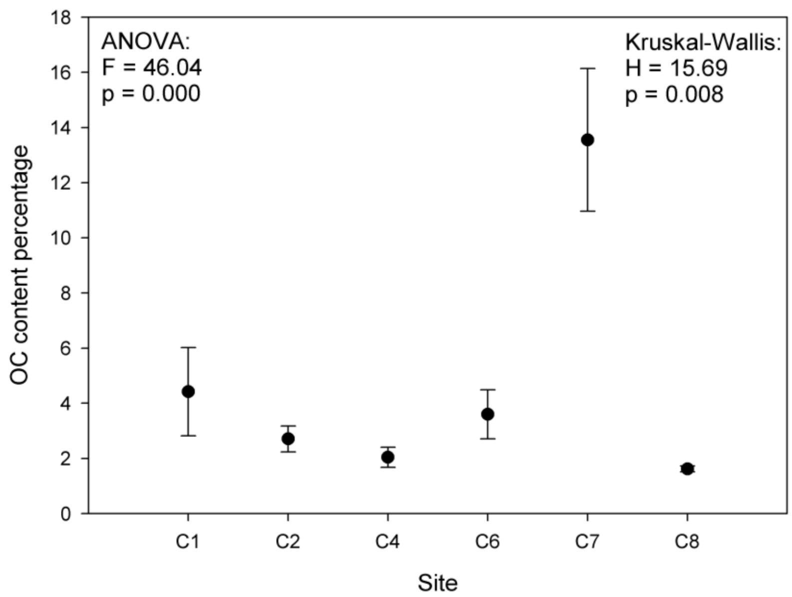


Figure 2.14: Organic Carbon content (weight percentage) at each field site; data are averages with corresponding 2SE bars (n = 3 for each site). As the datasets here have small n values (n = 3), standard tests for normality are not valid, these analyses were repeated using the non-parametric Kruskal-Wallis test with similar results.

In Figure 2.14 only the OC content data from site C7 is significantly different (this is supported by the ANOVA results shown in the figure; F = 46.04 and p = 0.000) from all the other sites studied and agrees with findings of Overnell et al. (1996 in Murray et al, 2003) who recorded organic content values of ~15% in sediment from near Bonawe deep in the upper Loch Etive basin. The higher OC content values at site C7, together with the quality of that organic material could influence the growth response of shells at this location more than at the other sites due to the high levels recorded at site C7 compared to the other five sites (Figure 2.14).

Site specific conditions, including variations in OC content, sediment grain size and sediment water content may all be of use later when investigating how shell growth at the six sites can be influenced by factors other than climate variability. From these results it is clear that site C7 is very distinct in terms of OC content (Figure 2.14) and sediment water content (Figure 2.5), while site C1 has a distinct sediment grain size type (Figure 2.9). Whether these site-specific factors influence shell responses to climate forcing will be investigated in Chapter 7.

3 Instrumental Data

3.1 Introduction

Marine instrumental data for Scotland rarely extend over 100 years, and are also spatially limited. The location (Figure 3.1) of the Scottish Association for Marine Science (SAMS) on the west coast of Scotland has resulted in multiple studies into the marine environment in this region (e.g. Gage (1972a);Gage (1972b) ; Tyler et al. (1983); Edwards and Edelstein (1977); Howe et al. (2001); Nørgaard-Pedersen et al (2006); McIntyre and Howe (2010); Cundill and Austin (2010)). The greater density of instrumental datasets for the region compared to other parts of Scotland is therefore part of the reason why this region was chosen for this study. However, many of the available datasets are limited as they rarely extend beyond 100 years (see Table 3. 1) meaning they are too short for comparative analysis with other instrumental records and shell chronologies. As a result there are only a limited number of local and regional climate series suitable for analysis (Table 3.1).

In Chapter 4, an empirical assessment is made between the shell chronologies and climate series using correlation analyses. For this so called “correlation response function” analysis (CRFA), it is important to identify the most suitable instrumental data. It is expected that if the mollusc growth series do record climate changes then the highest correlations would be with records local to the sample sites. As the local instrumental datasets are shorter than the length of the mollusc chronologies being analysed, they are therefore not long enough to assess effectively the mollusc data, meaning that it is important to identify other, longer records instead. In this chapter comparison is made between the short local and longer gridded records to investigate the presence of a common signal. Those gridded data which do share a common signal with the local/regional data can therefore be used to extend the period of analysis with the shell growth series beyond the limits of the local series.

3.1 Candidate Instrumental Datasets

There are six instrumental records examined in this chapter; two local, two non-local and two gridded (Figure 3.1 and Table 3.1). The two local series are Saulmore sea temperature and

Dunstaffnage air temperature, while there are also two non-local datasets (non-local is defined here as greater than 50 km away from the sample site): a sea temperature dataset from Millport (approximately 80km from the field area) and an air temperature series from Tiree (approximately 90km from the field area). The two gridded series (from grid 55°N-60°N, 10°W - 5°W) are HadSST2 (sea temperature) and CRUTEM3 (air temperature). The collection methods used to derive each of these instrumental datasets are summarised in Appendix 8.

Table 3.1: Instrumental data information

Dataset name	Map code	Type of data	Period of record	Depth of record (where applicable)	Source
Saulmore	S	Sea temperature	1996 – Present	10m below chart datum	Martin Sayer (NFSD/SAMS)
Dunstaffnage	D	Air temperature	1972 – Present	N/A	Met Office website (2011a)
Millport	M	Sea temperature	1952 – Present*	Surface	Tom Stevenson
Tiree	T	Air temperature	1931 – Present	N/A	Met Office website (2011b)
HadSST2	Black rectangle on Figure 3.1a	Gridded sea temperature anomalies	1850 – Present **	Various	Rayner et al. (2006)
CRUTEM3	Black rectangle on Figure 3.1a	Gridded air temperature anomalies	1890 – Present ***	N/A	Brohan et al. (2006)

*Millport: data collection began in 1952; however this dataset is only used from 1953 onwards for most analyses due to incomplete monthly measurements in 1952.
**HadSST2 data prior to 1903 has too many missing monthly values for meaningful analyses, therefore the correlations between HadSST2 and CRUTEM3 are undertaken from 1903 onwards, the exception to this is for winter, where incomplete monthly measurements for 1903 mean that analysis starts in 1904.
***Prior to 1890 the CRUTEM3 dataset has too many missing monthly values for this area to be used for analysis.
N.B. All series were only be analysed until 2008 (even if data is available after this date) as the last shells analysed were collected in 2009 and therefore their final complete year should be 2008. Only the period being investigated is presented in any figures.

Figure 3.1A: Location of the gridded dataset (black rectangle) and the two non-local datasets (Tiree – T and Millport – M) relative to the field site (red box).

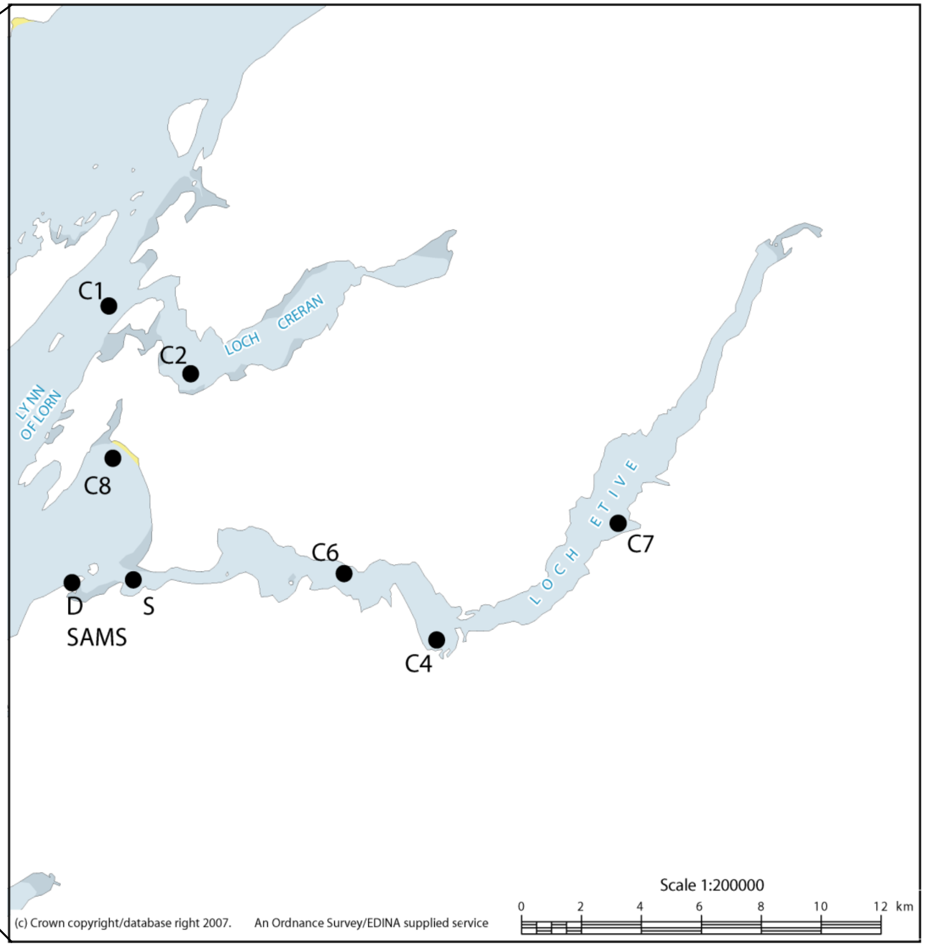


Figure 3.1B: Location of the six sample sites (see Table 2.1 for site names) in relation to the local fjordic instrumental datasets; see Table 3.1 for location names. Also indicated is the location of the Scottish Association of Marine Science (SAMS) research station.

The instrumental datasets are presented in Figures 3.2 (local), 3.3 (non-local) and 3.4 (gridded). On the whole, Dunstaffnage (Figure 3.2) shows an increase in temperature, although for autumn the rate of increase in temperature per year is lower than for the other seasons (see Table 3.2). Over the 1972 to 2008 period it is also possible to see an increase in annual temperature in the Tiree, Millport, CRUTEM3 and HadSST2 series (Table 3.2). Herein we define the four seasons as Winter – January to March, Spring – April to June, Summer – July to September and Autumn – October to December.

Table 3.2: Rate of temperature increase per decade (°C) using data collected over the period 1972 to 2008 at Dunstaffnage, Millport, Tiree, CRUTEM3 and HadSST2

Dataset	Season	Average temperature increase per decade (°C)[1]	p-value
Dunstaffnage	Annual	0.411	0.000
	Winter	0.408	0.012
	Spring	0.388	0.000
	Summer	0.379	0.002
	Autumn	0.162	0.216
Millport	Annual	0.319	0.002
	Winter	0.301	0.015
	Spring	0.384	0.002
	Summer	0.386	0.001
	Autumn	0.293	0.004
Tiree	Annual	0.279	0.000
	Winter	0.382	0.004
	Spring	0.279	0.001
	Summer	0.265	0.006
	Autumn	0.262	0.011
HadSST2	Annual	0.226	0.000
	Winter	0.198	0.001
	Spring	0.207	0.003
	Summer	0.231	0.001
	Autumn	0.267	0.000
CRUTEM3	Annual	0.334	0.000
	Winter	0.392	0.002
	Spring	0.317	0.000
	Summer	0.317	0.001
	Autumn	0.312	0.003

[1]Calculated by multiplying regression slope coefficient by 10

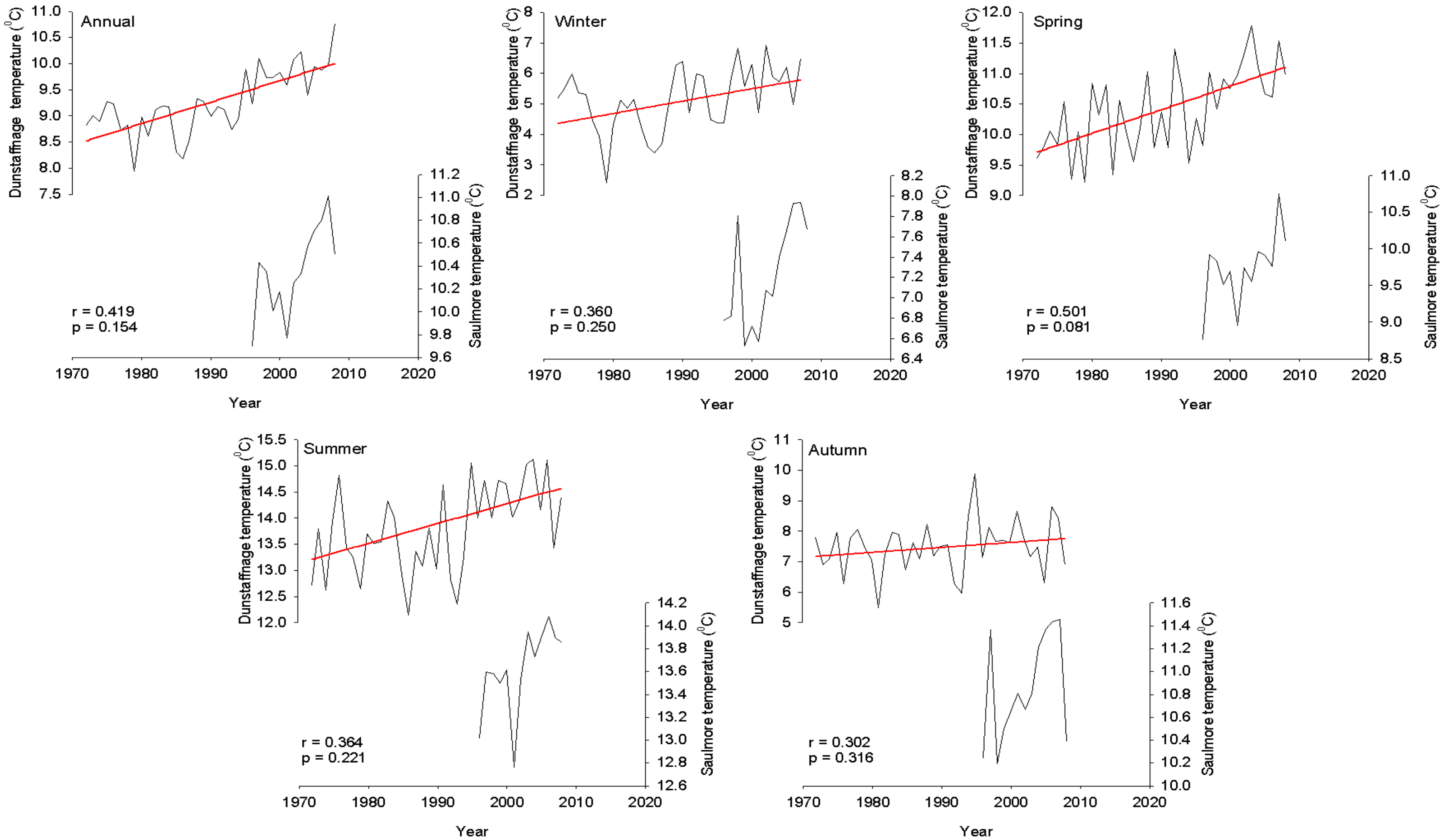


Figure 3.2: Local datasets used for analysis in this chapter, each season is presented for each of the two local series. The trend in the Dunstaffnage data is also indicated (Table 3.2) as are the correlation coefficients and their p-values between Saulmore and Dunstaffnage for each season.

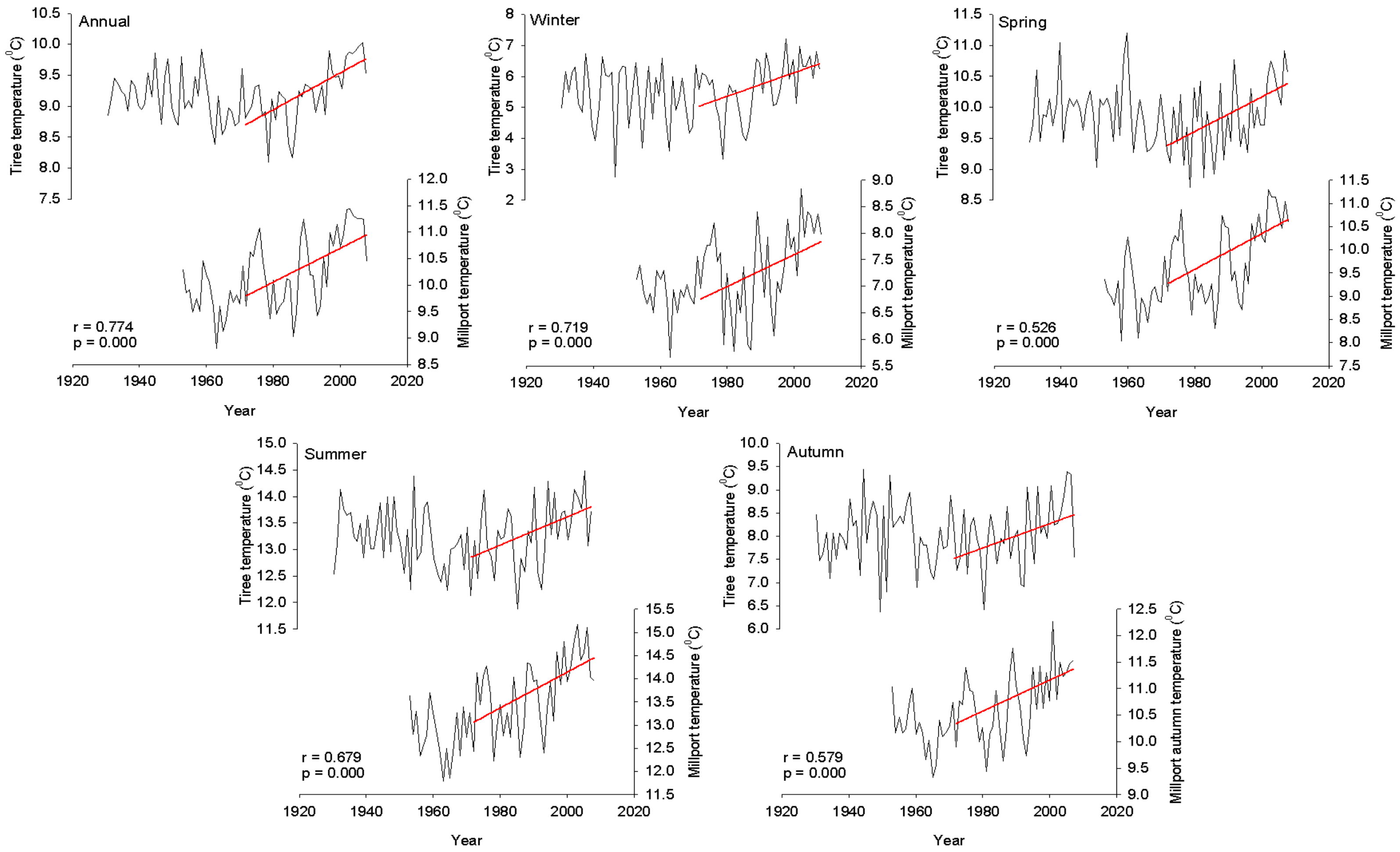


Figure 3.3: Non-local datasets (Tiree air temperature and Millport sea temperature) used for analysis in this chapter. Trends for the period 1972 to 2008 are shown for each series as are the r and p-values for the correlations between the two series for each season.

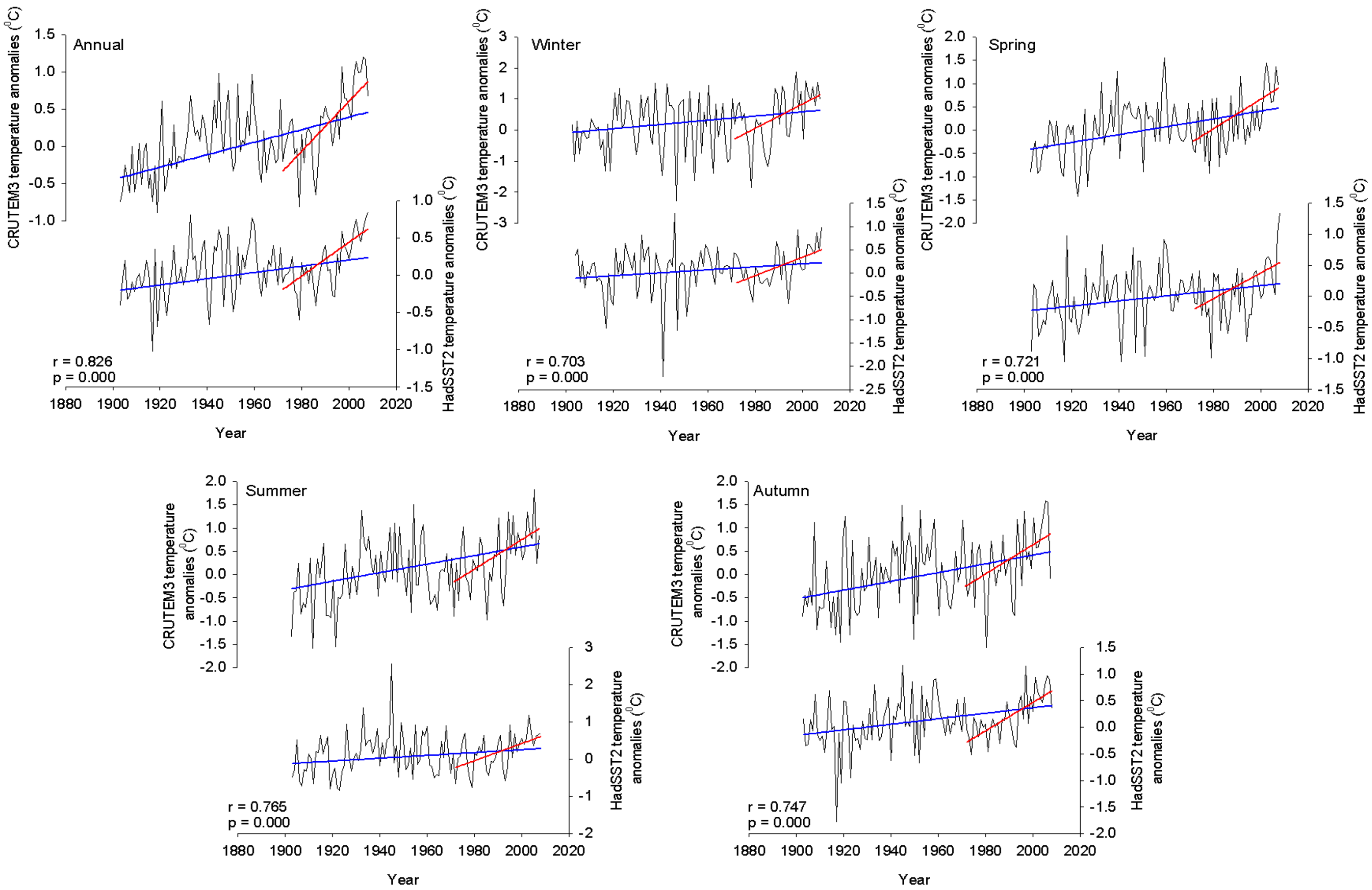


Figure 3.4: Gridded datasets (CRUTEM3 and HadSST2) used for analysis. The trend in the data series (1972 to 2008) are shown in red as well as the long-term trends (1903 to 2008). The correlation coefficient p and r-values between the series for each season are also shown.

3.2 Inter-series comparisons

Inter-series comparisons are carried out using two different methods. Initial analyses, presented in Section 3.3.1 used Pearson's correlation coefficient analyses between the instrumental records to investigate which instrumental series were suitable for comparisons with the shell master chronologies in Chapter 4. Following this, in Section 3.3.2, the six instrumental series were standardised to z-scores in order to investigate differences present between the series on an annual-level over a common period of analysis, along with a measure of variance between the series. The purpose of these analyses is to determine whether the gridded datasets, which have a much longer time-span compared to the local and non-local datasets, are representative of the shorter, more local, temperature series. Through testing the coherence between the gridded data and the local and non-local datasets using correlations (Section 3.3.1) and investigating variance between the series (Section 3.3.2) it should be possible to determine whether these longer series can be used for extended analysis.

3.2.1 Correlations

Correlation analysis was carried out between all six instrumental records to determine which are appropriate for comparison with the shell growth chronologies to assess their potential as proxy records (see Chapter 4). These comparisons were carried out for five seasonal parameters; annual average, Winter, Spring, Summer and Autumn. The results are presented in Tables 3.3 to 3.7. Local-local correlations are shown in blue, local-non-local in red and local/non-local- gridded in green. Table 3.9 shows the mean value (RBAR) of all correlations between each station and the five others analysed. Individual correlations were generated over the maximum period of overlap of all bivariate pairs. The RBAR value therefore represents a metric mean correlation statistic that should highlight which of the station records is most representative of the wider study region.

Table 3.3: Annual average correlations between all the datasets being analysed

	Saulmore	Dunstaffnage	Millport	Tiree	HadSST2
Dunstaffnage	0.419 p = 0.154 1996 to 2008				
Millport	0.509 p = 0.000 1996 to 2008	0.727 p = 0.000 1972 to 2008			
Tiree	0.866 p = 0.000 1996 to 2008	0.883 p = 0.000 1972 to 2008	0.774 p = 0.000 1953 to 2008		
HadSST2	0.704 p = 0.007 1996 to 2008	0.898 p = 0.000 1972 to 2008	0.668 p = 0.000 1952 to 2008	0.807 p = 0.000 1931 to 2008	
CRUTEM3	0.850 p = 0.000 1996 to 2008	0.887 p = 0.000 1972 to 2008	0.810 p = 0.000 1953 to 2008	0.981 p = 0.000 1931 to 2008	0.826 p = 0.000 1904 to 2008

All the instrumental records positively correlate (Tables 3.3 to 3.7), but not all are statistically significant. For all seasons the relationships between Saulmore and Dunstaffnage are not statistically significant, and these are the lowest correlations present for each of the seasons. The highest correlations present for each season are those between the CRUTEM3 and the Tiree series. These high correlations are due to the inclusion of the Tiree dataset in the CRUTEM3 grid being analysed here (Appendix 8). There are, however, several series other than Saulmore and Dunstaffnage with non-significant correlations between them in Tables 3.3 to 3.7 and these are summarised in Table 3.8.

Table 3.4: Winter correlations

	Saulmore	Dunstaffnage	Millport	Tiree	HadSST2
Dunstaffnage	0.360 p-value = 0.250 1996 - 2007				
Millport	0.589 p-value = 0.034 1996 – 2008	0.739 p-value = 0.000 1972 – 2008			
Tiree	0.541 p-value = 0.056 1996 – 2008	0.978 p-value = 0.000 1972 – 2008	0.719 p-value = 0.000 1953 – 2008		
HadSST2	0.790 p-value = 0.001 1996 to 2008	0.733 p-value = 0.000 1972 to 2008	0.660 p-value = 0.00 1953 to 2008	0.710 p-value = 0.000 1931 to 2008	
CRUTEM3	0.539 p-value = 0.057 1996 to 2008	0.972 p-value = 0.000 1972 to 2008	0.693 p-value = 0.000 1953 to 2008	0.992 p-value = 0.000 1931 to 2008	0.703 p-value = 0.000 1904 to 2008

Table 3.5: Correlations between Spring averages

	Saulmore	Dunstaffnage	Millport	Tiree	HadSST2
Dunstaffnage	0.501 p-value = 0.081 1972 – 2008				
Millport	0.639 p-value = 0.019 1996 – 2008	0.643 p-value = 0.000 1972 – 2008			
Tiree	0.751 p-value = 0.003 1996- 2008	0.935 p-value = 0.000 1972 – 2008	0.526 p-value = 0.000 1953 – 2008		
HadSST2	0.733 p-value = 0.004 1996 - 2008	0.799 p-value = 0.000 1972 - 2008	0.561 p-value = 0.000 1952 - 2008	0.700 p-value = 0.00 1931-2008	
CRUTEM3	0.608 p-value = 0.027 1996 - 2008	0.941 p-value = 0.000 1972 - 2008	0.584 p-value = 0.000 1953 - 2008	0.968 p-value = 0.000 1931-2008	0.721 p-value = 0.000 1903 - 2008

Table 3.6: Correlations between Summer average data

	Saulmore	Dunstaffnage	Millport	Tiree	HadSST2
Dunstaffnage	0.364 p-value = 0.221 1996 – 2008				
Millport	0.511 p-value = 0.074 1996 – 2008	0.719 p-value = 0.000 1972 – 2008			
Tiree	0.586 p-value = 0.035 1996 – 2008	0.962 p-value = 0.000 1972 – 2008	0.679 p-value = 0.000 1953 – 2008		
HadSST2	0.580 p-value = 0.038 1996 - 2008	0.839 p-value = 0.000 1972 - 2008	0.620 p-value = 0.000 1952 - 2008	0.782 p-value = 0.000 1931-2008	
CRUTEM3	0.570 p-value = 0.042 1996 - 2008	0.950 p-value = 0.000 1972 - 2008	0.724 p-value = 0.000 1953 - 2008	0.980 p-value = 0.000 1931-2008	0.765 p-value = 0.000 1903 - 2008

Table 3.7: Autumn average data correlation results

	Saulmore	Dunstaffnage	Millport	Tiree	HadSST2
Dunstaffnage	0.302 p-value = 0.316 1996 – 2008				
Millport	0.543 p-value = 0.068 1996 – 2007	0.495 p-value = 0.002 1972 – 2007			
Tiree	0.864 p-value = 0.000 1996 – 2008	0.764 p-value = 0.000 1972 – 2008	0.579 p-value = 0.000 1953 – 2007		
HadSST2	0.803 p-value = 0.001 1996 - 2008	0.538 p-value = 0.001 1972 - 2008	0.653 p-value = 0.000 1952 - 2007	0.696 p-value = 0.000 1931-2008	
CRUTEM3	0.902 p-value = 0.000 1996 – 2008	0.755 p-value = 0.000 1972 - 2008	0.637 p-value = 0.000 1953 - 2007	0.984 p-value = 0.000 1931-2008	0.747 p-value = 0.000 1903 - 2008

Table 3.8: Non-significant correlations (other than between Saulmore and Dunstaffnage) as seen in Tables 3.3-3.7

Season	Non-significant correlations	r	p-value
Winter	Saulmore and Tiree	0.541	0.056
	Saulmore and CRUTEM3	0.539	0.057
Summer	Saulmore and Millport	0.511	0.074
Autumn	Saulmore and Millport	0.543	0.068

Why Saulmore and Dunstaffnage do not significantly correlate with each other, and the reason behind the non-significant results outlined in Table 3.8, is not immediately clear and requires further analysis of the data. To do this, the correlations for each individual record versus the other series were averaged together to provide a summary diagnostic (RBAR) of overall station coherence (Table 3.9). This was done for each seasonal parameter. Additionally, the seasonal time series for each record was compared after being transformed to z-scores over the period 1996 to 2008; these are presented in Section 3.3.2.

Table 3.9: Average correlation values between each dataset and all other instrumental series are presented individually in Tables 3.3 to 3.7. The highest correlation values for each seasonal parameter are shown in bold, and the lowest in italics.

Data series	Series type	Average correlation (Annual average)	Average correlation (Winter)	Average correlation (Spring)	Average correlation (Summer)	Average correlation (Autumn)
Saulmore	Sea	*0.670*	*0.564*	0.646	*0.522*	0.683
Dunstaffnage	Air	0.763	0.756	0.764	0.767	*0.571*
Millport	Sea	0.698	0.680	*0.591*	0.651	0.581
Tiree	Air	0.862	**0.788**	**0.776**	**0.798**	0.777
HadSST2	Sea	0.781	0.719	0.703	0.717	0.687
CRUTEM3	Air	**0.871**	0.786	0.764	**0.798**	**0.805**
Mean	-	0.774	0.716	0.707	0.709	*0.684*

As already mentioned, an important consideration when looking at any of the correlations between Tiree and CRUTEM3 (either in Table 3.9 above, or in the individual seasonal parameter tables) is that the Tiree data were included in the construction of the CRUTEM3 grid (Appendix 8). This would lead to higher correlations between the two series and therefore introduce a certain level of bias into the analyses. However, as the local air temperature record (Dunstaffnage) also correlates significantly with CRUTEM3, it is felt that this potential bias in correlations between Tiree and CRUTEM3 does not pose a problem when selecting a suitable temperature record to use in Chapter 4.

The results in Table 3.9 also indicate that overall Saulmore has the weakest correlation with the other instrumental series, supporting earlier findings in this section. Correlation values between HadSST2 and CRUTEM3 and the rest of the series presented in Table 3.9 indicate high correlations between the gridded data and the local/non-local series. Of the two gridded series, HadSST2 has the weaker relationship with the other datasets, meaning that in theory CRUTEM3 is more regionally representative for both land and sea temperatures. However, as molluscs grow in the marine environment it is important to have a series representative of this setting and therefore both gridded datasets will be used so that there is also a sea temperature series analysed.

3.2.2 Between time-series variance

To better understand variability between the six instrumental datasets, they have been standardised by converting them to z-scores over the common period 1996 to 2008 to facilitate comparison (Figure 3.5). The average of the six datasets is also presented to provide a measure of how each instrumental record deviates from this value on a year-to-year basis. In Figure 3.5 it is possible to see that for each season there are several years of greater variance; these results are summarised in Table 3.10.Divergence has been used to investigate differences between the datasets as this is a suitable way to highlight potential problem datasets, and the value 0.7 used to highlight pointer years as a subjective value to help identify those years with greater variance from the mean value.

Table 3.10: Years of greater variance (i.e. those with highest spread between datasets present)

Season	Year(s) of greater variance	Datasets deviating from the mean and contributing to greater spread/higher variance
Annual	2004	Dunstaffnage
	2008	All
Winter	2000	Saulmore and HadSST2
	2002	Saulmore
	2006	All (except Millport)
Spring	2003	Saulmore
	2008	HadSST2
Summer	2001	Saulmore
	2007	Saulmore and HadSST2
Autumn	2001	Saulmore and CRUTEM3
	2005	Dunstaffnage

The results in Table 3.10 highlight that for all the seasons (except for the annual results), there is at least one year where the Saulmore dataset does not fit with the overall variability presented in the rest of the instrumental datasets. HadSST2 also shows this for three seasons (Winter, Spring and Summer). Periods of greater variance between the instrumental datasets illustrated in Figure 3.5 are reflected in the correlation results in Section 3.3.1 through lower r-values, and although the results in Figure 3.5 are only demonstrated over a short time frame (1996 to 2008) they do highlight why some of the results between Saulmore and the other datasets (Table 3.9) may be non-significant. However, the low degrees of freedom due to the short nature of analysis achievable between Saulmore (due to the short length of Saulmore) and the other series must also be taken into consideration. This means any minor differences between Saulmore and the other instrumental records, as seen in Figure 3.5, influence the correlation dramatically.

The results in the bar chart in Figure 3.5 vary from the mean results in Table 3.9. In Table 3.9 the highest average correlation between the series is the Annual period, while in Figure 3.5 it is Spring where the strongest between series common signal is noted. The most likely reason for these different results is the different time periods of analysis. These results indicate that trends and relationships between the different instrumental series may change over time and that a more robust analysis (e.g. Correlation Response Function Analysis) would be appropriate over as long a period as possible.

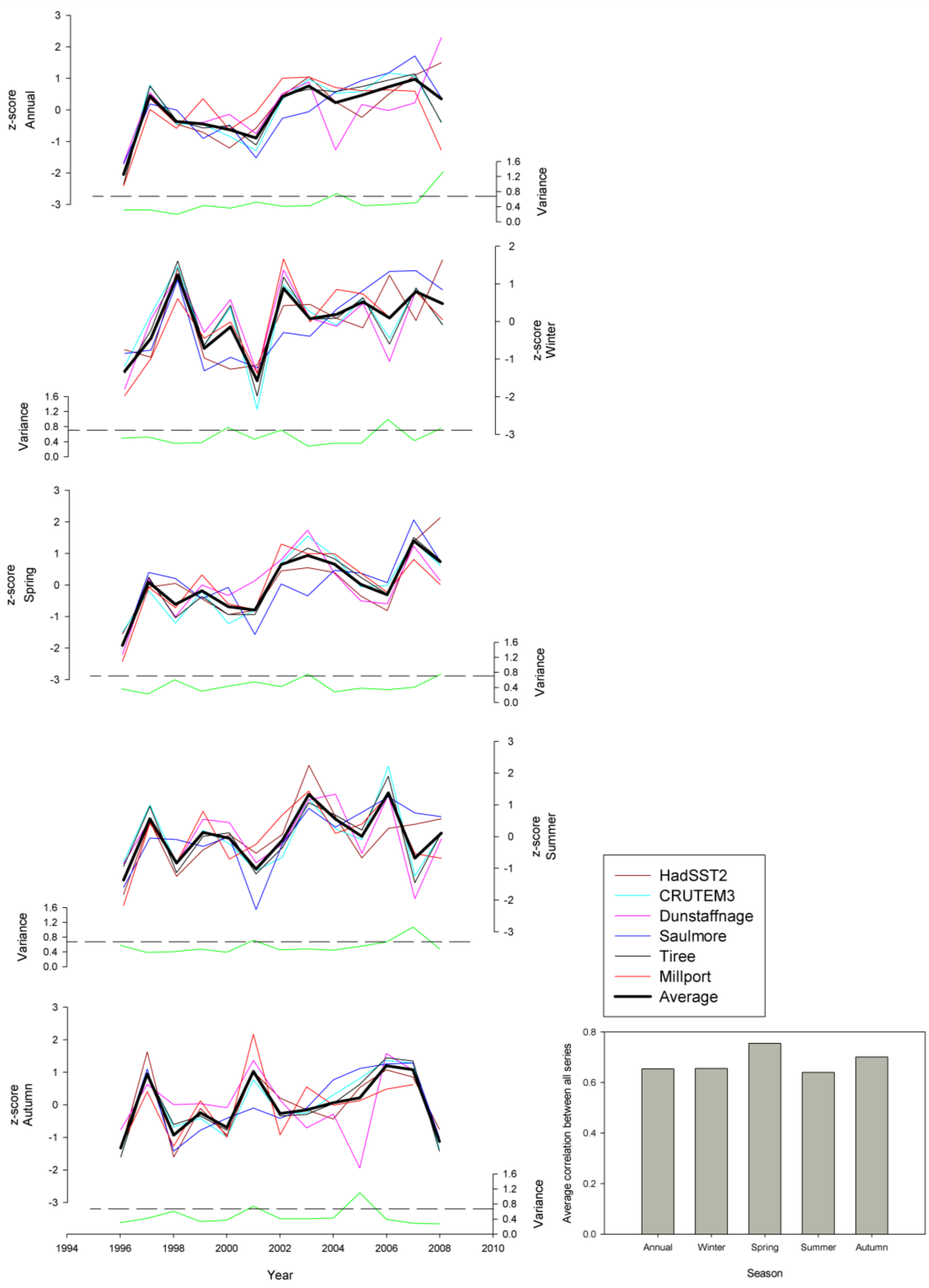


Figure 3.5: Time series - normalised to z-scores for each of the six instrumental datasets for the five seasonal parameters over which analyses are carried out. Also shown is a bar chart which indicates the RBAR values between all of the series for each period of analysis for the timeframe 1996 to 2008.
Below each graph of the instrumental data is a plot indicating variance between the data over time to help indicate years where the common signal between the series is either high or low. The dashed lines represent a variance of 0.7 and any value above this has been deemed a variable year, worthy of further investigation in Table 3.10. To identify pointer years 0.7 was chosen subjectively as the threshold value chosen to identify the top 2 or 3 years where datasets have deviated from each other.

3.3 Conclusion

Despite the lack of a significant correlation between Saulmore and CRUTEM3 in Winter, the relationships between the local and gridded data, and to a lesser extent the results from the non-local vs. gridded data, indicate that the CRUTEM3 and HadSST2 gridded temperature records appear to be appropriate datasets to use for expressing local and regional temperature variability. It is possible that the lack of a significant correlation between Saulmore and CRUTEM3 in the winter is due to the short nature of the analysis, therefore meaning that the two datasets only need to differ slightly over this period to lead to a lack of significant correlation. In Figure 3.5 it is possible to see that in winter the datasets for CRUTEM3 and Saulmore are diverging slightly from each other in the late 1990s and then again around 2006. Another possible reason for this difference is that the CRUTEM3 dataset represents a larger area which incorporates a variety of processes and input data collection sites, therefore meaning that in the winter it may not be truly representative of the sea temperature within the sheltered sea loch location of Saulmore.

Using the CRUTEM3 and HadSST2 datasets for correlation response function analysis (see Chapter 4) with the shell growth chronology records allows the analyses to be carried out over a longer time period than would be feasible using the local and non-regional series due to their short lengths, and allow for assessment of whether any of the shell chronologies have the potential to be used as proxy records for climate change. It is important to remember that out of the two gridded datasets HadSST2 has the weaker coherence with the other instrumental series. However, as HadSST2 is a sea temperature dataset and therefore theoretically records changes within the environment in which the molluscs are growing, it will still be used for analyses in Chapter 4. In addition to using the longer gridded datasets for analyses in Chapter 4 the two local datasets, Saulmore and Dunstaffnage are also analysed, this is in part due to the lack of a significant correlation between Saulmore and CRUTEM3 in the winter, which cannot be fully accounted for, but also because this takes into account the fact that HadSST2 does not correlate with the local datasets as strongly as CRUTEM3. One possible reason for this is that SST gradients are spatially complex and sometimes steep around the shelf seas (Austin et al., 2006; Hill et al., 2008). The gridded HadSST2 dataset may therefore be obscuring or averaging out some of the complex local SST changes that are present in the local Saulmore dataset.

4 Chronology construction and correlation response function analysis

4.1 Introduction

As detailed in Chapter 1 (Table 1.1) *A. islandica* have been used for a variety of purposes including; trace metal level analysis (e.g. Swaileh and Adelung, 1994; Swaileh, 1996), studying the influence of water temperature on recruitment (e.g. Harding et al., 2008) and as palaeoclimatic proxies (e.g. Helama et al., 2007 – off the coast of Tromsø; Butler et al., 2010 – 30 to 50 m water depth; Butler et al., 2013 – 81 to 83 m water depth). To date, however there is a lack of published research into using *A. islandica* from fjordic environments, for climatic analyses. This is surprising given the amount of research indicating the potential of fjords as sites for recording past climate change – for example Nordberg et al. (2010) used fjordic foraminifera records to study NAO variability (see Section 1.2). This lack of research into *A. islandica* from fjords for geochemical and palaeoclimatic proxies was a driving factor behind undertaking research into *A. islandica* growth at the six fjordic sites being investigated here.

The primary aim of this chapter is to detail the appropriate processing of mollusc shell growth data and ascertain whether there is a robust enough climate signal recorded in the annual growth variations with which a climate reconstruction can be developed. The secondary aim is to briefly review methods currently applied in sclerochronology and to highlight the potential of applying more refined data processing techniques that are commonly used in dendrochronology. Although sclerochronology has existed since the 1970s (e.g. Hudson et al., 1976), its application still has much to learn from dendrochronology (e.g. Fritts, 1976; Cook and Kairiukstis, 1990), which has a long and established history. Using methods prevalent in dendrochronology, a methodology for constructing growth increment (GI) chronologies in *A. islandica* is proposed. This refined methodology should facilitate the study of past climate and environmental change. These methods are outlined here, together with an investigation of the statistical relationships between shell chronologies and regional monthly climate variables from North West Scotland which were introduced in the previous chapter.

In sclerochronology, as in dendrochronology, there is the need to detrend raw GI data because of the presence of a non-linear ontogenetic growth effect (often referred to as the biological age trend in dendrochronology); typically a period of higher growth is observed during the juvenile stages which decreases as the individual gets older (Witbaard, 1997). To date, within the majority of *A. islandica* sclerochronology literature, detrending methods have involved using some form of smoothing filter, e.g. flexible splines (Scourse et al., 2006), or moving averages (Epple, 2004). The application of such flexible detrending methods has been used to remove the low frequency ontogenetic growth trend to maximise the high frequency year-to-year signal to facilitate crossdating (see Chapter 1 for a definition). However, such an approach fails to fully capture potential multi-decadal or longer time-scale trends present within the data. Alternative detrending methods are therefore advisable for the purpose of studying long-term environmental change and in recent years there has been a move to using methods more commonly used in dendroclimatology (e.g. Butler et al., 2009a; 2010; Stott et al., 2010). In this study negative exponential (NE) functions, which retain more information than spline functions at multi-decadal and longer time-scales, were used where possible.

4.2 Methods

4.2.1 Sample Preparation

Prior to analysis for chronology construction, samples were measured for weight (soft tissue and shell – both single and paired valves); maximum height, length and width (see Figure 4.1 for dimensions measured). Once these measurements were made the periostracum (in Figure 4.1C this is the brown material covering the outside of the shell) was removed, and the shells dried out and then weighed again for the dry shell weight.

4.2.2 Sectioning

To measure GIs, they need to be visible and this requires processing along the line of maximum growth/height (see Scourse et al., 2006 and Figure 4.1) as this enables examination of the internal structure of the shell (Figure 4.2). To prevent the shell from breaking while sectioning, the wings (Figure 4.1B) are removed using a circular diamond saw and the line of maximum growth (A on Figure 4.1A) is marked on the shell. The shell was mounted in Aeropia epoxy resin in Metprep moulds using a mix of 1/3 hardener to 2/3 epoxy and heated at a low temperature prior to pouring to remove bubbles in the mixture. Once the resin had set after 2-

3 days, sectioning along the line of maximum growth was undertaken using a circular diamond saw. In specimens where the hinge plate (see Scourse et al., 2006) is not sectioned properly it is possible to grind the section at a coarse level (120µm/74 µm) to reach the line of preferred sectioning (see Jones,1980). Once correctly sectioned, the working surface was prepared by following a grinding and polishing procedure, working with increasingly finer grinding levels on a rotating lapping machine with water dripping onto the grinding surface for lubrication purposes. Initial polishing was performed using silicon carbide powder; this was followed by using3µm and 1µm diamond paste on a polishing plate. All these stages require the operator to hold the resin block onto the surface of the grinding/polishing plates and continuously move it around to ensure even removal of any scratches present (see Appendix 9 for more details/timings on all the grinding/polishing stages).

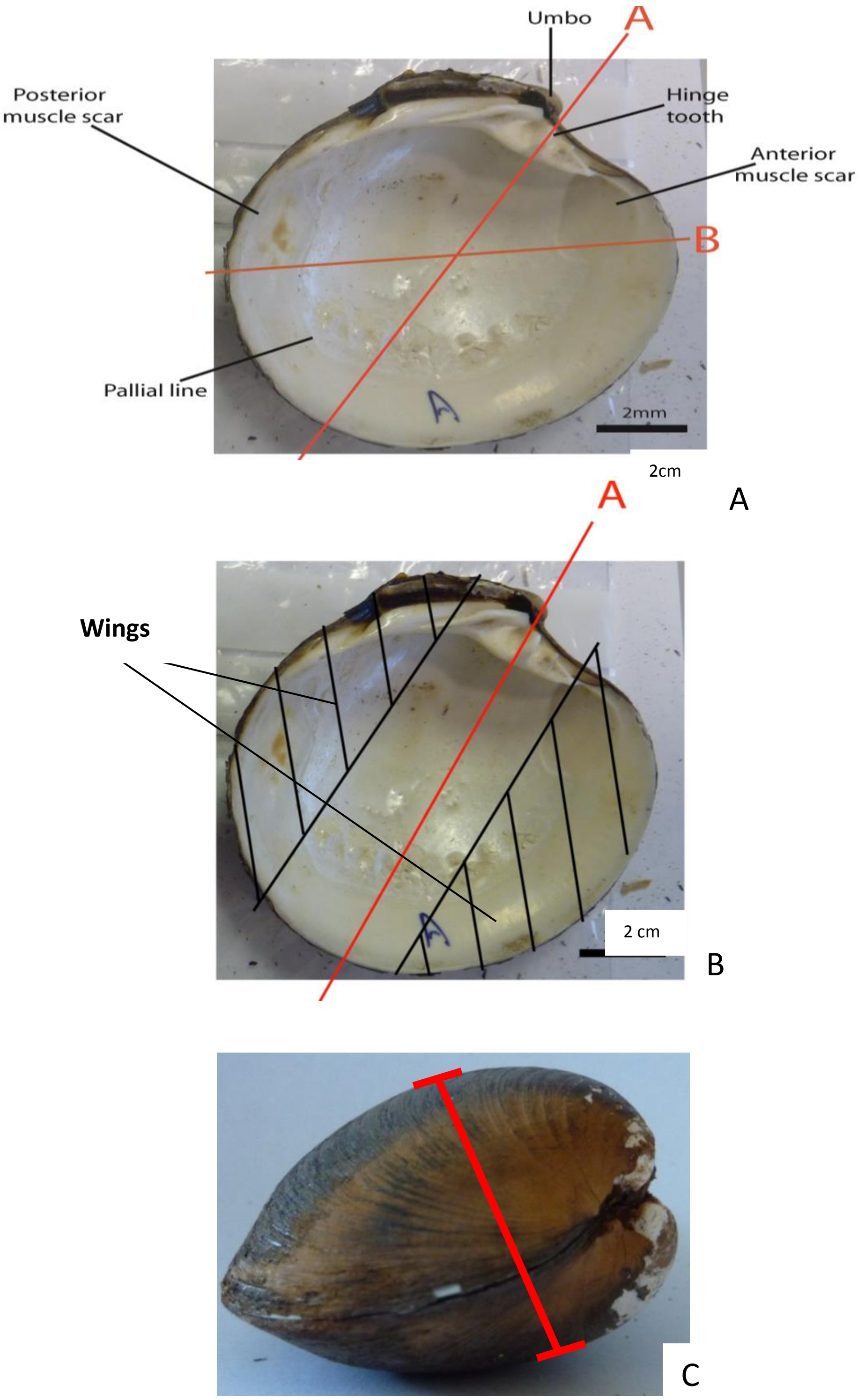


Figure 4.1: A) Left valve of *A. islandica* shell indicating the line of maximum growth/height (A), the line of maximum length (B) and the position of the pallial line, posterior and anterior muscle scars, the umbo and the hinge tooth. B) Image of shell indicating where the wings are cut off prior to being mounted in resin, indicated by black hatched off areas. C) Image of an *A. islandica* showing where width is measured (red line) on shell C7-L42 (width 36.9 mm). For those samples where only one valve was available for measurement the value was doubled to get the actual sample width.

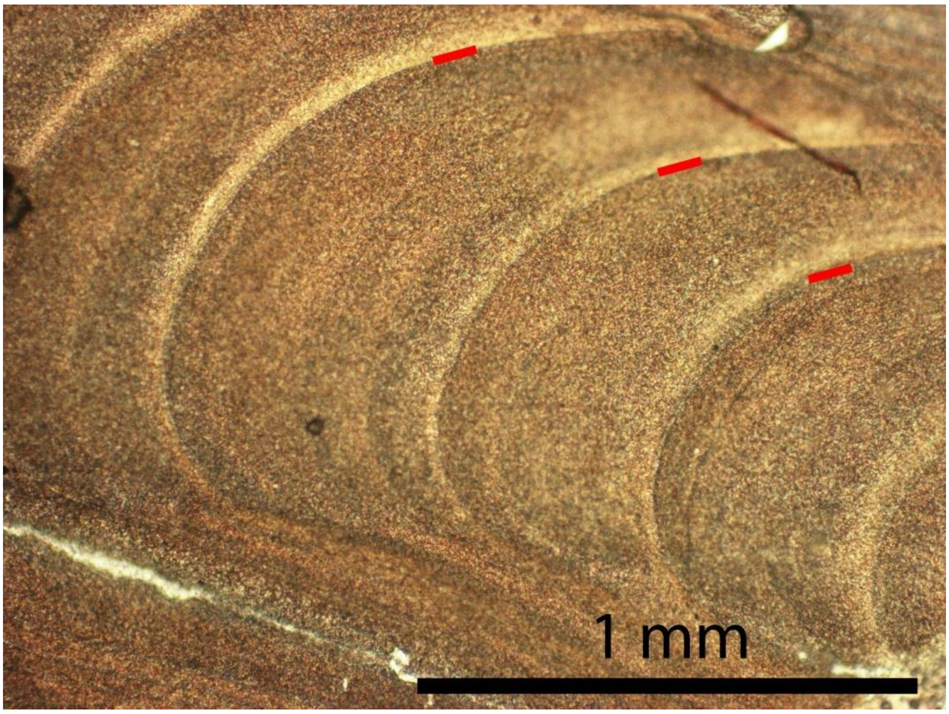


Figure 4.2: Image of a section of the umbo of a shell photographed under the microscope to illustrate a typical image analysed for measuring GIs. The red lines indicate the location of several GI lines.

Polished sections were then etched (Thompson et al., 1980) by submersion in a 1.5% Hydrochloric acid (HCl) solution for 1.5 minutes (based on previous testing, some of which is outlined in Daniels, 2010), rinsed in deionised water and left to dry under a fume hood. After the resin block dried, acetone was applied to the surface and then cellulose acetate placed on top. As the acetone dries out, the acetate ‘moulds’ itself to the relief of the etched surface. After an hour the process is complete and the acetate sheet can be removed carefully from the resin block. It is then trimmed to allow the peel to be mounted between a standard microscope slide (75x25x1.2 mm) and a coverglass (64x22 mm). When a peel was too large to fit onto a single slide, it was cut into two pieces and mounted on two different slides. Mounting peels between a slide and coverglass is undertaken as it reduces distortion (i.e. wrinkling) in the peel and improves the final image obtained when the peel is photographed.

4.2.3 Growth increment crossdating and measuring

Acetate peels were photographed using a digital camera paired with a microscope and stitched together in either Adobe Illustrator or Adobe Photoshop to create a composite from which GI widths were measured in the hinge plate/tooth (Figure 4.2 shows an example of a single photograph taken using this system). Before measuring GIs, crossdating was undertaken to try and ensure correct dating of the GIs, crossdating was not possible for many shells (see Table 4.3).

The concept of applying crossdating within sclerochronology is still relatively new (Marchitto et al.,2000; Helama et al.,2006; Scourse et al., 2006; Butler et al.,2009a; Stott et al.,2010; Brocas et al.,2013). Recently, the potential to cross match GI series for dead collected material has been demonstrated for North Sea *A. islandica*, where a floating chronology has been created for the period AD 1000-1400 by Scourse et al. (2006), who used radiocarbon dating to help constrain chronology dating and crossdated 3 shell series, whilst Butler et al. (2010) have successfully constructed a 489-year chronology from 30 shell series by cross matching both dead and live samples together for the Irish Sea, thus illustrating the potential of using shells to create long marine proxy records.

There are two commonly used methods for crossdating; skeleton plotting (see Stokes and Smiley, 1968 for more details) and the list method (see Yamaguchi, 1991 for a review). For the purposes of this study, the list method was used because it is known to be a robust method when crossdating living material. As robust dating using the list method was difficult to establish at times, all shell increments (for which readable peels were produced) were measured. Measurements were taken using the programme CooRecorder (version 7.1 – Larsson, 2008a). The programme CDendro (version 7.1 – Larsson, 2008b) was then used to graphically compare different growth time series, as well as to quantify the crossdating quality between series by using the Pearson’s correlation coefficient after the series have been high-pass filtered to remove the ontogenetic growth trends (see Section 1.3 and Equation 1.1 for more). If the crossdating is incorrect, then correlations will be weak and non-significant. Additional validation of the crossdating was carried out using the programme COFECHA which also uses cross-correlation analysis for assessing between series synchronisation (Grissino-Mayer, 2001). After these steps, only those shells showing robust within-site crossdating were used for the chronology construction step (Section 4.2.4).

4.2.3.1 Growth increment comparisons between the umbo and ventral margin

GI measurements can be undertaken in either the ventral margin or the umbo/tooth region of the shell. Generally, analysis of the GIs is carried out on the left-hand valve (illustrated in Figure 4.1A) of the shell (Ropes, 1987). Ideally GIs from both the ventral margin and the umbo should crossdate (Figure 4.3). Daniels (2010), using data from Stott et al. (2010) clearly illustrated this common growth signal between the ventral margin and the tooth (Figure 4.3).

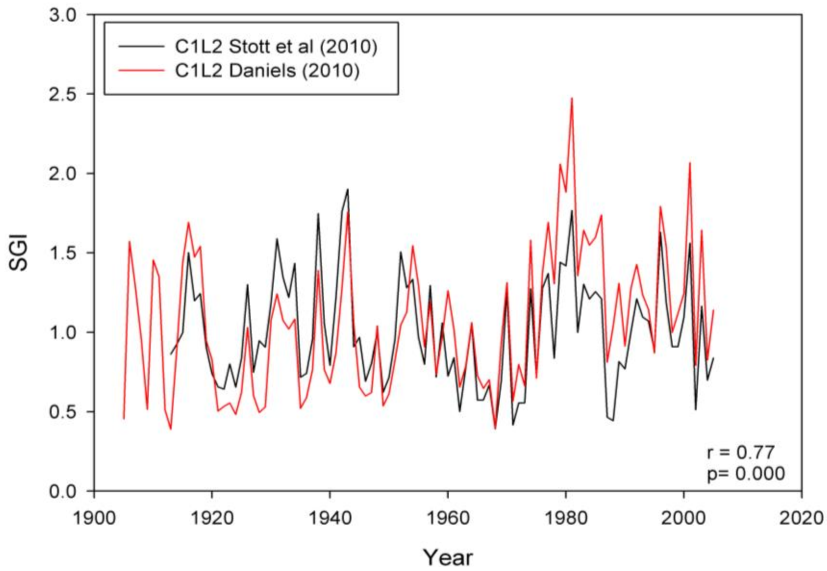


Figure 4.3: Two Standardised Growth Indexes (SGI) detrended series for shell C1-L2, one from the outer shell (Daniels, 2010 –red) and the other from the tooth (Stott et al., 2010 – black), the two series share a high visual coherence. The corresponding r and p-values between the two series (0.77 and 0.000 respectively) indicate that there is a common signal between the two SGI series.

However, it should be noted that the excellent crossdating between the inner and outer measurements illustrated in Figure 4.3 was a rare example of successful crossdating in shells studied by Daniels (2010) outlined in Table 4.1. To further the Daniels (2010) study an additional six shells (Table 4.2) were studied for this project and their umbo and ventral margin SGI measurements compared.

4.2.4 Chronology construction

Once crossdating had been carried out on the raw data, a site mean chronology was constructed. This procedure has multiple steps (Cook and Briffa, 1990). Firstly, the GI measurements were detrended to remove the ontogenetic growth trend present in the individual series (Figure 4.4). Detrending fits a series specific data adaptive function to the raw data using ordinary least squares and then removes the trend of this function using either division or subtraction. The result of this is a dimensionless index time-series with no age-related/ontogenetic trend. For this study the main method of detrending used was a negative exponential (NE) function (see Equation 4.1), or where this did not fit a linear function was used, using programme ARSTAN (Cook, 1985b). Division rather than subtraction was chosen as this helps stabilise the variance of the final series between the juvenile and more mature phases (Cook and Peters, 1997). For some series, detrending using the NE or linear function was not suitable as the fitted function went below zero resulting in indices greater than infinity. In these few situations a Hugershoff function (see Equation 4.2) was used (see Figure 4.4). A Hugershoff function was used as it is more flexible than the NE function and still retains some potential lower frequency information recorded in the growth records; as a result it is less likely to go below zero therefore minimising end effect index inflation. However, for very short series, as those seen in site C6, NE or Hugershoff functions are not appropriate (Figure 4.5) as the functions are essentially too 'stiff' for the short record and would go below zero. In these cases, a 10 year smoothing spline (Figure 4.5b) was used for detrending with the caveat that such a flexible option would remove any potential climatic information at time-scale longer than 5 years.

$$G_t = ae^{-bt} + k \qquad \text{Equation 4.1}$$

$$G_t = at^b e^{-gt} + k \qquad \text{Equation 4.2}$$

Where:

Gt is the growth trend of the raw data

a is the growth intercept of the function at year t

e is the exponential function

b is the decay constant

k is the positive asymptotic limit or function

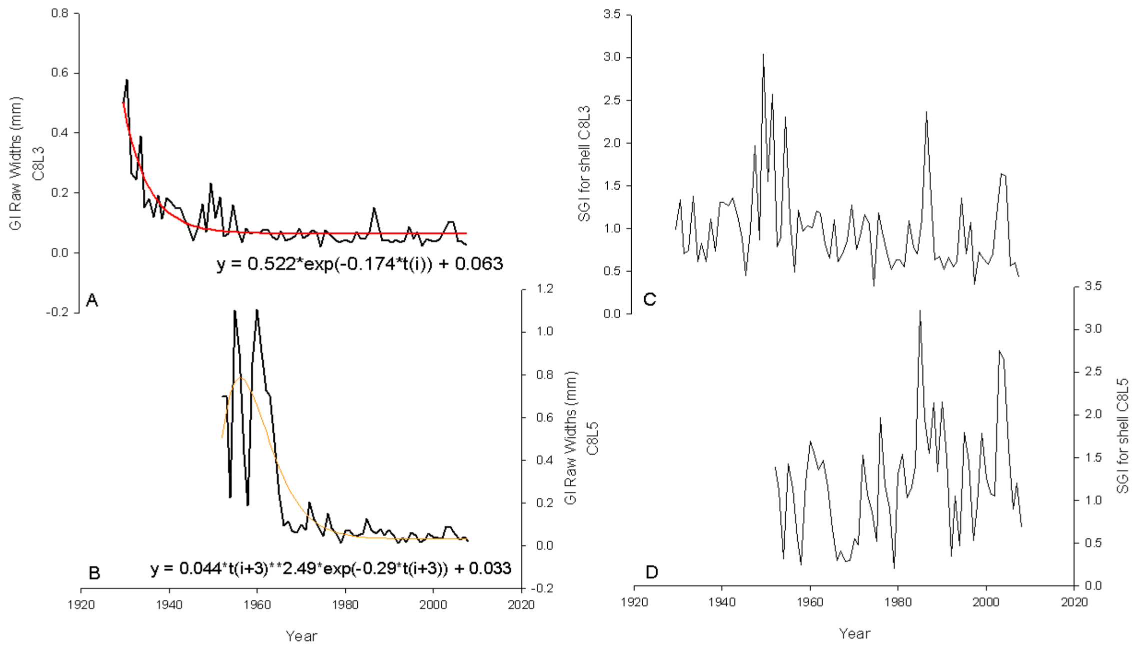


Figure 4.4: A) Graph illustrating the ontogenetic growth trend in the raw growth in *A. islandica* GIs and a typical negative exponential function detrending curve fitted to the data to remove this trend for shell C8-L3. B) Application of Hugershoff detrending to another *A. islandica* GI series. C and D illustrate the detrended SGI for each of the shells for shell C8-L5. C) Illustrates the detrended shell C8L3 series and D) shows the detrended series for shell C8L5.

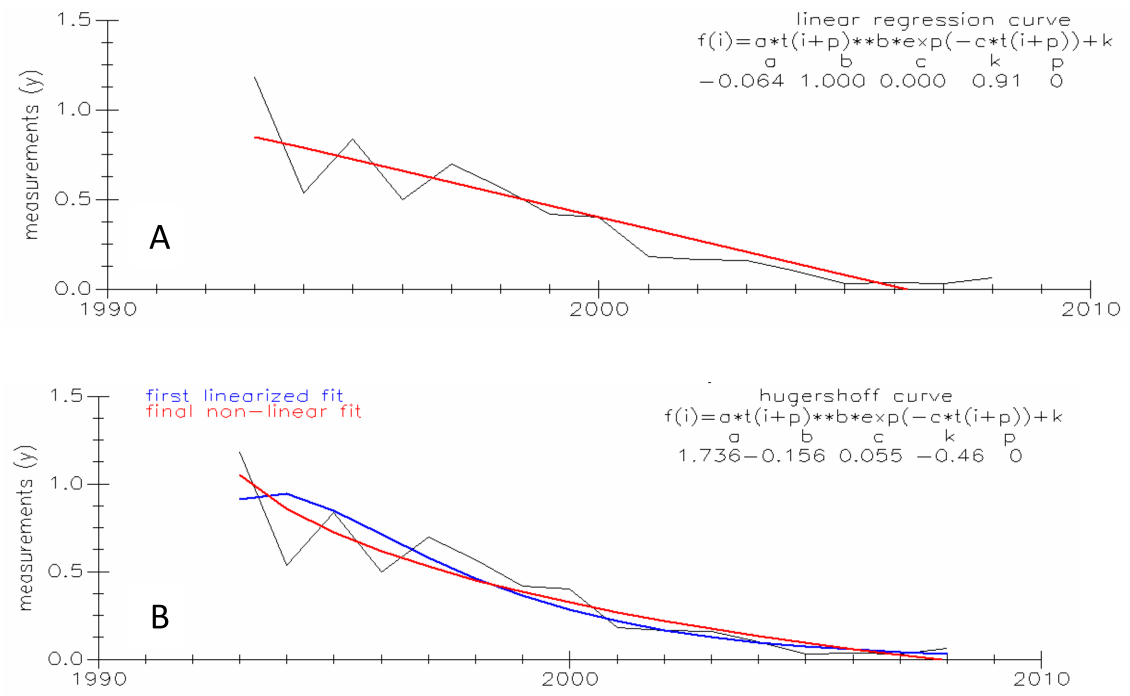


Figure 4.5: Examples of the application of A) a linear detrending function and B) a Hugershoff detrending function to the raw growth series for shell C6-L5 as seen in ARSTAN output when the functions go below zero and are therefore inappropriate for detrending.

The use of a NE function to detrend data is not new within sclerochronological literature. Strom et al. (2004), Strom et al. (2005) and Nielsen et al. (2008) used this method, but with different mollusc species, while Butler et al. (2009a; 2010) and Stott et al. (2010) applied NE function detrending to *A. islandica*. Witbaard et al. (2003) used a NE function to detrend *A. islandica* growth records, but this was in conjunction with a 66-year spline as a second processing step. Such a practice is also carried out by some dendrochronologists as it is believed that such a double detrending approach removes the juvenile growth and then secondly reduces the residual noise present within the record (Borgaonkar et al., 1999). However, such an approach also removes potential climatically driven long-term variability in the series. As the NE function both removes the ontogenetic growth trend and preserves the longer-term variability in the shell at frequencies up to the mean length of the samples (Cook et al., 1995), a double detrending approach is not used in this study.

Once the raw data have been detrended, the resulting individual index series are averaged together to derive a site specific mean index master chronology. The robustness of the mean chronology is related to both the number of series used and the strength of the common signal between them (measured by RBAR, where RBAR is defined here as the inter-series correlation between all possible pairs of time-series in the sample). The weaker the common signal, the greater the number of series needed to derive a robust mean chronology. It is common practice to use signal strength statistics in dendrochronology to assess the 'quality' of the resultant chronology. The seminal paper describing relevant signal strength statistics is that by Wigley et al. (1984) where the Expressed Population Signal (EPS) is derived. Essentially, the EPS can be thought of as an empirical assessment of how the average of a sample of time-series correlates with the theoretical infinitely replicated population time-series. The derivation of the EPS can be described as dividing the signal by the total variance (signal + noise). The EPS is calculated using the following equation:

$$EPS = \frac{n.\bar{r}}{n.\bar{r} + (1-\bar{r})} \approx \frac{signal}{total\ variance} \qquad \text{Equation 4.3}$$

Where EPS is the Expressed Population Statistic value

n is the number of time series

$\bar{r}$ is RBAR

Wigley et al. (1984) showed that an EPS value greater than 0.85 was desirable to ensure a robust mean chronology. The EPS equation (Equation 4.3) can be rearranged (see Wilson and Elling, 2004 for an applied example) to determine how many shell series would be needed to derive a robust chronology:

$$\hat{n} = \frac{(\bar{r}-1)EPS(x)}{\bar{r}(EPS(x)-1)}$$ Equation 4.4

Where EPS(x) is the 0.85 value suggested by Wigley et al. (1984) – although other values can be used

$\hat{n}$ is the predicted number of series required to produce a robust chronology

$\bar{r}$ is the inter-series correlation between the series in the master chronology.

As well as calculating the EPS, $\hat{n}$ and $\bar{r}$ values for all of the chronologies after they were detrended, the EPS value was also calculated once the series had been transformed using first differencing (FD) to provide a robust assessment of the inter-annual signal.

For the master chronology of each site, the EPS statistics for both the whole chronology (WC) period and period of maximum replication (PMR), i.e. the time frame for which all shells in a chronology are present, are detailed in Section 4.3.1. The RBAR for these periods are calculated and then these data are used to work out the theoretical number of shells required to reach an EPS value of 0.85 (n value as shown in Equation 4.3). Although not ideal, those chronologies where the EPS is below the required 0.85 value will still be compared to the instrumental datasets in Section 4.3.4 with the caveat that any results are purely preliminary and intended to be used only as a preliminary guide of how shells from different sites may be responding to different climatic and environmental conditions.

4.2.4.1 Inter site comparisons

If growth is dominated by regional influences (e.g. climate), then there should be a degree of common variability between the site chronologies. To determine whether there is a common signal between the sites, the chronologies (both unfiltered and FD) were compared using correlation analyses. The correlations were carried out with ±3 year lags to look for potential leads/lags between the series. While the outermost GI anchors the shell chronology to the time of 'live' collection, there can be difficulties in counting the outermost few GIs (see Section 4.2.2). This is because when creating a peel, the most recent GIs sometimes do not appear clearly on the image due to an edge effect where the shell and resin block meet. In addition, damage to the shell can cause the removal of GIs (although this is less common in the umbo compared to the outer shell).

4.2.5 Correlation Response Function Analysis (CRFA)

CRFA is a method to empirically test for relationships between shell growth chronologies and climate using correlation functions (Figures 4.14 and 4.15) and the two instrumental datasets (HadSST2 and CRUTEM3 – Chapter 3). Analyses were performed using both the unfiltered and transformed (FD) versions for the period of maximum replication (PMR). The exception to this is the site C6 chronology where the PMR is only five years, therefore analyse were undertaken over a longer period (1992 to 2007) which has six of the eight shells present in the chronology. The ideal correlation results would be ones which are consistent between the unfiltered and FD analyses, suggesting that any relationships found are consistent at all frequencies.

4.3 Results

4.3.1 Inner vs. ventral margin GI measurement comparisons

The additional material studied (Table 4.1) supports Daniels' (2010) findings with only two of the shells having reasonable strong correlations between the umbo and ventral margin measurements (C6L66 and C7L120).

Table 4.1: Correlation results between the umbo and ventral margin SGI data for five shells studied in Stott et al. (2010) and Daniels (2010) in rows 2 to 6 and the six site C7 shells analysed for this project in rows 7 to 12.

Shell ID number	Correlation between umbo and ventral margin SGI
C1L2	0.77
C1L4	0.009
C1L14	0.21
C1L17	0.25
C1L19	0.64
C6L66	0.895
C6L85	0.041
C7L14	0.094
C7L110	0.004
C7L120	0.444
C7L136	0.183

The combined results in Table 4.1 indicate a 36% success rate for crossdating SGI between the ventral margin and umbo of the 11 shells studied from sites C1, C6 and C7. Currently these are the only shells for which this information is available; part of the reason for this is that producing suitable peels for the ventral margin of shells is more difficult than for the umbo because the ventral margin portion of the peel is more likely to tear when being removed from the resin block.

Theoretically the GI measurements from the umbo and ventral margin should crossdate well, the results in Table 4.1 indicate a 36% success rate for shells studied from sites C1 and C7 with no clear reason for this low value. These results highlight a potential problem for any study that does not measure both the umbo and ventral margin GIs. It is therefore important that further work is undertaken into these relationships given that both areas of the shell GI record have been used in studies independently, but rarely are both presented in the same study.

4.3.2 Crossdating success rate

To better understand how many shells need to be collected and sampled to create a robust chronology, the success rates of crossdating individual series into the current site chronologies need to be considered, especially as this helps to explain the low replication in the final six site chronologies. These results are presented in Table 4.2.

Table 4.2: Cross processing and crossdating success rates for each site and an average result for all sites

Site	Shells Processed	Shells Measured/Analysed for age	Crossdated	Success Rate From Number of Shells Processed
C1	20	15	9	45%
C2	38	32	9	25%
C4	49	38	5	10.2%
C6	37	35	8	21.6%
C7	45	34	5	11.1%
C8	33	30	8	24.2%
All	222	184	44	19.8%

The results in Table 4.2 indicate a wide range of crossdating success rates between the sites. The reason that not all the processed shells were measured is because of poor peel quality. In some cases peels were constantly tearing when removed from the resin blocks, often with the acetate getting caught on the portion of the shell where it meets the resin block and a small gap occurs. However, it is not always possible to determine the cause for peel breakage. With other shells, although complete peels were produced, when they were investigated under the microscope, GIs were not clearly visible; therefore measurements could not be made. It should be noted that where there were peel quality issues, either due to tearing of the acetate or GIs being difficult to read, multiple peels were made to see if this improved the quality. This was done up to a maximum of four times, at which point if the peels were still not usable then analysis of that specimen was not pursued for chronology creation purposes.

The differences in crossdating success rates between the sites may also be linked to the other site specific parameters discussed in Chapter 2 (grain size, sediment water content and OC content, as well as local SST data discussed in Chapter 3). For example, Figure 2.9 indicates that site C1 has a distinct sediment make-up present compared to the other five sites and it has the highest crossdating success rate (see Chapter 7). However, for all the other sites there does not appear to be a clear relationship present between sediment type and crossdating success, as a result this apparent relationship for site C1 may be purely coincidental or, indirectly, related to other environmental variables.

Currently, there is a lack of published data concerning crossdating success rates in *A. islandica*. As a result, findings cannot be compared to those from elsewhere to see if the ranges found here are unusual or not. However, the sclerochronology group at the University of Bangor (School of Ocean Sciences) report crossdating success rates varying from 30 to 100%

depending on species and site, with *A. islandica* from shallower sites situated at the lower end of the range (Reynolds, pers. comm., 2012). It is therefore suggested that collating such information may be of use for determining which sites are better to target for sampling of *A. islandica*. There is also potential to use other annually-resolved bivalve species for climate reconstruction for Scottish marine waters as demonstrated in Reynolds (2011).

4.3.3 Shell growth chronologies

The growth chronologies for each site are presented in Figures 4.6 to 4.11. For each site the $\overline{r}$, EPS and $\hat{n}$ values for both the unfiltered and FD chronologies are also presented in these same figures. A regression line has been fit to each master growth chronology to see the overall trend in the data.

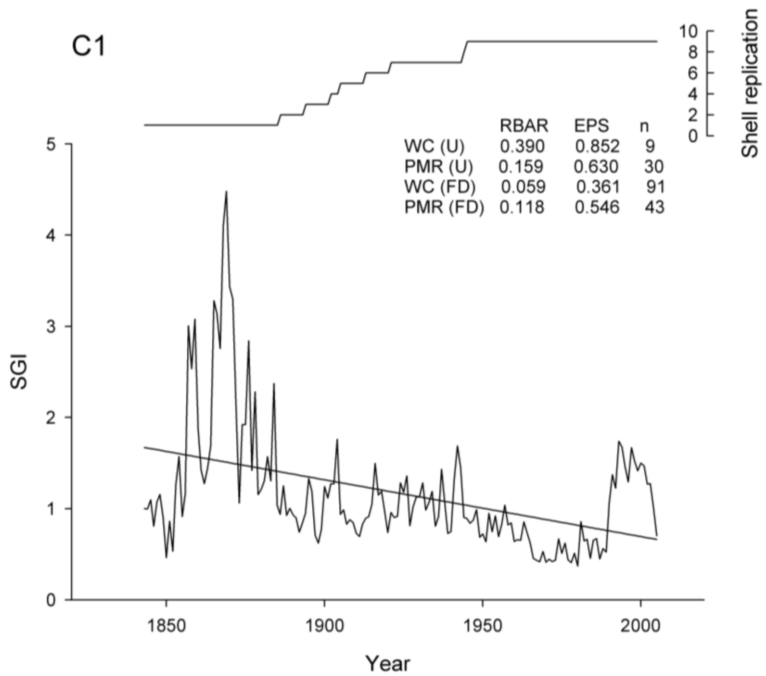


Figure 4.6: SGI chronology for the site C1 shell series. Also shown at the top of the graph is the level of replication throughout the chronology and the RBAR, EPS and n value (theoretical number of shells required to gain an EPS value ≥0.85) statistics for the Unfiltered (U) and FD chronologies for the whole chronology (WC) and period of maximum replication (PMR).

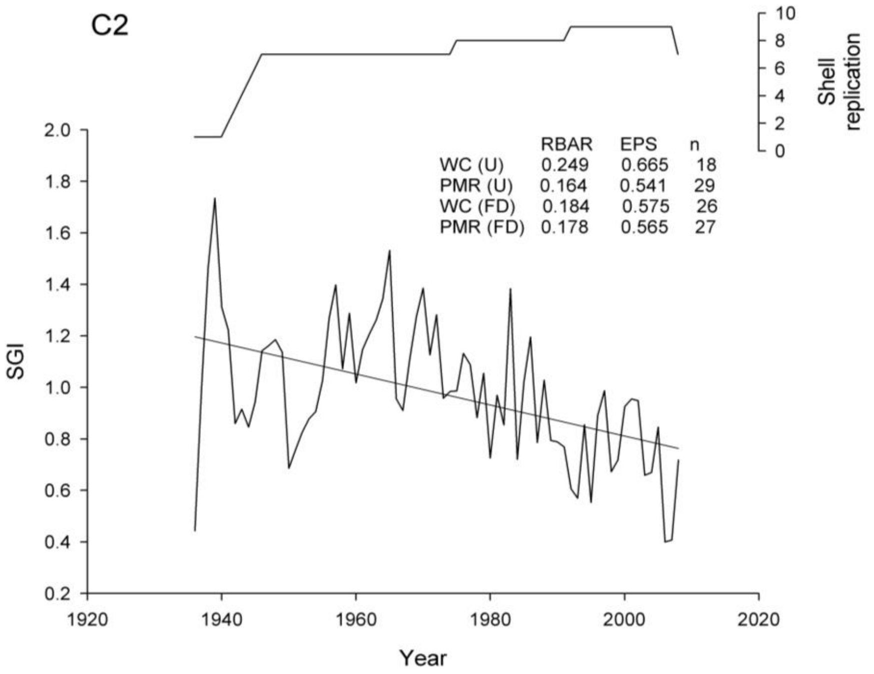


Figure 4.7: Same as for Figure 4.6 but for site C2.

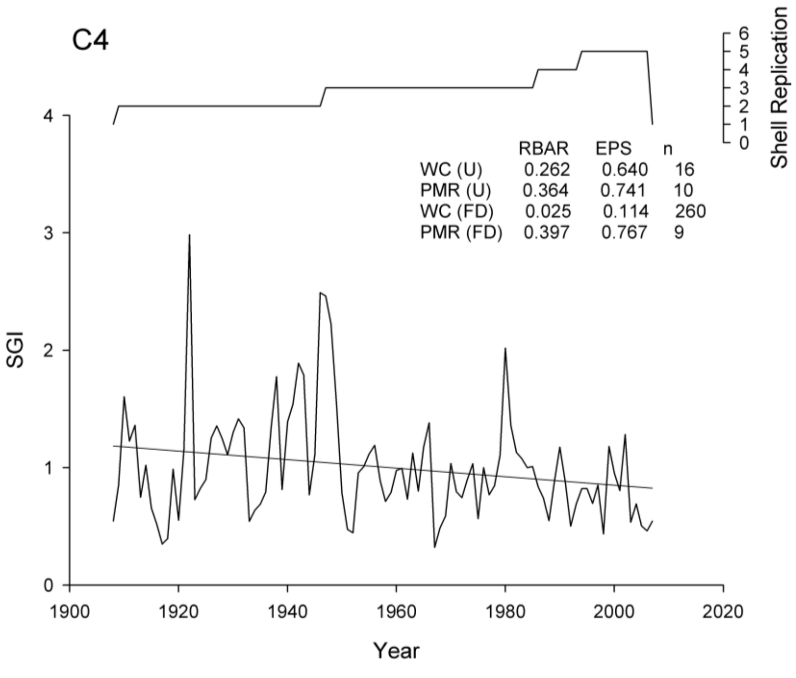


Figure 4.8: Same as for Figure 4.6 but for site C4.

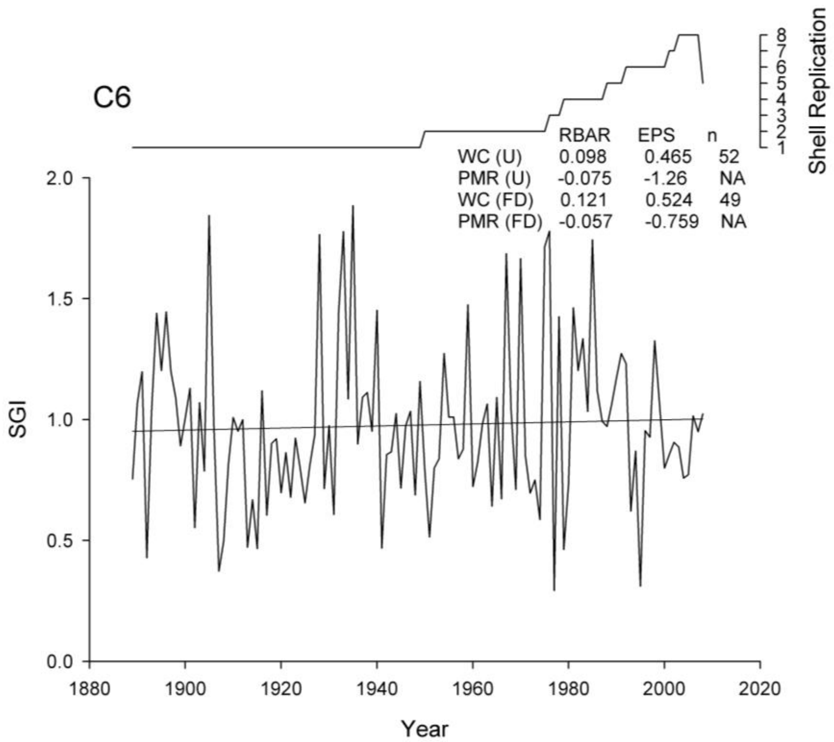


Figure 4.9: Same as for Figure 4.6 but for site C6.

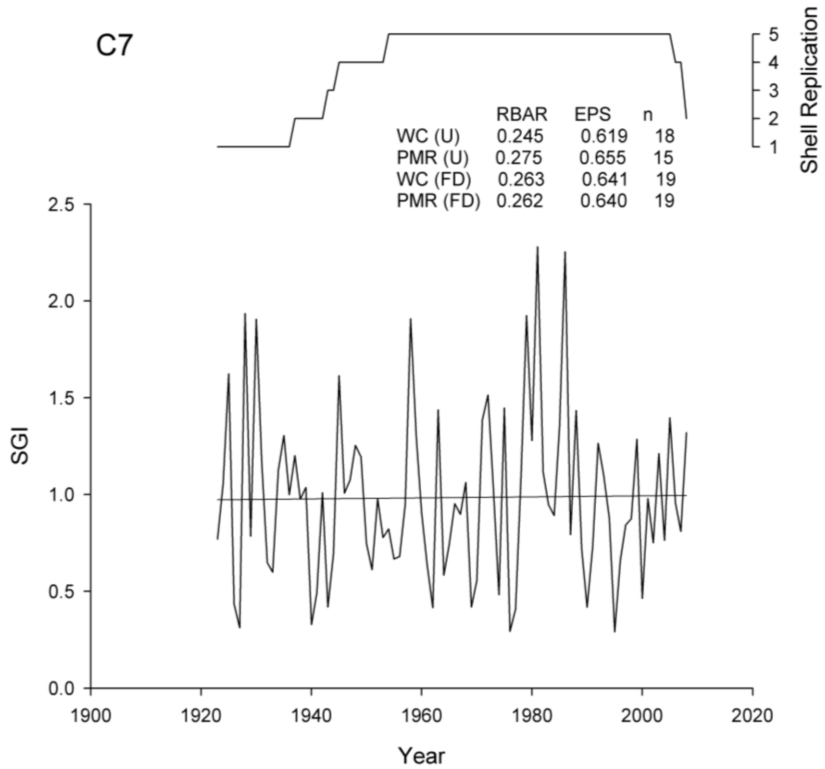


Figure 4.10: Same as for Figure 4.6 but for site C7.

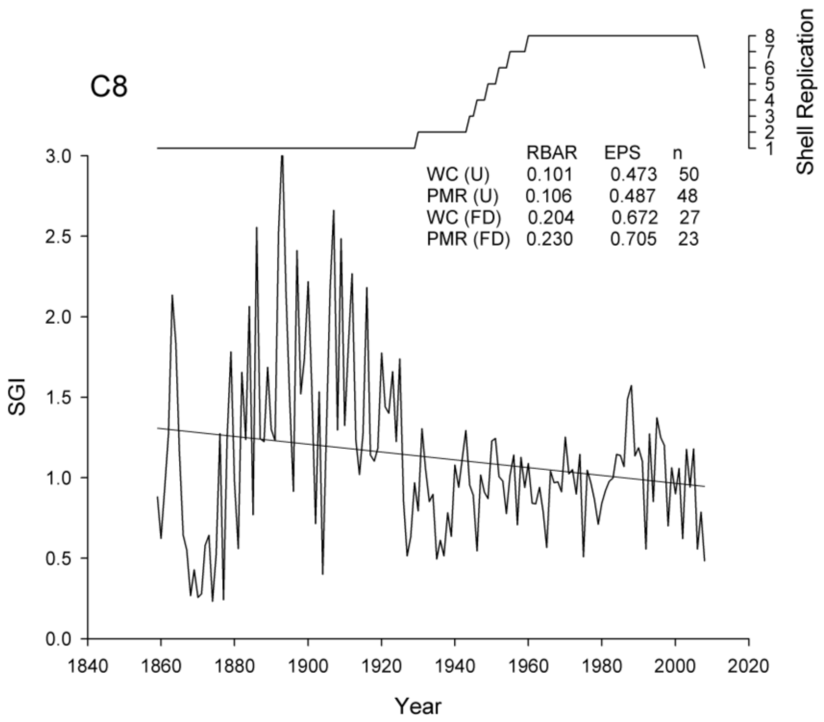


Figure 4.11: Same as for Figure 4.6 but for site C8.

The fact that in general the EPS values are weak and change between the unfiltered and filtered chronologies, WC and PMR, simply highlights the overall weak common signal in these data and the resultant sensitivity to subtle changes to the data.

When determining the number of shells that should be included within a chronology an EPS value of 0.85 (see Section 4.2.4) is recommended (Figures 4.6 to 4.11) and therefore caution must be advised in the interpretation of the current results. Firstly, this is because the RBAR values are derived from a very small number of series and so the resultant measure of coherence could change markedly as more data are added to the series. Secondly, the analyses only used series that crossdated; of all the shells sampled, only 19.8% were used in the final chronologies (see Section 4.3.2).

From the results presented in Figures 4.6 to 4.11 it is clear to see that none of the chronologies have an EPS of 0.85 or above for the period of maximum replication (PMR) and only C1 has the required EPS value when the whole chronology (WC) is examined (unfiltered). This means that when carrying out CRFA with the instrumental datasets (Section 4.3.4), none of the chronologies are theoretically robust enough (in how the sample expresses the theoretical population) for the results to be taken as more than simply preliminary indicators of the potential for shells to be used as proxies for marine climate change. At sites C1, C2 and C4 when the master chronologies are transformed (FD) for the WC, the n values required to reach an EPS of 0.85 increases, this is also the case for the PMR FD series at sites C1, C6 and C7, i.e. the inter-annual signal strength is weaker than for the decadal and longer-term signal. For those cases where the opposite occurs (WC – sites C6, C7 and C8; PMR – sites C2, C4 and C8) the results suggest that longer term (mid frequency) variability is potentially more coherent between individual series.

4.3.4 Inter-site comparisons

Cross correlation analysis was used to ascertain whether there is common covariation between shell growth in the unfiltered (Figure 4.12) and FD (Figure 4.13) site chronologies. As it was not known if the outer increment at the time of collection existed in the samples and therefore there is no guarantee that the internally cross dated chronologies were exactly calendar dated, this analyses was carried out with ±3 year lags between series. This approach therefore allows for some realistic movement based on potentially missing GIs in the outermost sections of the chronologies. Of interest here are only those correlations that are positive.

There are several chronologies that have the same lag suggested between the unfiltered and FD results (Figures 4.12 and 4.13). The most promising results are summarised in Table 4.3:

1) C6 and C7 where the 0 year lag indicates that for the period of analysis these two series are correctly dated in relation to each other,
2) C2 and C6 (-3), C2 and C7 (-3), C4 and C6 (-3), and C4 and C7 (-3); these results suggest that relative to C2 and C4 both C6 and C7 should be shifted back by 3 years.

Despite these promising findings there is a general lack of consistency in the results presented in Figures 4.12 and 4.13, suggesting that there may be some dating control issues with the shell chronologies being analysed, something that is not that surprising when the low EPS values are considered. As a result, no shifting of the chronologies will be applied to any of the chronologies related to data presented in Figures 4.12 and 4.13. For example, in Table 4.3, the results indicate that the C7 and C8 chronologies are both correctly dated in relation to the site C6 chronology, however when the C7 and C8 chronologies are compared the results indicate that relative to each other they are miss-dated by two years. The idea of dating control issues in sclerochronology is not unfamiliar (e.g. Butler, 2008), and is difficult to determine. In dendrochronology growth chronologies can be compared to the pre-existing online archives, such as the online International Tree-Ring Data Bank (ITRDB) depository, to verify dating. However, there are no such depositories currently available for similar analyses by the sclerochronological community (Butler, 2008); creating such datasets for sclerochronology would represent an important development within the field. However, it is important that there is a 100% certainty in the dating control of the chronologies used for these comparisons, otherwise, as with this thesis, there would be a situation where analyses is not really possible due to poor dating control in the chronologies being compared.

Table 4.3: Suggested lag chronologies consistent between U and FD series

Chronologies	Lag	Chronologies	Lag
C1 and C2	-1	**C4 and C6**	-3
C1 and C6	-1	**C4 and C7**	-3
C2 and C6	-3	**C6 and C7**	0
C2 and C7	-3	**C6 and C8**	0
C2 and C8	-1	**C7 and C8**	-2

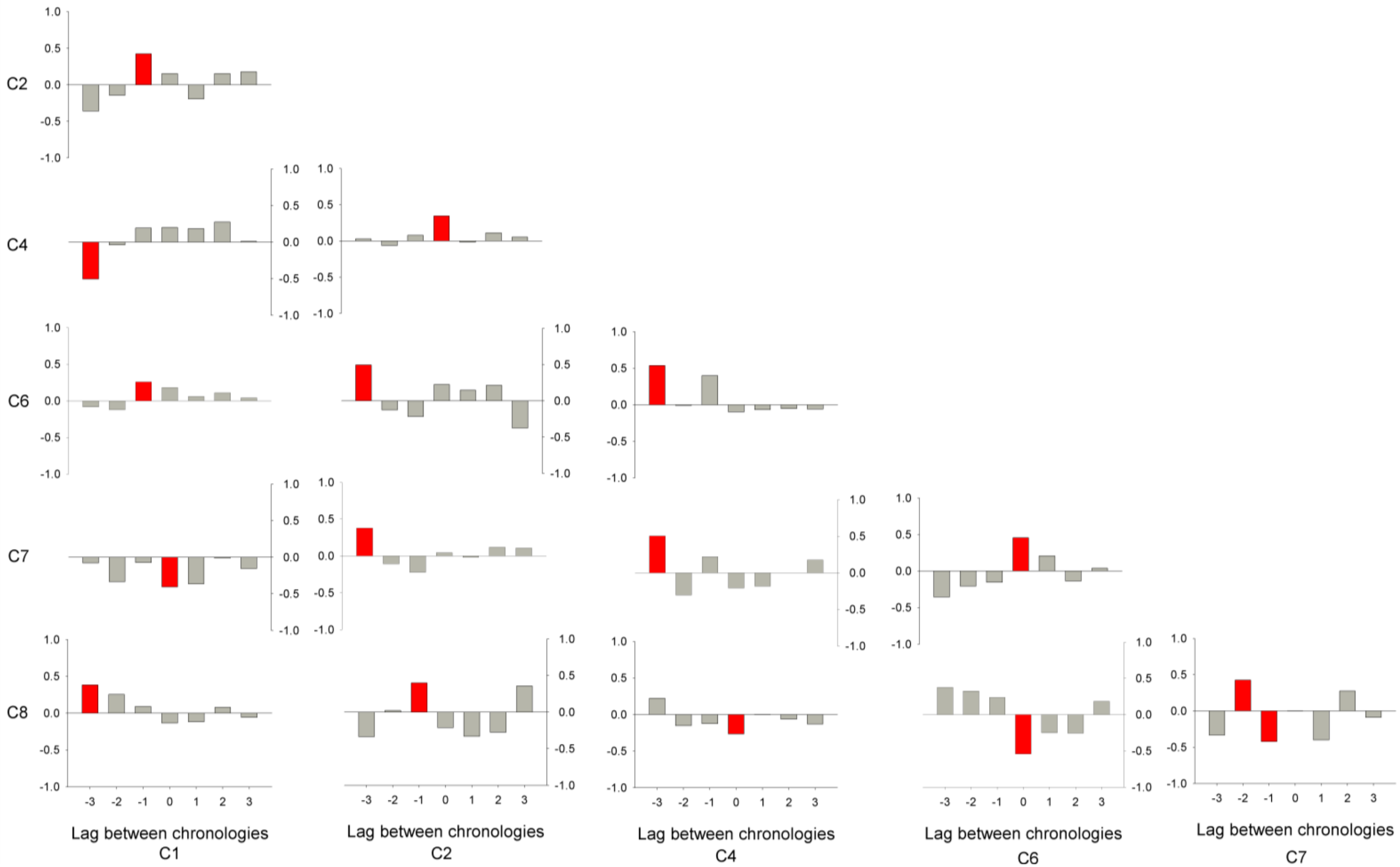


Figure 4.12: Inter-site correlation results for the unfiltered datasets. The red bars represent the highest correlation between the two chronologies being compared; of most interest are those correlations which are positive as this indicates that both chronologies are responding the same way to a common signal. Analysis is carried out over the period of maximum replication for all sites (1993 to 2005). The y-axis on each graph indicates the correlation coefficient for each analysis. NB for the C7 - C8 comparison there are two correlations highlighted using red due to these results being exactly the same numerical value except one is minus (-1 lag) and the other is positive (-2 lag).

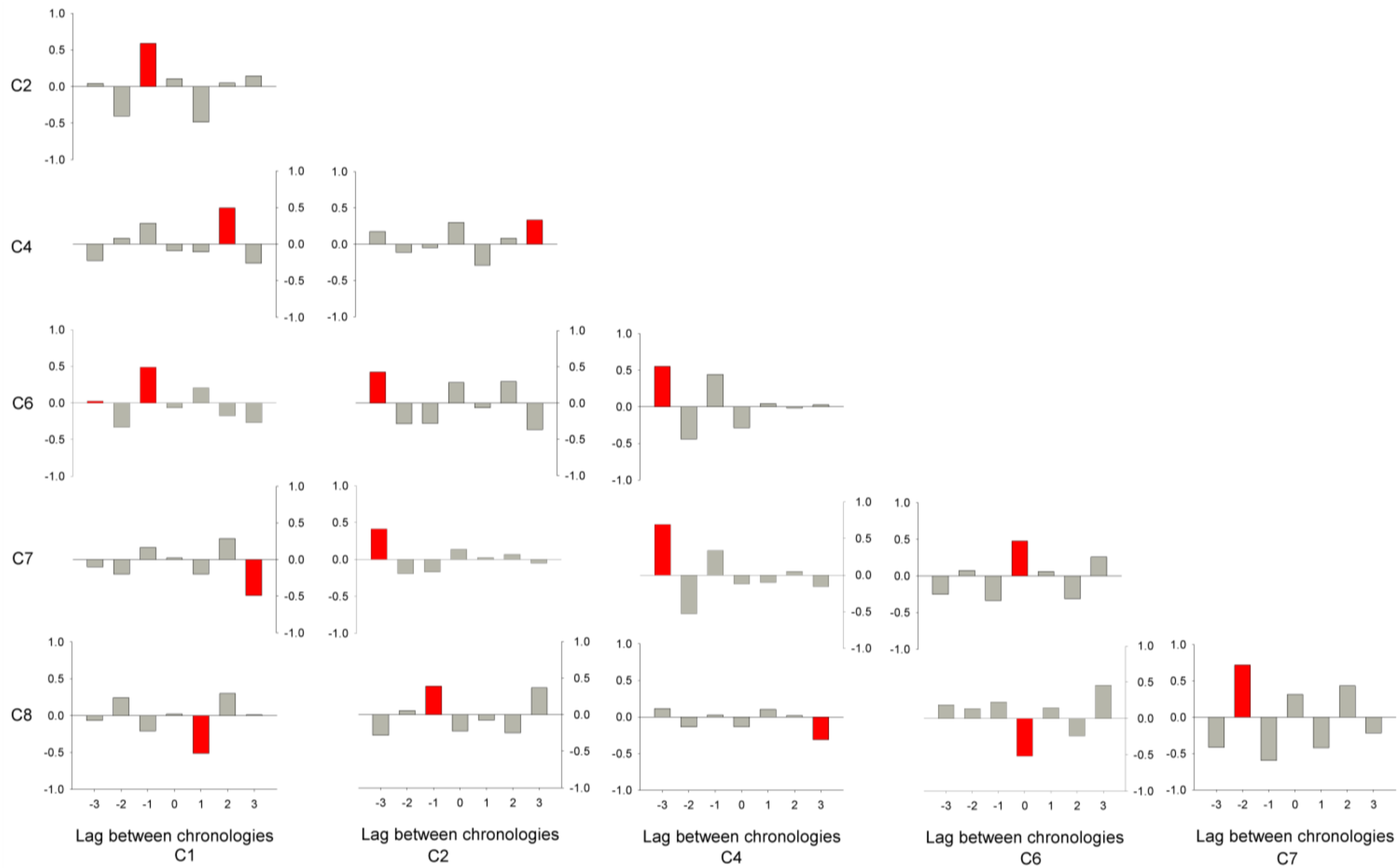


Figure 4.13: Inter-site correlation results for the FD datasets. The red bars represent the highest correlation between the two chronologies being compared; of most interest are those correlations which are positive as this indicates that both chronologies are responding the same way to a common signal. Analysis is carried out over the period of maximum replication for all sites (1994 to 2005). The y-axis on each graph indicates the correlation coefficient for each analysis.

4.3.5 Correlation Response Function Analysis (CRFA)

The CRFA results (Figure 4.14) between the growth chronologies and the gridded instrumental datasets for the period of maximum replication for each site are mainly weak and non-significant for all six sites. When the results for the six sites are compared (Figure 4.14) it is clear there are no consistent inter-site signals between correlation results. This, along with the weak signal strengths (refer to relevant tables/figures) and lack of significant inter-site correlations res (Section 4.4.3) strongly indicates that there is no common signal and that the environmental controls on growth are likely to be site-specific with climate being a weak factor at best. There are a range of anthropogenic factors in the region that are potentially influencing shell annual growth rates, thus dampening the influence of temperature. These anthropogenic factors are discussed in Section 4.6.2. To further investigate what factors may be causing the lack of a consistent inter-site signal both between the six master chronologies, and between the growth records and instrumental datasets, the RBAR and crossdating success results are compared to the site property data (e.g. OC content, sediment water content and grain size data) in Chapter 7.

The length of the PMR for the site C1 chronology (1945-2005 U and 1946-2005 FD) allowed for the assessment of the temporal stability of the signal by undertaking the CRFA over two independent periods. The results in Figure 4.15 indicate that the relationship between C1 and HadSST2 is not time stable.

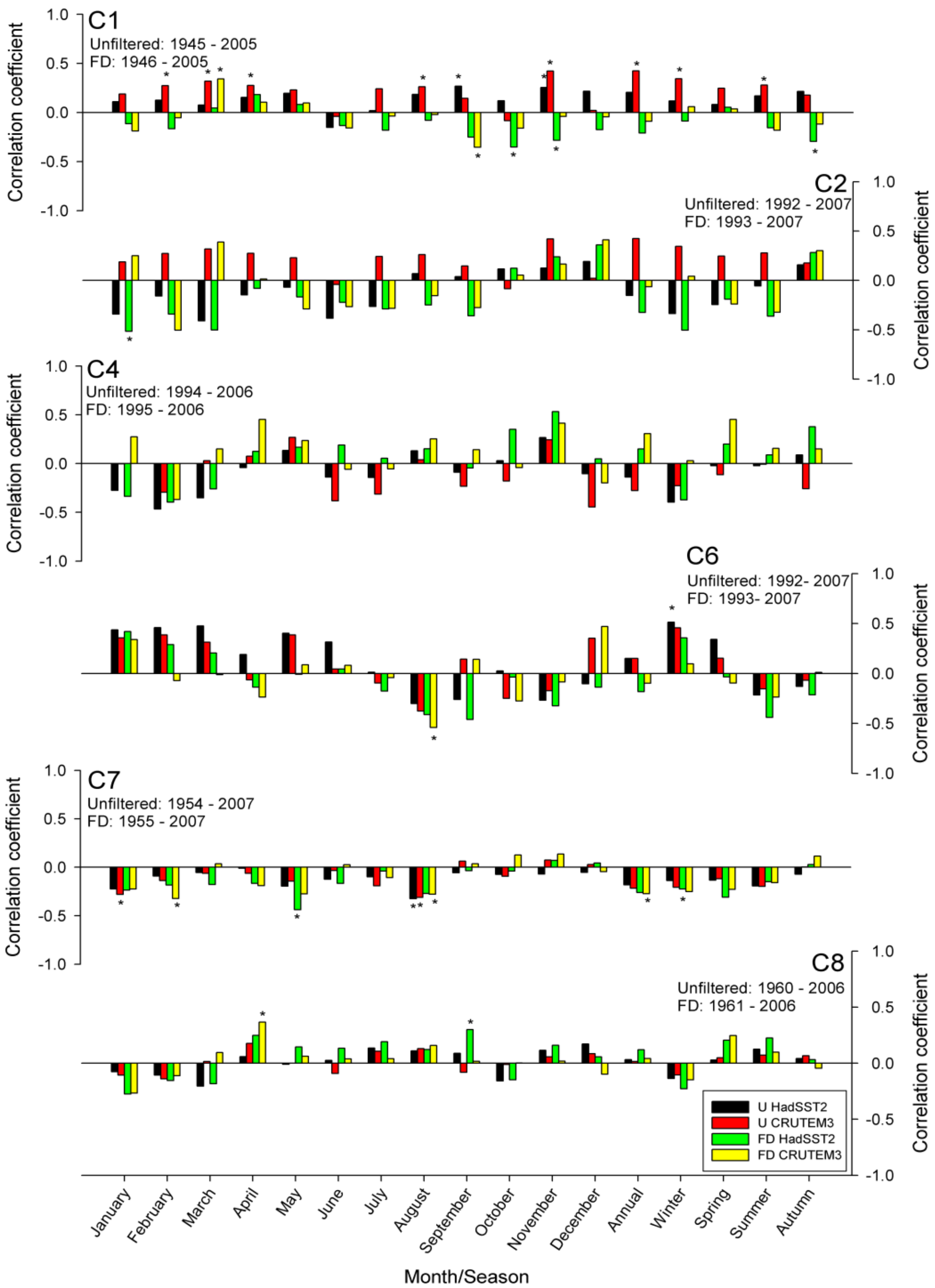


Figure 4.14: Correlation response analysis results between the six master chronologies and the HadSST2 and CRUTEM3 instrumental datasets (both unfiltered and FD). Periods of analysis area indicated in the figure. Those correlations that are statistically significant, at the 95% confidence level, are indicated with an * over the corresponding bar in the graph.

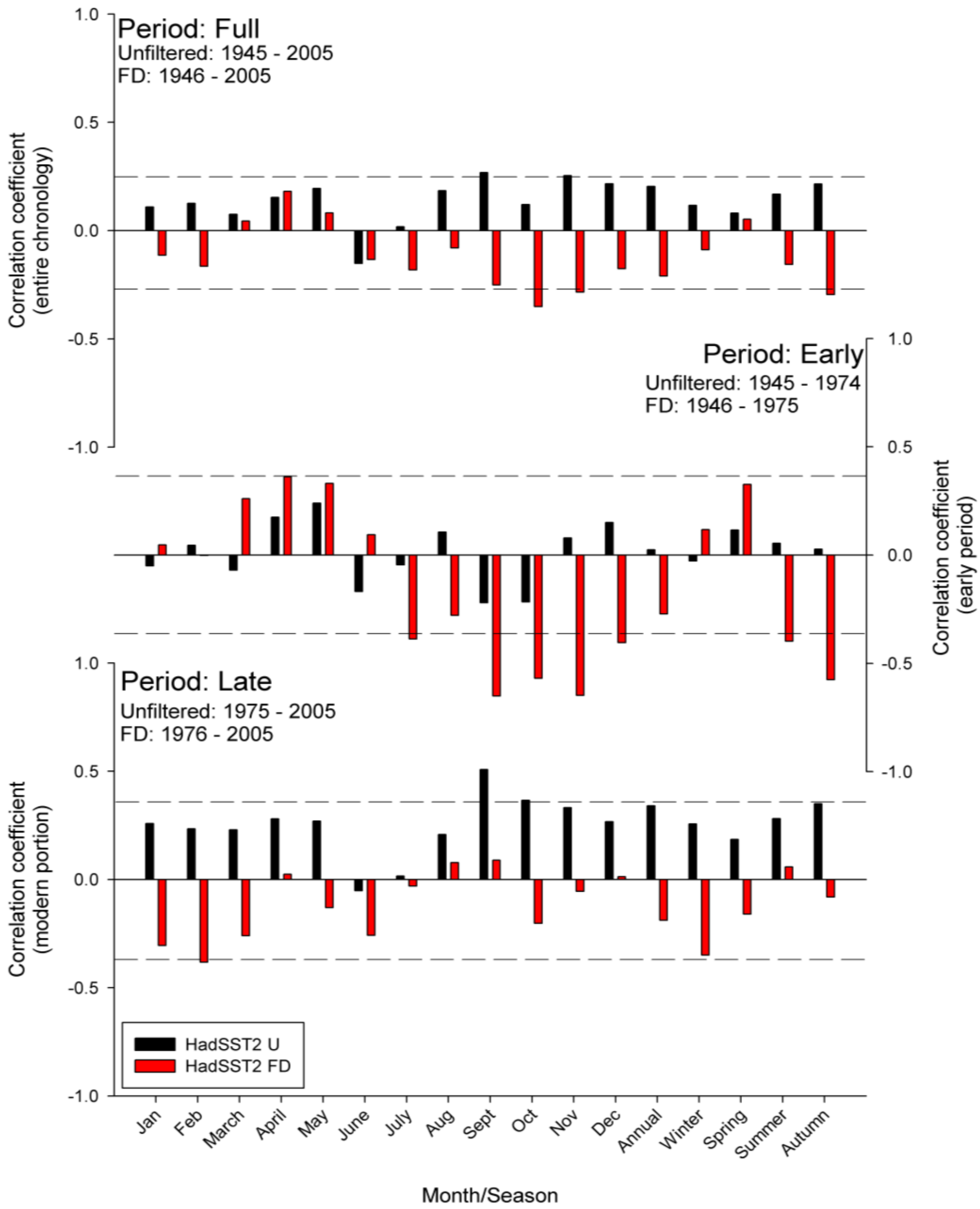


Figure 4.15: Graphs investigating the time-stability of the relationship between the C1 chronology and the HadSST2 instrumental dataset (both unfiltered and FD).

4.4 Discussion

The fact that the shell chronologies from this study do not show a common signal across the region (Figures 4.12 and 4.13) together with the overall weak common signal at each of the sites (Figures 4.6 to 4.12) may be due to hydrographical differences between the sites, the nature of the shallow water environments, site-specific conditions (e.g. sediment water content) and anthropogenic influences on the sites (e.g. fish farming). The lack of a clear common signal between the sites and the lack of any notable climate signal in any of the chronologies means that *A. islandica* may be of more use to study site specific changes, such as the influence of fish farming or local industry, on shell GI growth rates. However, until the EPS/replication values for all six site chronologies are improved it will not be possible to do this with any confidence.

4.4.1 Inner vs. ventral margin GI measurements

There are various reasons for the low correlations reported between the umbo and ventral margin measurements both for the Daniels (2010) study and this research including;

1) Peel quality difference between the ventral margin and umbo. For example, the ventral margin images of shells C6L85 and C7L14 were unfocussed in places which may account for the low correlation between the two measurement series for these samples.
2) The ventral margin is more prone to damage by predators and trawl fishing due to its life position (Figure 4.16), meaning that it is more likely to be damaged than the umbo. This may account for some of the differences in the umbo vs. ventral margin measurements recorded.

The potential damage to the ventral margin is one of the advantages of working in the umbo, although crossdating should help to remove the issue of missing bands. Another reason for using the tooth is that it is easier to work with – partly as there is less chance of damage to this portion of the shell. The compact nature of the GIs in this part of the shell allows processing using fewer photographs, thus speeding up the imaging part of the methodology. Although geochemical analyses can often be undertaken in the umbo due to improvements in technology, for this research, this was not done and for ^{14}C and $\delta^{13}C$ analysis the outer shell was used as there is the ability to get larger samples from this part of the shell. There are some differences of opinion in the literature as to whether to focus on the tooth GI or the outer margin (see Appendix 10).

Figure 4.16: Life position of *A. islandica*: *in situ* photographs of *A. islandica* shell courtesy of M. Sayer (NFSD), the first with it mainly closed, the second with both valves open – from these images it is clear to see that part of the shell is near the sediment surface and therefore prone to damage. Each image is approximately 12 cm across from left to right.

4.4.2 Chronology construction

Overall, these results suggest that replication at all the sites needs to be increased to improve the robustness of each chronology (see Figures 4.6 to 4.11). There are some potential issues concerning these chronologies and their construction:

(i) Although the increment data from C6 were mostly detrended using NE and Hugershoff functions, a 10 year smoothing spline was applied to those shells too young to be detrended using these methods (C6L5, C6L68) resulting in a bias towards the high frequency domain compared to the other site chronologies and the instrumental records. To overcome this all the chronologies could be created using the same detrending method to allow for consistency in the frequency domain. However, using a 10-year smoothing spline for all sites would mean none of the six chronologies would retain potential low and high frequency information in the same way as the NE function allows. It should also be noted that it may also be achievable to overcome such bias through the use of the Regional Curve Standardisation (RCS) method

(Mitchell, 1967; Briffa et al., 1992; Cook et al., 1995; Briffa et al., 1996; Esper et al., 2003; Briffa and Melvin, 2010) which applies a common age/size growth curve for detrending to all samples at a site (Cook et al., 2005). However for this to be viable sample replication must be much higher. Therefore, while this is not possible at this time, there is potential to apply this method in the future.

(ii) Another concern are the generally low number of shells successfully crossdated into each site's master chronology, and the low inter-series (RBAR) correlations observed. These implications are further developed in the next section (4.3.2). The causes of the inter-annual variability and its instability between shells at the same site may be attributed to anthropogenic influences or possibly site heterogeneity.

Further discussion of how site differences may influence shell growth are detailed in Chapter 7.

4.4.3 Site Chronologies

Site C1 has two unusual features, making its chronology stand out from the rest of the records (Figures 4.6 to 4.11). The first is the inflated growth indices in the early portion of the chronology (1843 to the 1890s); this is likely an apparent inflation of the index values as the result of an imperfect fit of the NE function to the one shell present in the series at this point (C1-L4). This bias can be minimised by increasing shell replication in this period and is in fact of no particular concern for this study as this portion of the record is not utilised for analysis. A more flexible detrending function (e.g. a spline) would also lower these higher index values. A similar pattern of apparently inflated annual growth rates is also seen in the C8 master chronology which has an unusually high peak present in the early portion of the chronology. This may also be due to the poor fit of the detrending curves along with low replication during this time frame. To determine if the high peaks do truly represent periods of higher mean annual growth rates, replication in the earlier chronology portion must be increased. To further illustrate this, all the individual detrended series for each site are presented in Appendix 13.

The second unusual feature in the C1 chronology is the suppressed period of growth in the 1940s to 1980s, followed by a period of release. The reasons behind the lower annual growth rates in the 1940s to 1980s are not clearly known, particularly as there appears to be no direct link to climate; the potential anthropogenic influences on shell growth at the six sites requires careful investigation.

4.4.3.1 Inter-site comparisons

Butler et al. (2009b), using five North Sea sites (115 m to 150 m deep) investigating the presence of a common signal between sites, found a coherent signal between sites which were up to 80 km apart. This is in contrast to the results presented here where there is no clear common signal between the six fjordic sites over significantly shorter distances. It is feasible that the North Sea results reflect a more stable/homogenous water mass system than those in the fjords being studied and therefore would be more likely to record a clearer climate signal than in the sea lochs. The deeper water at the North Sea sites may therefore have a bearing on the different outcomes recorded. Other researchers have also found common signals between sites some distance apart; for example Witbaard et al. (1997b) found a common signal between two North Sea chronologies 75 km apart for the earliest part of the records, although in the 1960s onwards the two chronologies become inversely correlated. Marchitto et al. (2000) carried out research into how the correlations between shell growth series differ over increasing distances in Georges Bank (NW Atlantic Ocean). They found an overall decrease in correlation the greater the distance between sites, indicating that even where the water masses between sites are very similar, *A. islandica* do not always show the same common climate signal. However, as climate changes spatially, this is not entirely unexpected.

The potential to use *A. islandica* chronologies from different geographical locations is important as it allows samples from many kilometres apart to be used to provide an insight into climate change on a larger spatial scale (Butler et al., 2009b) (Figure 1.8 shows where *A. islandica* are found around the North Atlantic). Butler et al. (2009b) suggest that multiple sites from across different stratification depths may be able to provide information of past changes in stratification. In fjords studying multiple sites may be of use for identifying when anthropogenic activity, such as pollution or organic enrichment, began to impact on the environment. This, however, is only achievable if the chronologies have robust dating control.

4.4.4 Anthropogenic Influences

When considering anthropogenic controls that may influence shell annual growth rates, there are several main factors that must be considered; these are outlined in Figure 4.17 and Table 4.4. At site C1 there is little evidence of any human influence on growth during the period of increased growth starting in the late 1980s when the factors outlined in Table 4.4 and Figure 4.18 are considered. Possibly the only factor which fits with respect to timing and location is the Baracaldine alginates factory which has been operating since the 1940s and reaching peak productivity in the 1970s (Black et al., 2000). The factory was responsible for the discharge of alkaline liquid whey, formaldehyde and organic particles into the surrounding area (Black et al., 2000). The toxic nature of this discharge could very well have had a negative effect on *A. islandica* GI growth rates, especially as it has already been shown that historical discharge from the factory had resulted in a lack of *Serpulid* reefs along 1 km of the coastline around the factory (Moore, 1996). This evidence, coupled with the suppressed period of growth in the C1 chronology, suggests that discharge over the years has directly acted to cause this suppressed period at C1. To fully investigate these effects it would be necessary to extend the length of the site C2 master chronology to determine if there is a similar impact on annual growth rates at the site. Something else that must be considered when investigating site C1 is that out of the six sampling locations, this is the one that would probably be most influenced by water from the North Atlantic due to its location (Figure 2.1).

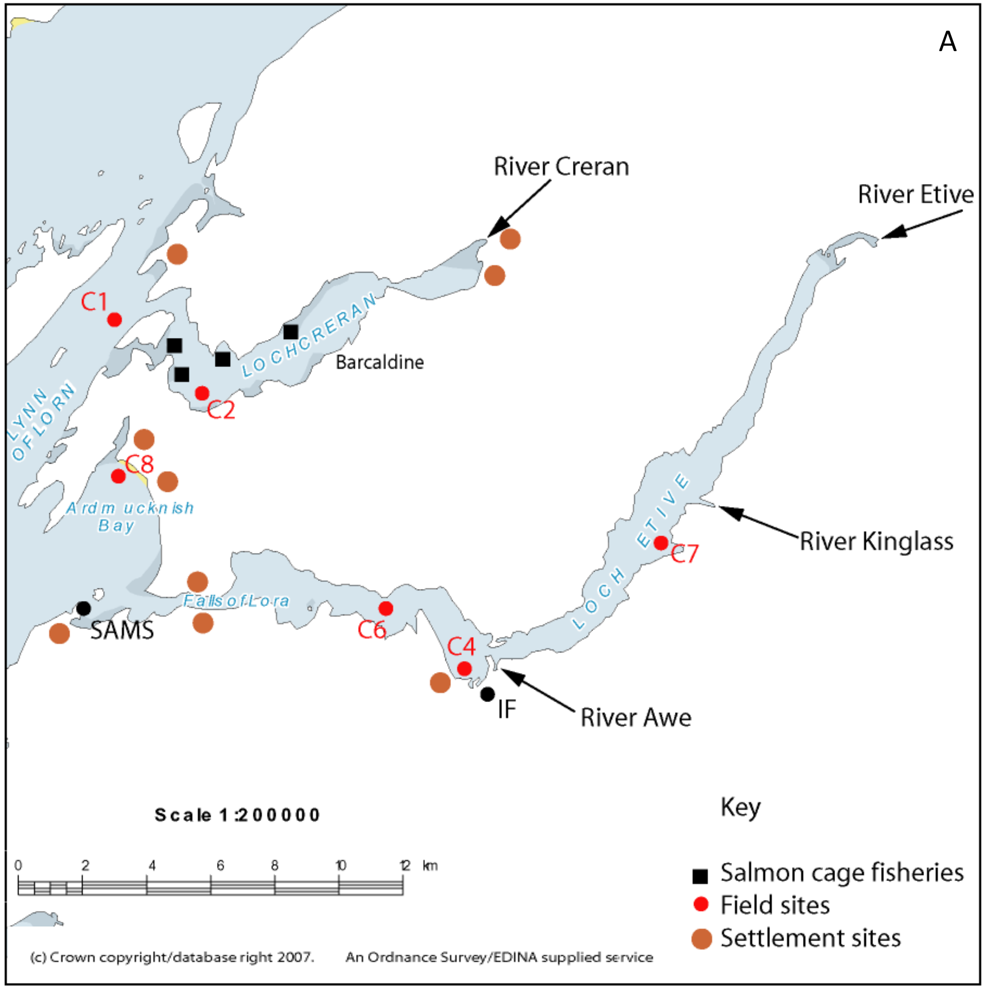


Figure 4.17 (Continues on next page): A) Map illustrating the location of local anthropogenic sites which may influence shell growth rates. Salmon cage (black square) information from Moore (1996). IF denotes the location of the Iron Furnace and Baracaldine shows the location of the alginates factory. Also shown are the points at which the Rivers Awe, Etive, Kinglass and Creran enter the lochs, and the location of substantial human settlements. B) More detailed land use map for Loch Etive is shown in the bottom panel (Generated from data in the Loch Etive Integrated Coastal Zone Management Plan, 2011a, b, c, d, e, f).

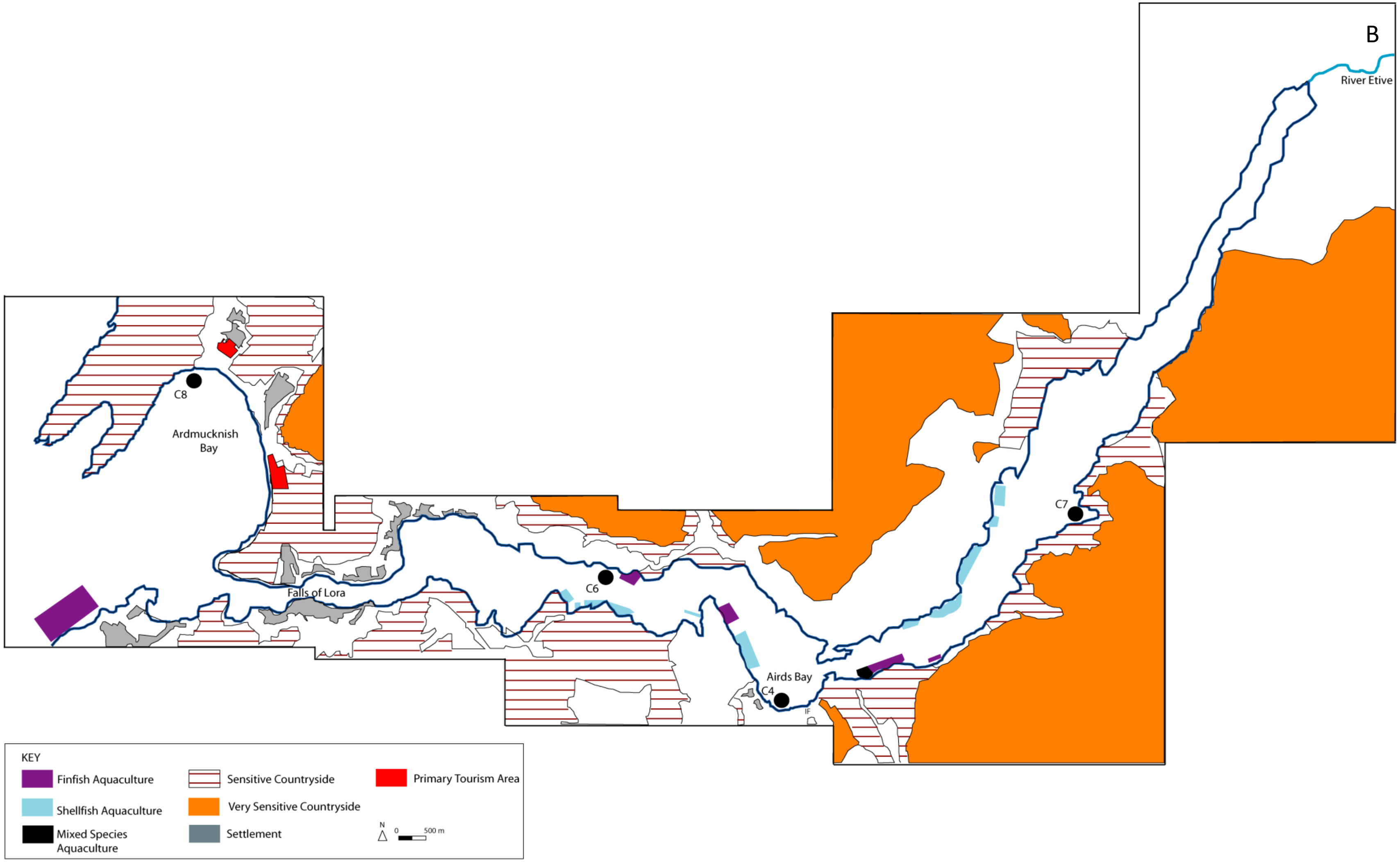

B
River Etive
C7
Airds Bay
C4
IF
C6
Falls of Lora
C8
Ardmucknish Bay
KEY
Finfish Aquaculture
Shellfish Aquaculture
Mixed Species Aquaculture
Sensitive Countryside
Very Sensitive Countryside
Settlement
Primary Tourism Area
N
0
500 m

Table 4.4: Anthropogenic activity in the local area

Anthropogenic factor	Influences
Fish Farming	1) Fish farming was introduced in Loch Creran in the 1970s by Golden Sea Produce (Black et al., 2000), with alternating sites being used. Oysters have been fished in Loch Creran since 1990 with three oyster farms present within the loch, and two mussel farms are also present (Donovan, 2006). Research by Chamberlain et al. (2001) indicated that mussel farms can lead to organic enrichment in the area beneath the farm due to faeces and pseudofaces, which may cause macrofaunal abundance to be reduced. However, their research indicated this is not the case for all mussel farms, but this may also be a contributing factor in altering shell annual growth rates. 2) In Loch Etive, as of June 2010, there were five finfish farm sites operated by Dawnfresh which are used in rotation, producing approximately 1,500 tonnes p.a. of trout in 2009 (Argyll and Bute, 2011). Loch Etive is ideal for use by Dawnfresh for trout fisheries due to the brackish nature of the site (Argyll and Bute, 2011).
Bonawe Iron Furnace (IF – Figure 4.17)	In 1753 an iron furnace was in place at Bonawe due to the abundance of woodland in the area for charcoal production and water for power, it was closed in 1876 (Scotland, 2010) and is now a tourist attraction maintained by Historic Scotland. Such production rates are bound to have had a significant impact on the woodland in the area during the time the furnace was in use. The iron furnace also had an impact on forestry in the area: in 1789 Glasdrum Woods were sold to the Lorn Furnace company who cleared the wood for converting into charcoal. This area is now a NNR and is run by the SNH (Donovan, 2006). In the mid-1700s Glasdrum was being used for black Highland cattle grazing (Taylor and SNH, 2004) and in 1833 there were 600 sheep being grazed on Glasdrum, which increased during the second world war and during the 1950s and 1960s (SNH, 2005).
Alginates factory (Baracaldine – Figure 4.17)	Since the early 1940s there has been an alginates factory at Baracaldine (Figure 4.18)which was still in operation in 2000, seeing peak productivity in the 1970s (Black et al., 2000). This factory was responsible for the discharge of alkaline liquid whey, formaldehyde and organic particles into the area surrounding it (Black et al., 2000).

The post 1980s increase in GI growth rates at C1 may reflect a return to ‘normal’ annual growth rates after the period of lower growth rates preceding this increase in GI widths. However, it is also possible that it is due to an increase in nutrient loading at the site as a result of the onset of fish farming in the region during the 1970s. Since the 1970s the commercialisation of farmed salmon, trout, shellfish and oysters has taken place in the field area as a whole with fish farms present in both Loch Etive and Loch Creran. Figure 4.19 shows the main fish farming locations in the area relative to the sample sites and other anthropogenic sites of interest. It is common practice in aquaculture to attempt to minimise the effects of fish farms on the local environment by rotating sites, as this should help reduce the enhancement of oxygen uptake in sediment below fish farms, as well as higher nutrient fluxes (as seen by Nickell et al. (2003) at some sites). However, research by Pereira et al. (2004) indicated that nutrients deposited by fish farms do stay in the fjord environment for up to 15 months, and so they may have an influence on nutrient availability downstream of the farming areas. With the exception of site C7, all sites are downstream of fish farms (although it must be noted that there is a shellfish aquaculture site near C7). Therefore, while an increase in nutrient availability in the fjords due to fish farming may be causing the annual growth rates to be higher in the most recent part of the C1 chronology, it is unusual that this effect is not seen at any of the other sites also downstream of the fish farming activities. It is of course feasible that site C1 receives more of the nutrients entering the waters by the farming activities for some reason. Alternatively, it is more likely that the nutrients are influencing GI growth rates at all of the sites, however due to the suppressed growth period prior to the onset of fish farming the effects of nutrient loading may have had a more pronounced impact on the site C1 chronology.

To test whether any anthropogenic factors (especially those outlined in Figure 4.17 and Table 4.3) have any influence on GI widths, it is important to test the hypothesis that anthropogenic disturbances are behind the differences seen in the six GI chronologies (Figures 4.6 to 4.11). To do this a "clean" site, clear of anthropogenic factors need to be used as a control site – site C7 is the best candidate. If anthropogenic factors are indeed influencing annual growth rates at other sites then it would be expected that the common signal at this site would be the strongest, which may be seen by a higher crossdating success rate at the site compared to sites C1, C2, C4, C6 and C8. However, this is not the case, with the highest success rate being recorded at site C1 (Table 4.2).

It is possible that the C1 chronology may actually have a higher crossdating success rate due to non-climatic environmental forcing influencing the shells; e.g. fish farming influencing GI growth rates at the site almost simultaneously creating a stronger common GI width signal. In addition to this there is the added complication that C7 has very different site conditions compared to the other sites including significantly different sediment OC content (Figure 2.5) (at the 95% level) and the lowest average grain size mode, which may influence the poor crossdating at the site. As a result it is currently very difficult to determine with any certainty whether anthropogenic activity is causing the lack of common signal between the six growth chronologies. However, the similar timings between the start of fish farming and the sudden change in GI widths at site C1 means it is possible that anthropogenic factors, possibly coupled with site-specific conditions (e.g. sediment grain size and OC content), are influencing shell annual growth rates. To fully test this it would be necessary to undertake further analysis. Ideally this should be undertaken on specimens from a variety of other site conditions both with and without anthropogenic influences acting on the site. It is however suggested that future work to investigate the potential of *A. islandica* from Scotland for reconstructing past climate is that sampling is undertaken at deeper sites away from possible sources of anthropogenic pollution/influence.

At present it is difficult to fully explore the impact of anthropogenic influences on shell GI growth rates as the experimental design was never set up to test this – the primary research objective being to investigate annual shell growth rates at six sites and see how this relates to climate. The results presented in this chapter indicate that there is not a common inter-site growth signal, or a common response to climatic. Therefore, it is important to try and understand what may be causing these results, with one potential influence being anthropogenic activity. As a result it is only possible to speculate on the influence of anthropogenic activity and additional sampling would be required to further investigate this.

4.4.5 Site Conditions

Epplé et al. (2006) noted low inter-series correlations between mollusc shells sampled from shallow marine settings (15-20 m deep) in the inner German Bight (North Sea). This apparent lack of synchronicity was attributed by the authors to the conditions in which the shells had grown. Factors such as tidal movements, salinity fluctuations, temperature fluctuations and turbidity, which are more prominent in a shallow, coastal water environment, were some of the reasons suggested for a lack of common signal between the shells. It is likely that shallow water environments create problems for obtaining a synchronous growth between *A. islandica* shells and these likely accounts for not only the poor signal strength, but also why the relationships between the shell growth chronologies and the instrumental datasets are complex (as in Figures 4.14 and 4.15). However, this anecdotal observation requires further exploration before any conclusions can be drawn as to the potential effects of shallow water environments on *A. islandica* sclerochronology. In order to investigate this potential link, more sites from around the Scottish coast, including sites from different sea fjords and deeper locations should be studied. It is also important to consider that the low EPS values here may be improved if shell replication is increased for each of the master chronologies.

Overall, the results in this chapter suggest that the shells from the field area cannot be used as proxies for past climate. The reasons behind this are not clear at this point and require further investigation; this is partly covered in Chapter 7 where site water depth, OC content, sediment water content and sediment grain size are compared to master chronology RBAR and crossdating success rates. The aim of doing this is to investigate whether these site-specific conditions are controlling the ability for shells to exhibit synchronous GI growth rates and therefore crossdate. Work on increasing replication in the master growth chronologies may be of use in improving the clarity of the climate signal in the records, however the cost-benefit of this must be fully considered as the future of this type of analyses may well lie in deeper, non-fjordic locations.

5 Biometrics and Morphology

5.1 Introduction

Biometric data (height, weight, length, width and age) can be used to provide a variety of insights into *A. islandica* including information on population age structure (e.g. Witbaard, 1997; Zettler et al., 2001; Kilada et al., 2007), the relationship between shell weight/height and age, and shell morphology properties using allometric analysis (e.g. Seed, 1968; Dame, 1972; Murawski and Serchuk, 1979; Seed, 1980; Gaspar et al.,2002; Kovitavadhi et al., 2009; Sangun et al., 2007; Ramesha and Thippeswamy, 2009). The analysis of shell properties for morphometrics (the study of change in size and shape) is based on research dating back to 1891 (Shell - Reiss, 1989), which became known as allometry in 1924 (Huxley, 1924). Allometry is the bivariate study of variables such as height, shell weight, soft tissue weight and width, to determine if shell properties fit within the 'normal' growth patterns expected. Where the relationship fits with the expected it is termed isometric; if the growth in the independent variable (e.g. length) is greater than that in the dependent (e.g. width) then the relationship is negatively allometric and when the reverse is the case it is positively allometric. The concept is discussed later in more detail in Section 5.2.1.

Within the literature there are several examples of biometric analysis for shell population age structure being applied to *A. islandica*; in the North Sea (Witbaard, 1997), the Baltic Sea (Zettler et al., 2001) and the east coast of Canada (Kilada et al., 2007). These studies can therefore be compared to findings from the west coast of Scotland to determine how population recruitment and juvenile survival compares between different locations. Allometric analysis of bivalve shells have previously been carried out in a variety of species and used to investigate relationships between shell morphology and water depth (Claxton et al., 1998; Lajtner et al., 2004), currents (Fuiman et al., 1999), different river regimes (Blay, 1989), sediment type (Lajtner et al., 2004), field site location in relation to tide (e.g. tidal vs. sub-tidal in Dame, 1972), season (Ramesha and Thippeswamy, 2009) and site crowding (Seed, 1968). Currently only a few morphological studies have been undertaken on *A. islandica* (Murawski and Serchuck, 1979; Begum et al., 2010).However these did not use the same bivariate pairings undertaken in this study. For example in Murawski and Serchuck (1979) *A. islandica* length and drained soft tissue weight data for mid-Atlantic Shelf specimens were analysed and morphological differences were explained as being due to factors including: salinity, food supply, temperature and nutrients.

For this research, shell age, weight (analysed valve), maximum height, length and width were recorded for biometric and allometric analysis (see Figure 4.1 for the lines along which height and length are measured and Figure 4.1C for where width is measured). Morphological analysis of shell weight, height, length and width are analysed for the entire field site population, as well as for each site, in order to determine whether there are any morphological differences between shells from the six field sites. As already mentioned, there is a lack of similar research carried out on *A. islandica*. However, such work may help highlight why some sites have a stronger common signal for their chronologies when this is considered in Chapter7. Those samples for which age are available have been analysed on both the individual and whole site level, but also with all data analysed together to create a 'field site' dataset, to determine if either height or weight can be used as predictors of specimen age. Using height, and to a lesser extent weight, to predict the age of specimens would be beneficial if it allowed divers and researchers in the laboratory to use either variable to estimate shell age without the need to section specimens. In addition, population age structure analysis can also be undertaken and the results compared to similar research (Witbaard, 1997; Zettler et al., 2001; Kilada et al., 2007).

The primary aim of this chapter is to provide more information concerning site differences relating to specimen morphology and age-related differences. Such information for the six sites (Figure 2.1B), together with data from Chapter 2 (site sediment OC content, sediment water content and sediment grain size data), may help to explain some of the results already presented in Chapter 4 concerning the Correlation Response Function Analysis (CRFA) results between the climate series and the shell growth chronologies.

5.2 Methods

5.2.1 Shell Morphology

To determine how the four morphometric variables being investigated (height, length, width and weight) relate to each other, it is important to establish whether the regression slope value for each relationship is isometric. An isometric relationship between the length, width and max height variables has an 'expected slope' value ($\hat{\beta}$) of 1 (Goldman et al., 1990), while for weight and length $\hat{\beta}$ = 3 (Ewa-Oboha and Abby-Kalio, 2006). Data were logged prior to analysis, as this allows the linear plotting of the relationship (Huxley, 1924), thus allowing a simple linear regression between the variables to be performed. The resulting regression equation is written as:

$$\log y = \log a + \hat{\beta} \log \mathrm{x} \qquad \text{Equation 5.1}$$

Using this equation, it is possible to determine whether the slope of the regression line is statistically significant from the isometric ideal (either 1 or 3). The hypothesis (adapted from Ogle (2011) – also illustrated in Figure 5.1) being:

H_0; $\hat{\beta}$ = 1 or 3 (depending on parameters being investigated) → H_0; Isometric growth

H_1; $\hat{\beta} \neq$ 1 or 3 (depending on parameters being investigated) → H_1; Allometric growth (either positive or negative depending on whether value is above (positive) or below (negative) the expected β – see Figure 5.1 for more information).

To determine which hypothesis is correct the following equation (Ogle, 2011) is used:

$$t_{n-1df} = \frac{\hat{\beta}-\beta}{SE\hat{\beta}}$$ Equation 5.2

Where β is the isometric value (either 1 or 3)

$\hat{\beta}$ is the slope value determined in Equation 5.1

SE $\hat{\beta}$ is the standard error of the slope coefficient.

If t_{n-1df} is greater than the t-test value for the sample size minus one (n-1), then the slope is significantly different from the isometric value and is allometric; whether it is positive or negative depends on whether the value of $\hat{\beta}$ is greater than or less than the β value outlined in hypothesis H_0 (if $\hat{\beta}>\beta$ then the slope is positively allometric, if $\hat{\beta}<\beta$ then the slope is negatively allometric – see Figure 5.3).

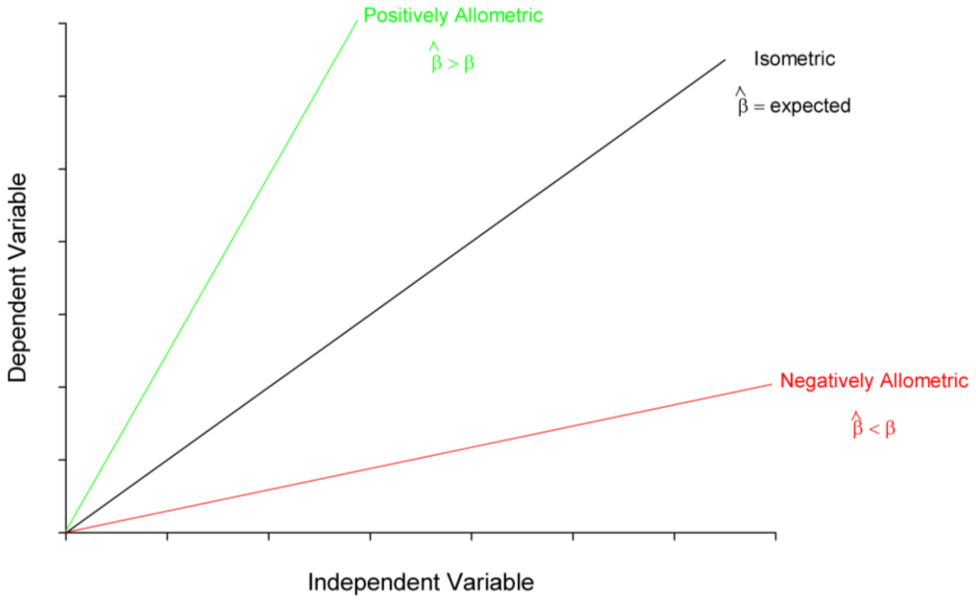


Figure 5.1: Allometric analysis $\hat{\beta}$ is the slope of the relationship between the variables being analysed. The expected value of $\hat{\beta}$ in this chapter is either 1 or 3 depending on which variables are being considered.

The allometric analyses carried out have the potential to be used for a variety of purposes. Although age ranges at the six sites are too different to allow for direct comparisons to be made, the results of the individual site analyses can still be used to identify overall growth patterns between sites, with the caveat that until the datasets span the same sample age range the results are only preliminary. This work was also carried out by pooling data from all the sites together to see how the morphology of *A. islandica* in the field area plots as a whole. Each of the bivariate datasets from the individual sites were also plotted and compared to the whole field area datasets. Such information can be useful if any unusual patterns are seen for certain sites; this may help explain some of the differences between annual growth rates at the sites as well as why some sites do not show the same response to climate (see Chapter 4.)

Biometric results can also be used to investigate differences in the environment that have the potential to influence GI growth rates. For example, temperature changes have been shown to influence soft tissue and skeletal growth rates (Rhoads and Lutz, 1980) and this explains why previous research by Butler et al. (2010) has been able to link *A. islandica* growth rates with sea temperature changes. Seed (1968) suggested that shell morphology is also influenced by population density, i.e. in areas of high population density growth may be restricted in certain dimensions – something that allometric analysis can help determine.

5.2.2 Age Predictions

The height, length and weight data collected for all aged samples in Chapter 4 were used along with width (see Figure 4.1) to carry out a variety of analyses to investigate how shells at the sites compare. For the age prediction work linear regression was used to explore the relationships between all bivariate pairs.

Additional analyses were performed using age, weight and height data to see how data from the six sites compare to one another and as well as the all site dataset[1]. This was done in two ways, initially all data were plotted in a single graph with a regression line and corresponding

[1] For some samples damage to the shell meant that it was not possible to take height and/or weight data. Therefore the number of shells is not the same for all analyses using height/weight/age data.

95% prediction bands for the all sites data to see how they plotted against each other (with age plotted on the x-axis and either height or weight on the y-axis) and the regression line (e.g. Figure 5.6). All the regression lines for the six sites are compared together, along with their 2SE[2] bars. This makes it possible to determine which site-specific regression lines are significantly different from each other. The median and quartile deviation (QD) for height, weight and age for each site are also compared and Kruskal-Wallis analyses were undertaken to test whether the samples represent the same population by investigating whether the medians for the six datasets are similar. Kruskal-Wallis analysis was chosen as not all the data are normally distributed.

5.2.3 Population Age Structure

An understanding of population age structures can be used to indicate population recruitment and future viability. They can also provide site-specific data for regional comparisons. However, no direct comparisons between populations of different age structures can be made using allometric analyses. To produce a picture of site recruitment, the age distribution of the six sites are compared using histograms with bins of 15 years.

5.3 Results

5.3.1 Shell Morphology

The individual site results are summarised in Table 5.1, with the respective graphs in Appendix 14; from Table 5.1 it is possible to see that the data for site C6 are all isometric, site C8 has all isometric relationships apart from length and weight which is negatively allometric. The results for sites C6 and C8 indicate that at these locations there is little/nothing limiting the growth of shells regarding physical constraints on specimen growth e.g. over-crowding. On the other

[2] Where 2SE is used to represent the 95% confidence range of the predicted values around the regression lines.

hand the C1, C4 and C7 results are an even split of negatively or positively allometric and isometric; indicating that at both these sites there is probably at least one factor other than climate causing growth restrictions in various dimensions. The results for site C2 suggest that this is the most restricted, with length-width, length-height and height-width all being negatively allometric, while only length-weight is isometric.

Table 5.1: Allometric relationships present at the six field sites

	Length – height	Length – width	Height –width	Length – weight
C1	Isometric	Isometric	Negatively allometric	Negatively allometric
C2	Negatively allometric	Negatively allometric	Negatively allometric	Isometric
C4	Positively allometric	Isometric	Isometric	Negatively allometric
C6	Isometric	Isometric	Isometric	Isometric
C7	Isometric	Negatively allometric	Isometric	Negatively allometric
C8	Isometric	Isometric	Isometric	Negatively allometric

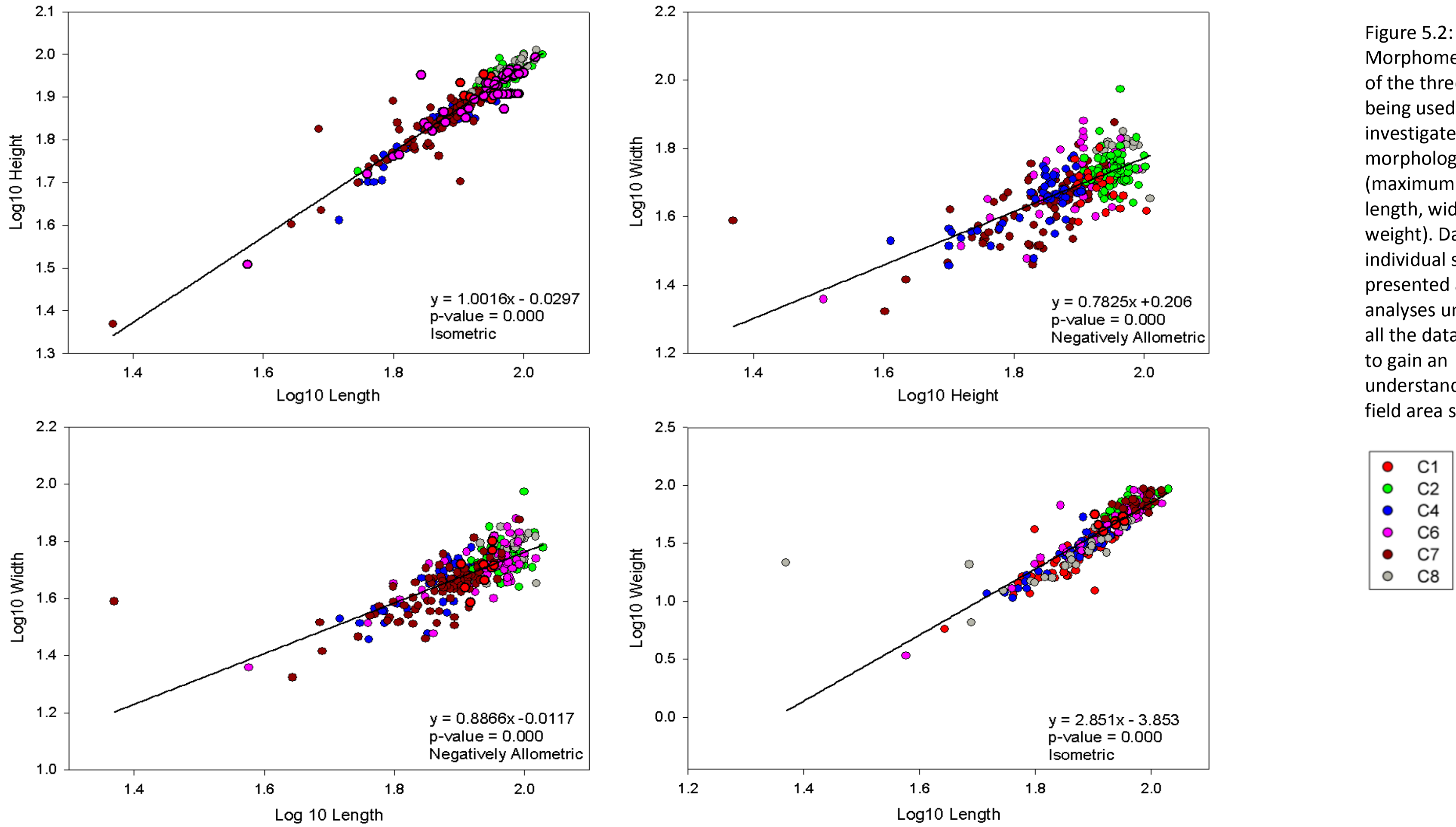


Figure 5.2: Morphometric analyses of the three variables being used to investigate shell morphology properties (maximum height, length, width and weight). Data for the individual sites are presented as are the analyses undertaken on all the data combined to gain an understanding of the field area signal.

Figure 5.2 summarises the entire field area dataset and indicates that out of the four analyses, two are isometric (length-height and length-weight), while the other two analyses are negatively allometric. From the data analysed and presented in Figure 5.2, the results for C8 consistently plot near the top end of the graphs (with the exception of the length-weight graph). Initially, these results appear to contradict those in Table 5.1 which indicate predominantly isometric growth at the site, however it is entirely feasible that the C8 results appear to be different compared to the other site data in Figure 5.4 because of the different population age structures at the six sites (Figure 5.7). The results in Figure 5.4 may also be down to the height/weight data for the sites – in Figures 5.4a and 5.6a, the C8 data for the age-height and age-weight relationships respectively generally plot higher than the other site data. It is possible this is the reason for the C8 data plotting near the top in three of the graphs in Figure 5.2 rather than the shell morphology (i.e. a sampling bias due to a wide range of shell weights and heights).

There are some problems with the use of isometric analyses to investigate the morphology of samples. When carrying out such work, the comparisons are only between two variables at a time and this is somewhat restrictive (Seed, 1980). In addition, although there are ideal relationships between variables, such as a regression equation slope (β) of 1 between height and length, these may not relevant for all species. Seed(1980) highlighted that these relationships are not always present in older samples of the species *Mytilus edulis*. It is therefore important to highlight that these 'ideal' relationships may not be relevant for all species and locations. There is currently a lack of available literature detailing how the variables studied here relate to one another in *A. islandica* specimens from different populations. Therefore the assignment of morphometric terms isometric, positively allometric or negatively allometric to any of the bivariate analyses carried out and illustrated in Figure 5.2 must come with the caveat that these are being presented as relating to the ideal relationships which are not *A. islandica* specific. Seed (1968) highlights that environmental conditions influencing morphology vary both over time and space, therefore it is conceivable that animals from the same field site may show differing responses; this could be the reason why some of the sites have different allometric relationships (Table 5.1).

5.3.2 Age Predictions

5.3.2.1 Height and age

The height and age data for all six sites are presented in Figure 5.3 as stacked scatter plots to highlight differences between the data from all the sites. For each plot the regression lines and 95% prediction bands are plotted along with the regression line equation, p-value and n-value.

In Figure 5.3 it can be seen that at sites C1 and C2 the relationship between age and height is not significant and therefore from the data currently available it is not possible to use height at these sites to predict age. At the other four sites there are statistically significant relationships present between the two variables, suggesting that sample ages at sites C4, C6, C7 and C8 can be predicted using height. It is conceivable that at site C1 the reason behind the lack of a significant correlation between the variables is partly down to low data replication at the site - the n-value is 15. At site C2 it is not clear why the relationship is not significant. However, the results in Table 5.1 indicate negatively allometric relationships between height and length and height at width at site C2, therefore it is conceivable that environmental conditions at the site are having a negative influence on specimen height and overall growth rates, which may explain the lack of a relationship between age and height.

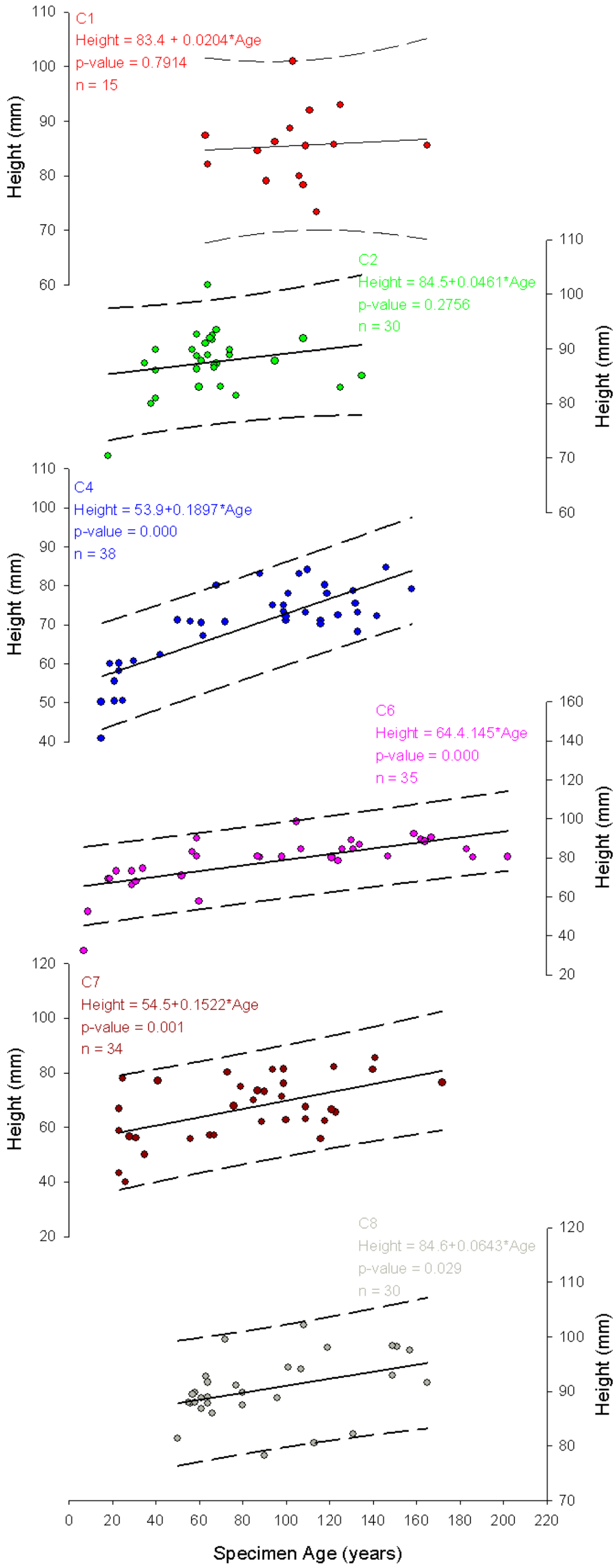


Figure 5.3: Age – height scatter plots with regression line/equation and corresponding 95% prediction bands (dashed lines) for each of the six sites.

To better understand how data from each site compares, all data are plotted in Figure 5.6A along with the all data regression line, corresponding 95% prediction lines and a regression line fitted to the data. Figure 5.4a illustrates that four of the sites have data that plot either entirely or predominantly to one side of the regression line; these are C8 (almost entirely above), C2 (almost entirely above), C4 (almost entirely below) and C7 (almost entirely below).

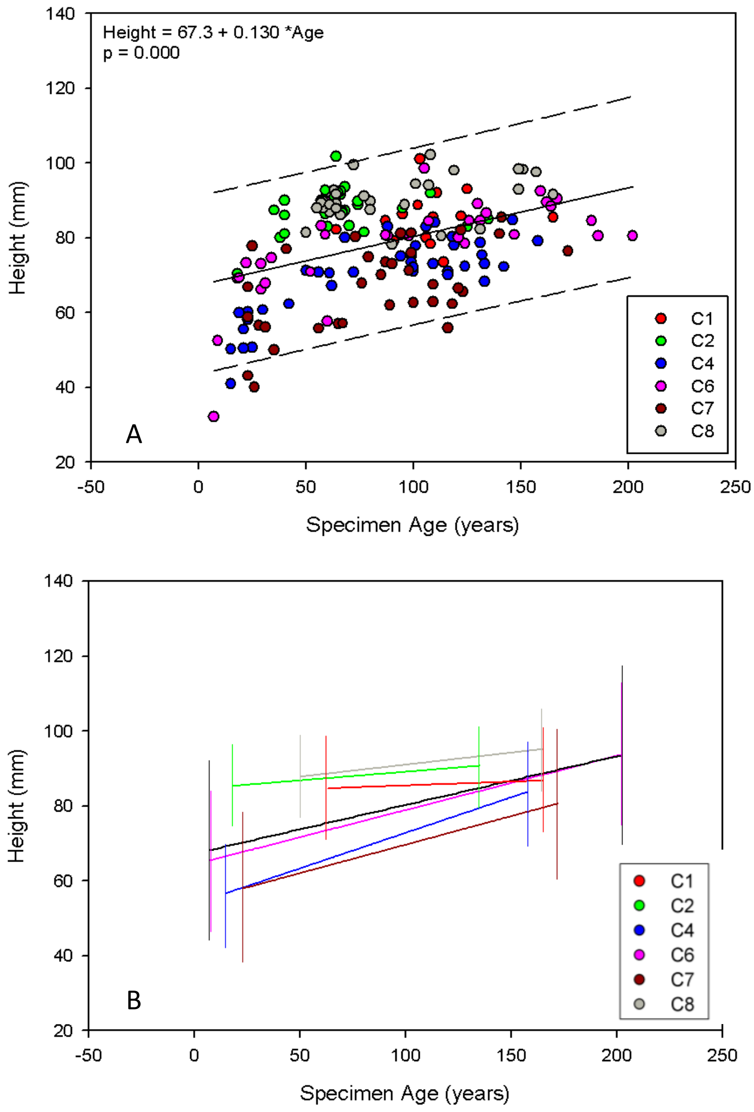


Figure 5.4: Graphs illustrating the age-height A)regression line and related 95% prediction bands (dashed lines) for the entire dataset and how the data from each site plots in relation to this, B) regression lines from each site and the entire dataset with 2SE bars fitted to the data to investigate significant relationships.

When the regression lines (with associated 2SE lines) for each site, as well as the regression line representing all the data, are compared (Figure 5.4B), it is clear that none of the individual series are significantly different to the all data series (in black) and they are also not significantly different from each other. For example, the slope of C1 is less than for C7. These growth rate differences may be explained by site differences (see Chapter 2) and are discussed further in Chapter 7.

To test for significant differences between height data from all six sites the median and IQR, and the maximum and minimum values are presented in Figure 5.5 along with the Kruskal-Wallis analysis results. These results indicate that there is a significant difference at the 95% confidence level between the height data for the six sites.

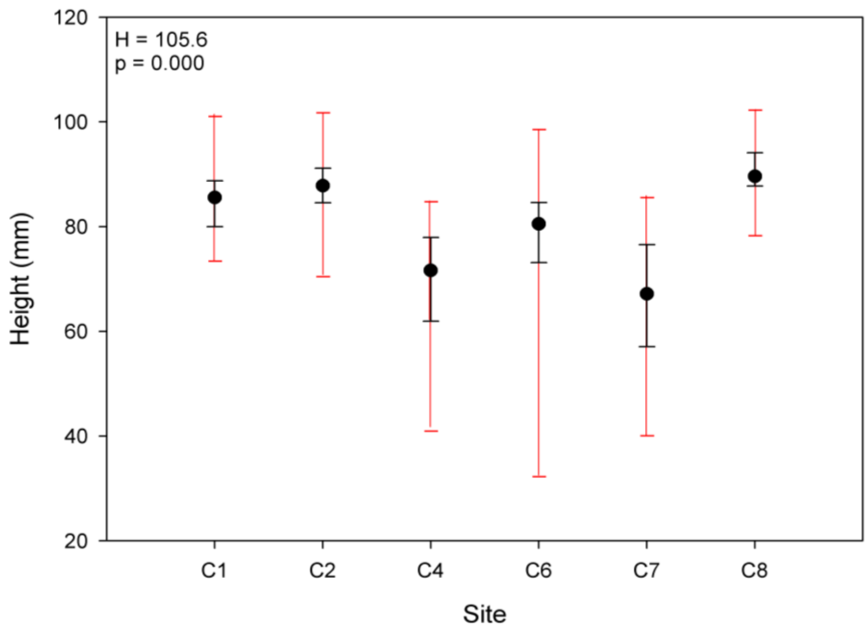


Figure 5.5: Median and IQR values for height data from each site in black. Also included is the range of the data in red with the maximum and minimum values indicated. The H and p values included in the figure relate to the Kruskal-Wallis analysis undertaken on the datasets.

5.3.2.2 Weight and age

In Figure 5.6 the weight-age data for all six sites are illustrated as stacked scatter plots to allow easy comparison between the data. For each plot the regression lines and 95% prediction bands are plotted along with the regression line equation, p-value and n-value.

As with the age-height data presented (Figure 5.3) the age-weight data (Figure 5.6) indicates that at sites C1 and C2 weight is not a suitable predictor of sample age. These results suggest that at sites C4, C6, C7 and C8 there is potential to use sample weight as a predictor of a shell's age, however as this cannot be used *in situ* it is not as useful as height as a predictor of age. As with height it is possible that the relationship between weight and age at C1 is not statistically significant due to the low n-value. It is not as clear as to why the relationship at C2 is not statistically significant and this requires further investigation.

When comparing all the site data together in a single graph (Figure 5.7A) it is possible to see that the data from sites C8 and C2 plot almost entirely above the regression line and the C4 and C7 data are almost entirely below the line, as was the case in Figure 5.4A for age-height. As with the age-height data (Figure 5.4) these differences between where data plot may explain why there is an apparent lack of common climate signal in shells from the region.

In Figure 5.7B it is possible to see that there are differences between the slopes of the seven regression lines plotted, however the only datasets where this is statistically significant at the 95% confidence level are between sites C2 and C7, and C4 and C8. All the datasets overlap with the regression line and 2SE bars plotted for the entire dataset, therefore it is possible that for those sites with no significant relationship between age and weight (C1 and C2) the entire dataset regression equation may potentially be used to predict shell ages, although this is with a large associated error.

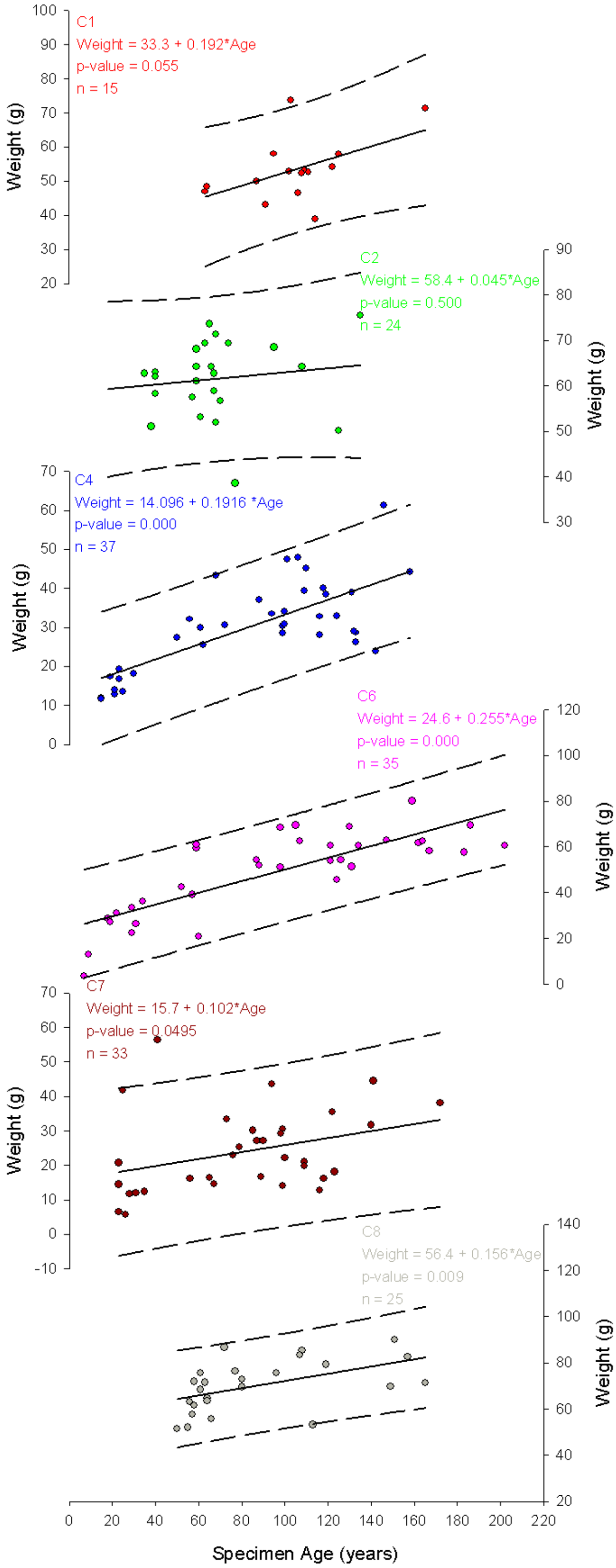


Figure 5.6: Age – weight scatter plots with regression line/equation and corresponding 95% prediction bands (dashed lines) for each of the six sites.

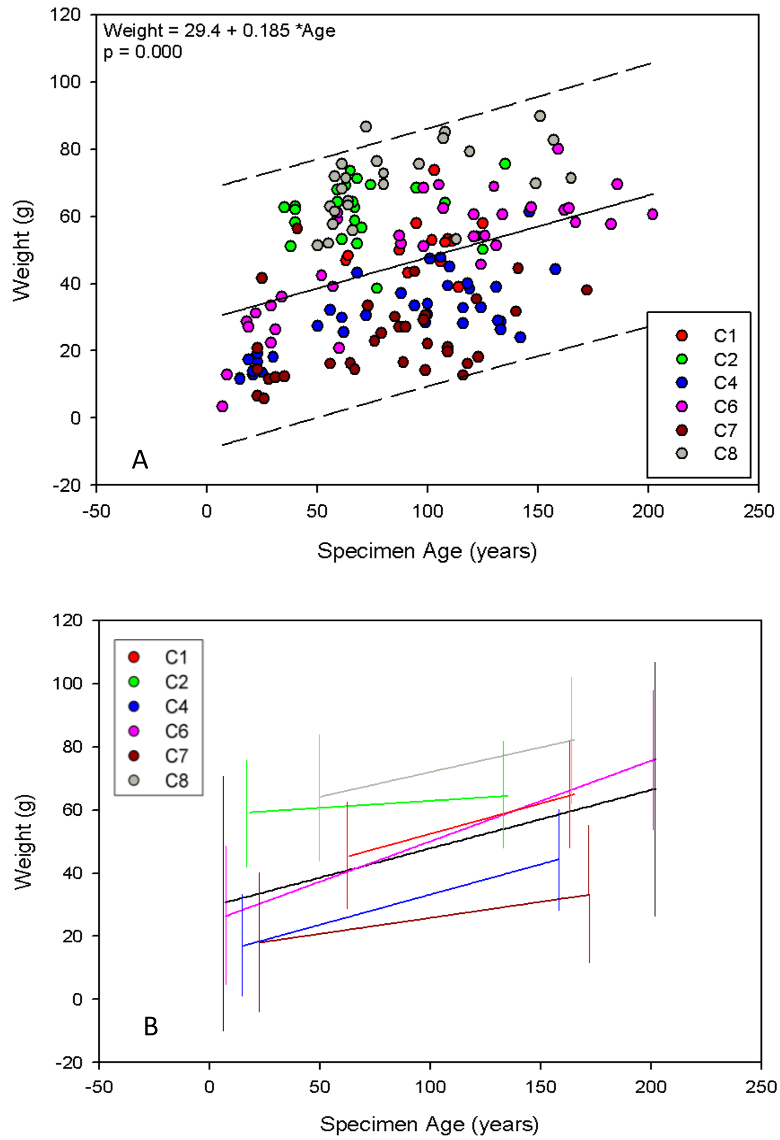


Figure 5.7: Graphs illustrating the age-weight A) regression line and related 95% prediction bands (dashed lines) for the entire dataset and how the data from each site plots in relation to this, B) regression lines from each site and the entire dataset with 2SE bars fitted to the data to identify significant relationships.

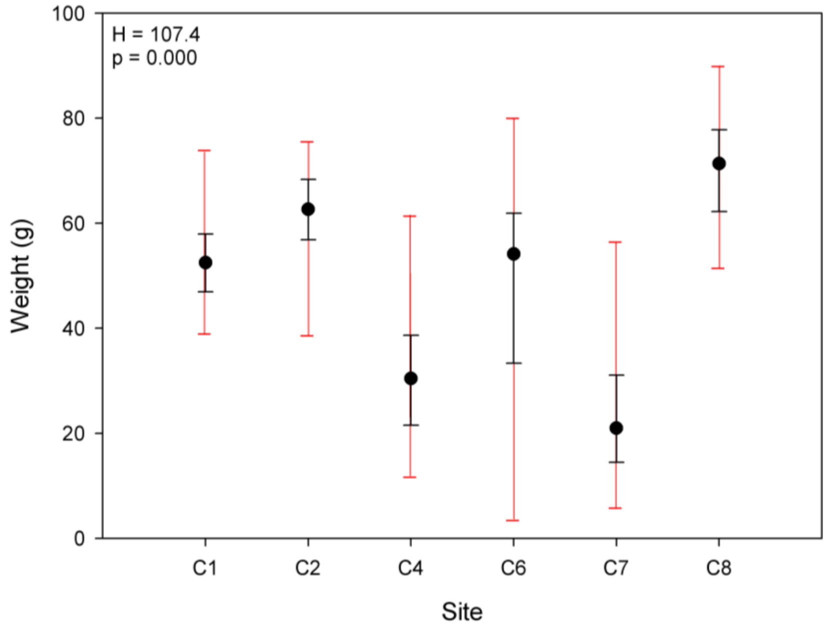


Figure 5.8: Median and IQR data for weight data from each site in black. Also included is the range of the data in red with the maximum and minimum values indicated. The H and p values included in the figure relate to the Kruskal-Wallis analysis undertaken on the datasets.

To test for significant differences between weight data from all six sites, the median and IQR, together with the maximum and minimum values, are presented in Figure 5.8 along with the Kruskal-Wallis analysis results. These results indicate that is a significant difference at the 95% confidence level between the weight data for the six sites.

5.3.2.3 Predicting age from height/weight

The data presented in sections 5.3.2.1 and 5.3.2.2 are useful for investigating the relationships between age and height, and age and weight respectively, however the regression equations in Figures 5.3 and 5.6 cannot be used to predict age. To produce regression equations that can be used to predict age, the axis used for the graphs in Figures 5.3 and 5.6 must be inverted so that age is on the y-axis. These analyses are presented in Figure 5.9 for age-height and 5.11 for age-weight. At sites C1 and C2 it has been shown that neither height nor weight can be used to predict age. To determine whether the regression equation fit to all the datasets can be used instead, the regression lines, with 2 SE bars, for all six sites, along with the regression bars for the whole dataset are presented in Figures 5.10 and 5.12 respectively.

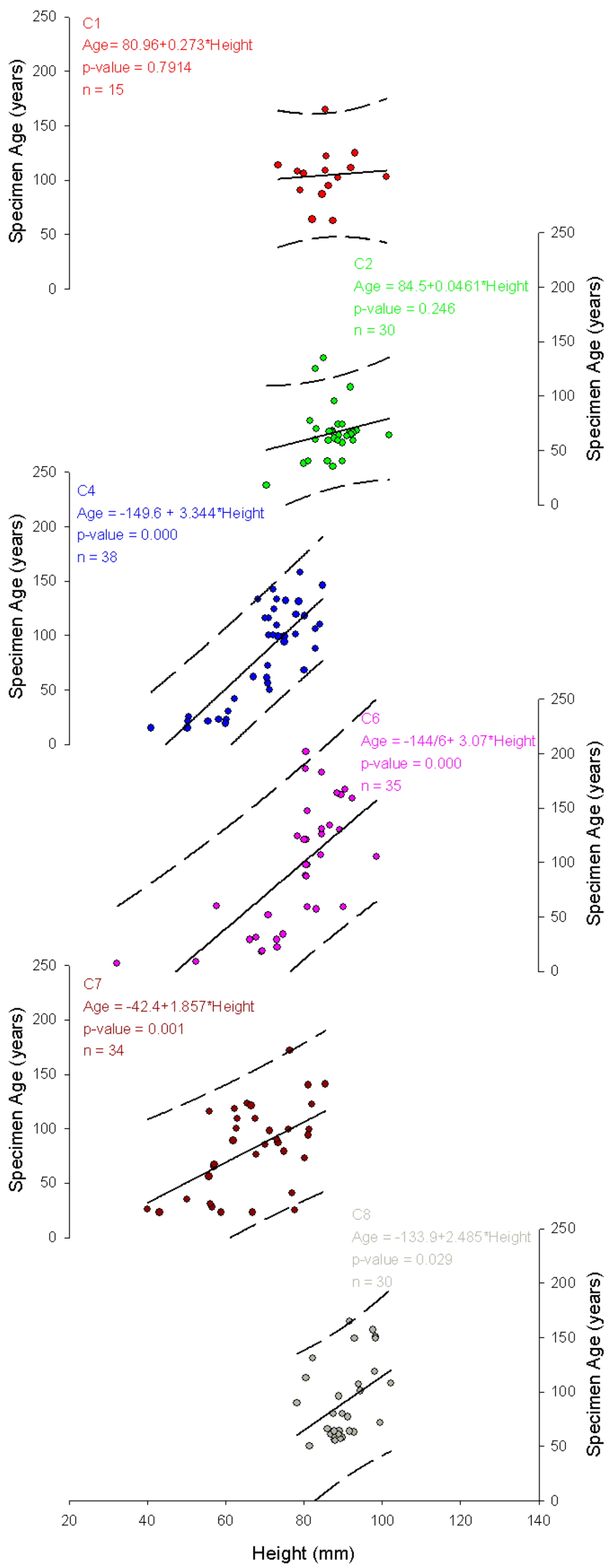


Figure 5.9: Age – height scatter plots with regression line/equation and corresponding 95% prediction bands (dashed lines) for each of the six sites. Data are plotted with age on the y-axis so that the resulting regression equation can be used to predict age using shell height.

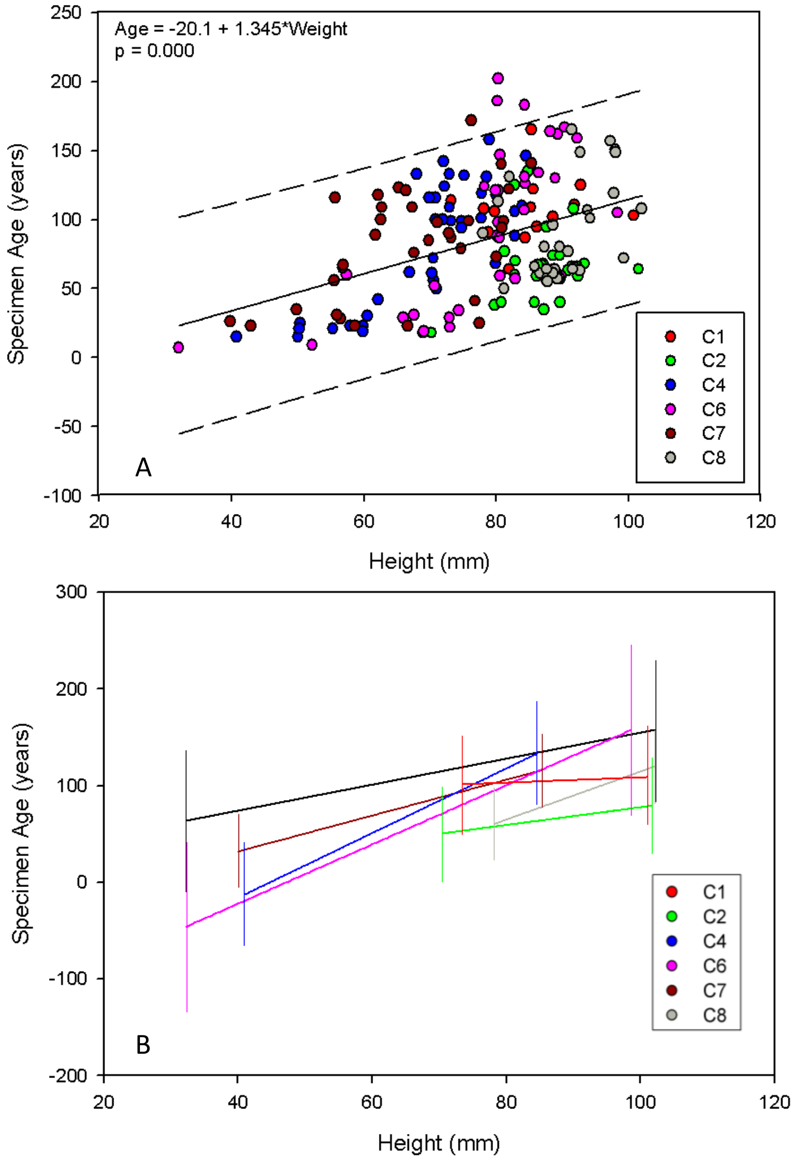


Figure 5.10: Graphs illustrating the age-height A) regression line and related 95% prediction bands (dashed lines) for the entire dataset and how the data from each site plots in relation to this, B) regression lines from each site and the entire dataset with 2SE bars fitted to the data to identify significant relationships.

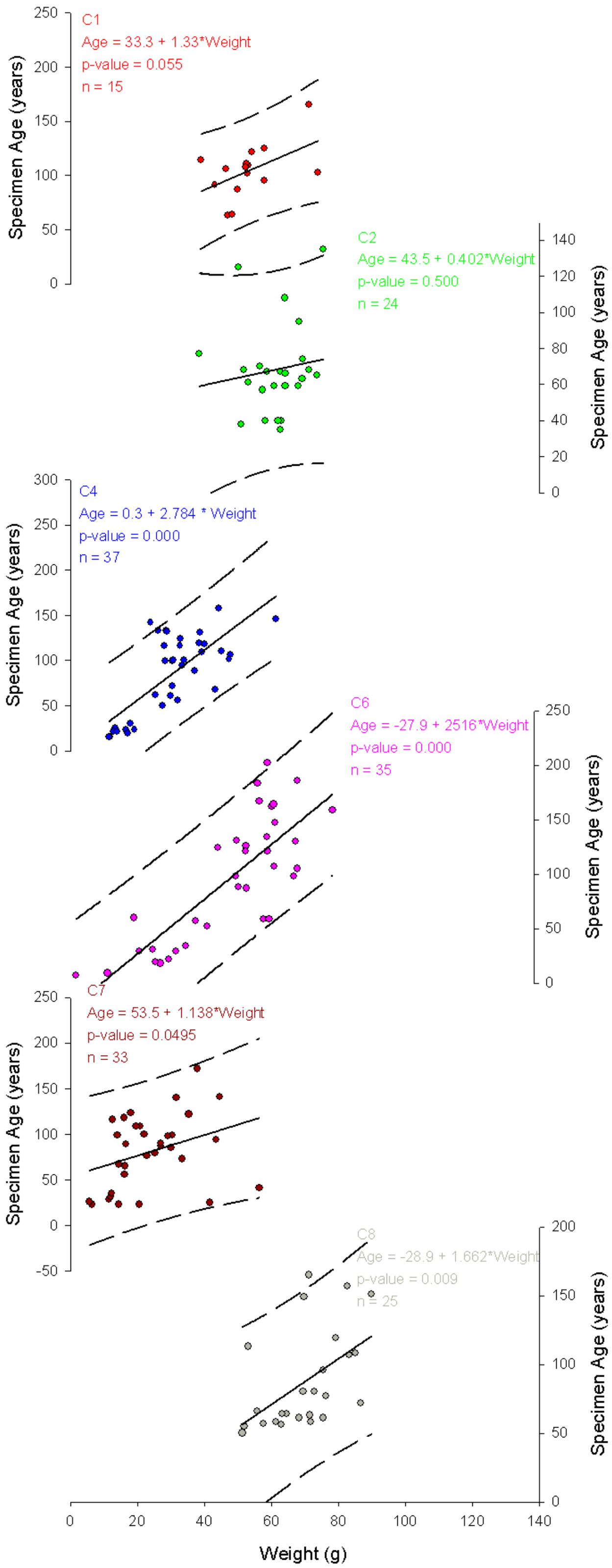


Figure 5.11: Age – weight scatter plots with regression line/equation and corresponding 95% prediction bands (dashed lines) for each of the six sites. Data are plotted with age on the y-axis so that the resulting regression equation can be used to predict age using shell weight.

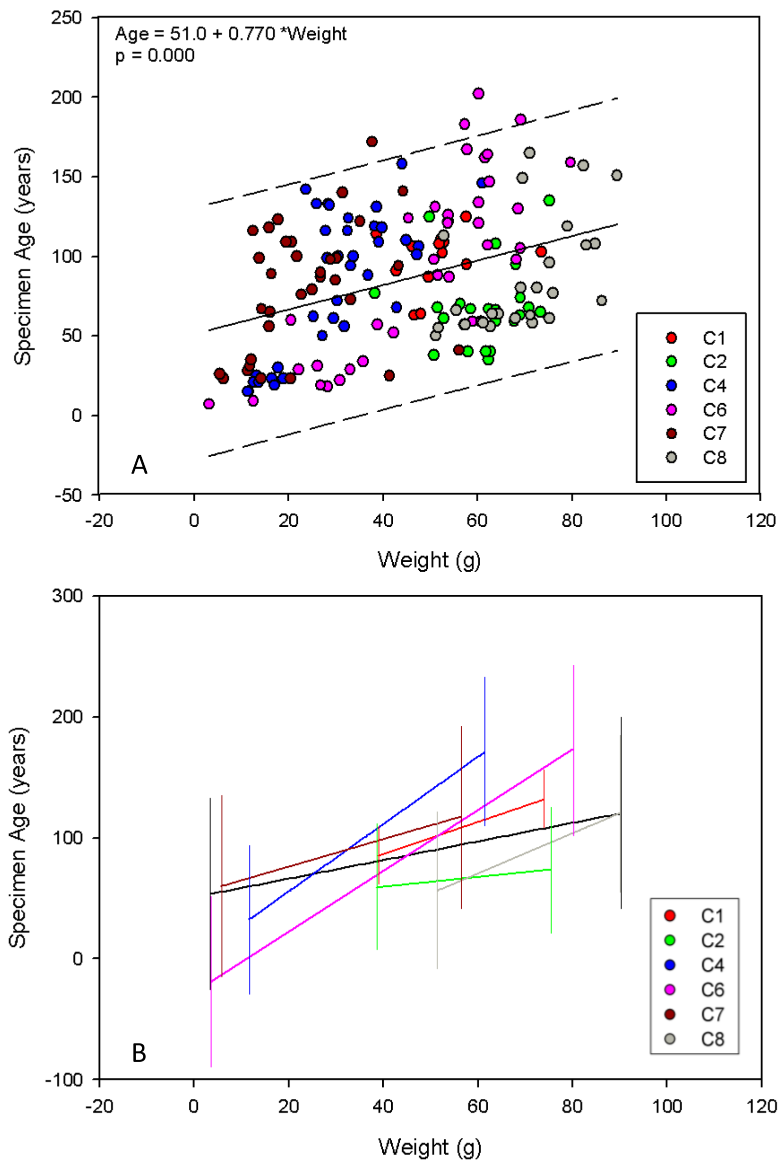


Figure 5.12: Graphs illustrating the age-weight A)regression line and related 95% prediction bands (dashed lines) for the entire dataset and how the data from each site plots in relation to this, B) regression lines from each site and the entire dataset with 2SE bars fitted to the data to identify significant relationships.

The results in Figures 5.3, 5.6, 5.9 and 5.11 indicate that the relationship between height and age, and weight and age are statistically significant for sites C4, C6, C7 and C8, therefore the site-specific regression equations summarised in Table 5.2 should be used to predict sample ages for these sites. The results in Figure 5.10 indicate no statistically significant differences between any of the regression lines plotted at the 95% confidence level for age-height. Therefore, the regression equation for the whole dataset could potentially be used to predict age using height for both sites C1 and C2. For age-weight (Figure 5.12) there are also no statistically significant differences between the regression lines plotted and therefore the age for specimens from sites C1 an C2 may potentially be predicted using the regression equation for the whole dataset.

Table 5.2: Regression equations to work out age from Figures 5.7 to 5.10.
The ± value relates to the 2SE of the estimate.

Site	Age-height regression equations	Age-weight regression equations
C1	Age = 80.96 + 0.2734 * Height ±51	Age = 33.3 + 1.33 * Weight ±24
C2	Age = -14.29 + 0.9181 * Height ±49	Age = 43.5 + 0.402 *Weight ±52
C4	Age = -149.6 + 3.344 * Height ±54	Age = 0.3 + 2.785 * Weight ±61
C6	Age = -144.6 + 3.065 * Height ±88	Age = -27.9 + 2.516 *Weight ±70
C7	Age = -42.4 + 1.857* Height ±38	Age = 53.5 + 1.138 *Weight ±76
C8	Age = -133.9 +2.485 * Height ±37	Age = -28.9 + 1.662 *Weight ±64
All sites	Age = 20.1 + 1.345 * Height ±78	Age = 51.0 + 0.770 *Weight ±80

The potential problem with using the whole dataset regression equations to predict age is that this may increase the error associated with the predicted age compared to using a site-specific equation. Additionally, it is not clear why there are not significant relationships between age and height/weight at sites C1 and C2. As already mentioned the n-value for site C1 is low (n = 15) which may account for the lack of a significant relationship at this site. To determine if this is the case, increasing the sample size at the site may be beneficial to determining a relationship between the two variables. At site C2 it is possible that environmental factors are limiting shell height growth (Table 5.1) causing the lack of a relationship between age and height. To determine if this is the case and to see what may be causing the lack of a relationship between age and weight additional samples should be analysed. It is possible that at sites C1 and C2 there is an external factor causing a lack of a significant relationship between age and height/weight at these sites. If this is the case then it may not be appropriate to use the regression equation for the whole datasets to predict sample ages for sites C1 and C2.

5.3.3 Population age clustering

The results concerning age prediction using height and weight indicate that there are differences between the relationship of age and height at the six sites; shells of the same height are not necessarily the same age between sites. This is most likely due to differences in site conditions causing shells to grow at different rates, as illustrated by the allometric results in Table 5.1 and the different slopes of the regressions shown in Figure 5.3.

To test whether the specimens with similar heights have different age structures between the six sites, additional age analyses were undertaken on shells within the height range of 90 and 100 mm (inclusive). This height range was chosen to represent mature adult specimens, typically aged > 50 years old; at sites C4 and C7 no shells were present in the collection of this height (Figure 5.9). Normality tests were undertaken on the data being analysed, the results (presented in Appendix 15) appear to indicate that some of the datasets are non-normally distributed, however the low n-values at each site may make these results unreliable (C1 = 2, C2 = 7, C6 = 4, C8 = 12). As a result of this the data were analysed using both parametric and non-parametric analyses and the results compared. The parametric analysis of the data was undertaken by first generating the mean and 2SE values for age data at each site, an ANOVA analysis of the raw data was then carried out (Figure 5.13). The results from the ANOVA indicate that there is not a statistically significant difference between age data from the four sites analysed based on their height range.

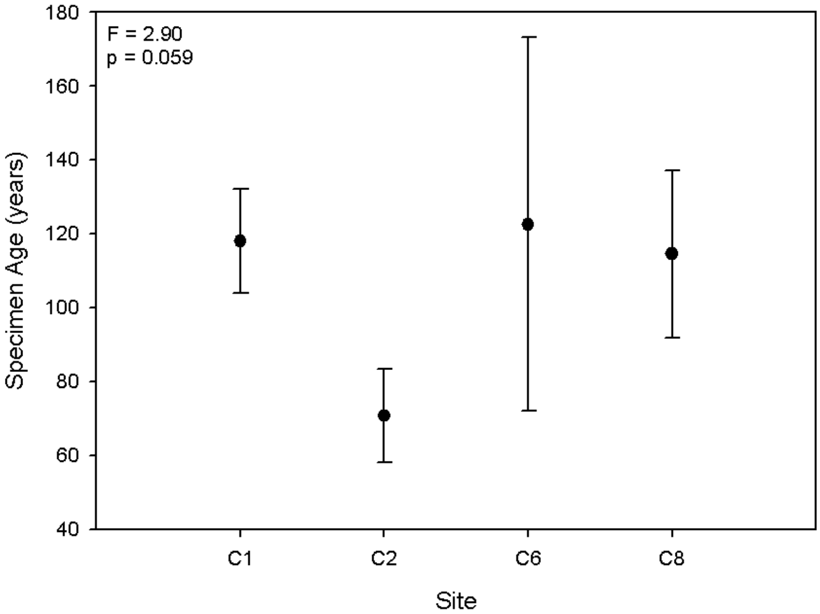


Figure 5.13: Mean age and 2SE data for sites C1, C2, C6 and C8 to investigate the age distribution of shells from the sample sites with heights ranging between 90 and 100 mm inclusive. Also included are the results from the ANOVA analysis undertaken on the data.

5.3.4 Population Age Structure

The population age structure data for the six sites are presented in Figure 5.14. For site C2 the majority of shells are from cohorts dating between 1934 to 1948 and 1949 to 1963, while sites C4 and C6 are the only ones to have any shells younger than 15 years old in the sample population. However, C2 and C7 do also show signs of recent recruitment (1993 to 1979). These results indicate that the populations at sites C2, C4 C6 and C7 show signs of recent recruitment, which coupled with the presence of some older shells at all these sites, means that future sampling, may be able to target shells from a range of ages. Sites C1 and C8 do not have any shells younger than 62 and 50 years old respectively in their sample populations (Figure 5.15); this could be because of two reasons: (1) the lack of younger shells at sites C1 and C8 may purely be due to a lack of recent recruitment at the sites, (2) divers collecting the shells may have introduced a bias into the sampling process, focusing on collecting larger shells, or may not have been able to see/find younger shells due to bottom water conditions. However, the NFSD divers were asked to collect samples from a wide range of sizes at each field site – this sampling strategy was clearly observed at other sites, and is unlikely to have been disregarded at sites C1 and C8.

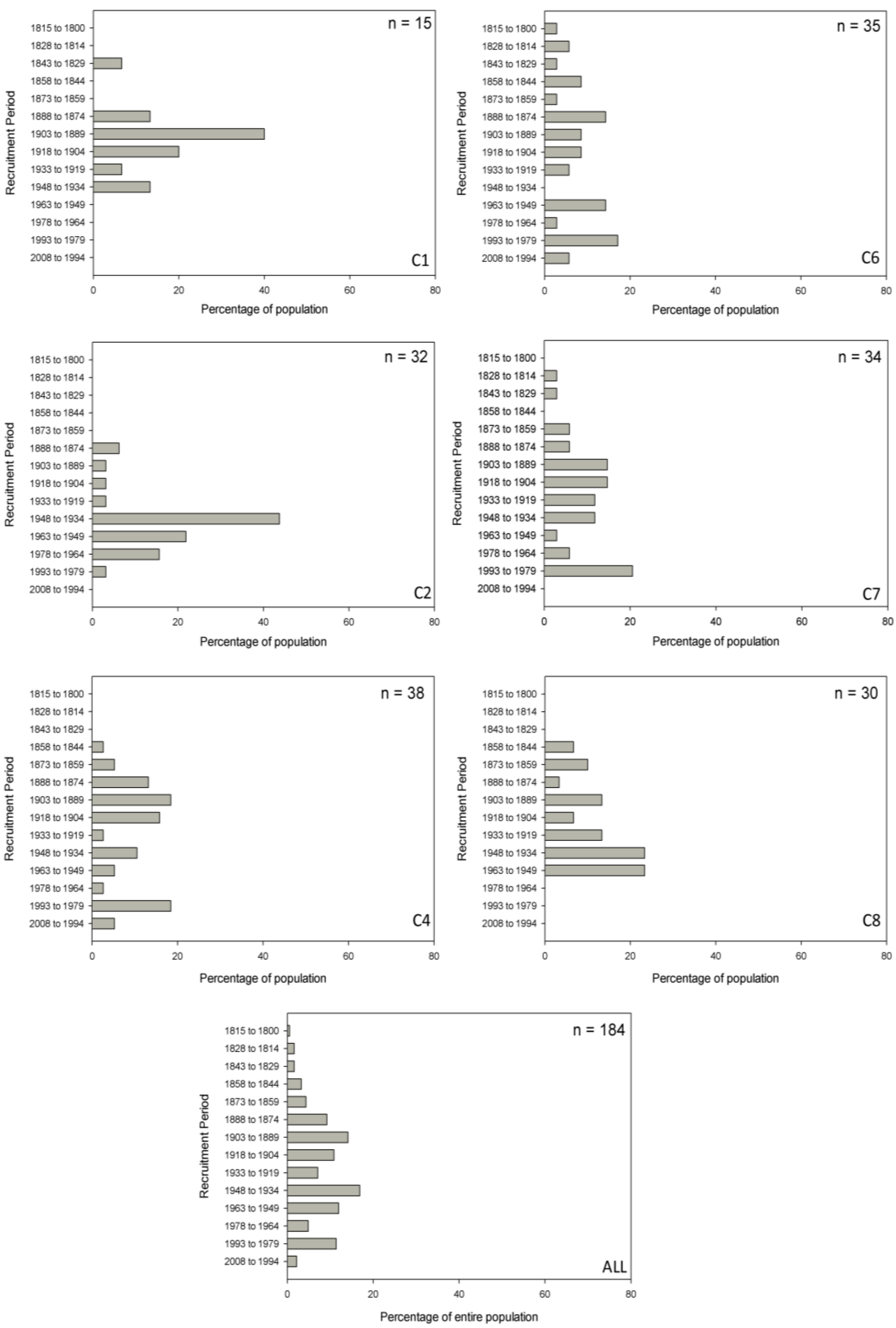


Figure 5.14: Population age structure data for each site and also for the entire field site dataset. N.B. Some of these ages come from specimens not crossdated into the chronologies.

In Figure 5.15, a comparison of the median age of shells from a site (and the corresponding QD and minimum/maximum bars) shows that while the age structure at site C2 is younger compared to the other sites, all the sites have some degree of overlap regarding their age structure data ranges. The Kruskal-Wallis analysis of the data indicates that there is a significant difference in terms of shell ages between the datasets at the six sites.

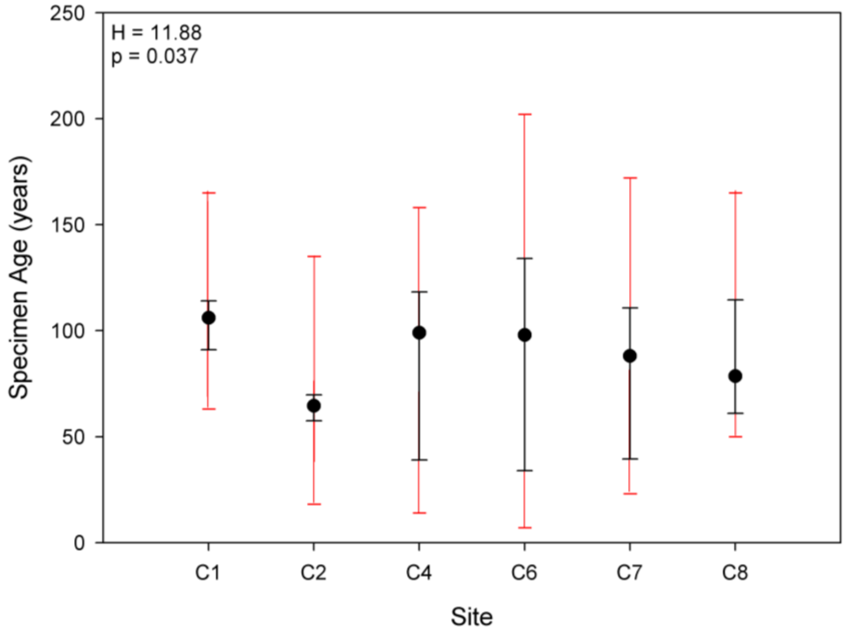


Figure 5.15: Median shell age with corresponding inter-quartile range data, also shown are the minimum and maximum shell ages for each site (red error bar lines)
n-values: C1 = 15, C2 = 32, C4 = 38, C6 = 35, C7 = 34, C8 =30

5.4 Discussion

Currently the regression analyses used to determine whether shell age can be predicted using either height or weight indicate that there are statistically significant relationships present between age and both height and weight at sites C4, C6, C7 and C8. At sites C1 and C2 the results indicate no statistically significant relationship exists between age and height/weight. The results are promising for using the site-specific regression equations to predict age using either height or weight for sites C4, C6, C7 and C8 and the regression equation fit to all the data for predicting age using height/weight at sites C1 and C2. However, the results in Table 5.2 indicate that there is a large error associated with the predicted ages for specimens.

The results in Table 5.1 suggest that growth at sites C4, C6 and C8 are less likely to have been influenced negatively by factors restricting their growth in any of the morphometric variables investigated when compared to the other three sites due to the prominence of isometric and positively allometric relationships between variables at these sites. As discussed in Chapter 4 (Section 4.3.1) it may be that historic discharge of various pollutants from the alginates factory in Loch Creran (see Figure 4.11 for location of factory) has influenced shell growth rates at these sites C1 and C2, this in turn could explain the negative allometric results in Table 5.1. The negatively allometric results at C7 also suggest some external influences which impede growth rates, but there is little evidence of this in the C7 chronology itself (Figure 4.9).Hydrographic controls at site C7 may play a significant role in controlling shell growth and thus explain the allometric results in Table 5.1. Appendix 12 illustrates the juvenile growth trend in the raw data; from this data it is possible to see that there are no obvious differences in juvenile growth trends between the six sites with the exception of site C1 however this is likely due to shells at this site growing in different conditions during their juvenile period. These results aid with the understanding of how the strength of trends observed in the data reflect shell age.

The findings of the age cluster analyses presented in Section 5.3.3 support the data presented in Figures 5.5 and 5.10 where the regression analysis lines and their associated 2SE bars indicate that there are no statistically significant differences between the age-height datasets for all the samples which have been age determined. Although there appears to be differences between the distribution of specimen ages at sites C1, C2, C6 and C8 from the height range 90 to 100 mm (Figure 5.13), these are not statistically significantly different at the 95% confidence level.

Further investigation of population age differences based on sample height should be undertaken with two potential lines of enquiry. The first would be to increase sample sizes and including sites C4 and C7 in the analyses; this would require the collection of additional shells from all six sites using targeted sampling techniques i.e. by asking the SCUBA divers to collect shells between 90 and 100 mm in height. The second option would be to repeat the analyses carried out in Figure 5.13 for shell samples from a different height (and presumably age) range to see how those data compare.

Within the field area (Figure 2.1) there are signs of younger shells (those younger than 30 years old) at four of the six sites (Figure 5.13), indicating conditions at these sites are favourable for continued recruitment. However, it is important to note that only site C6 has any juveniles present (specimens younger than 10 years old). As already mentioned in this section there are two reasons as to why the sample population data in Figure 5.7 may be showing no recent recruitment at sites C1 and C8. However, to determine why there are no younger shells at some sites more sampling and fieldwork is required to check if there really is a lack of recent recruitment. This would further sampling, which has not been feasible within the time constraints of this study.

Other researchers have also found variable age ranges at sites located close to one another; Zettler et al. (2001) presented shell height data (taken as a rough estimate of age) from ten sites in the Baltic Sea. Out of the ten sites only 40% showed any indication of juveniles present (Zettler et al., 2001). Research by Kilada et al. (2007) off the east coast of Canada found a few juveniles at two sites at Sable Bank, but a mainly adult population at the nearby St Mary's Bay. While in the North Sea, Witbaard (1997) found very few small/juvenile shells present in the two populations studied.

The findings from this research, combined with those from Witbaard (1997), Zettler et al. (2001) and Kilada et al. (2007), indicate that different populations in the same geographical region can show variable recruitment rates. This may be due to changing environmental conditions at one site compared to the others which cause juvenile mortality, as proposed by Witbaard (1997), based on work by Murawski et al. (1982). The results herein also indicate some recent recruitment (at the time of sampling) in NW Scotland, the North Sea (Witbaard, 1997), off the east coast of Canada (Kilada et al., 2007) and in the Baltic Sea (Zettler et al., 2001). The presence of juveniles at 40% of the Zettler et al. (2001) sites, 67% of the sites studied here, 50% of Canadian sites (Kilada et al., 2007) and only a few North Sea juveniles (Witbaard, 1997) suggests that while there may be some positive signs of recent recruitment at all these sites relative to the sample dates, there are still signs of population ageing in all the studies reviewed here. The caveat to add here is that these studies are not all up to date, and in order to really determine the current state of the populations, it would be necessary to re-visit and re-sample to see how the population structures have changed since the original studies. Such follow up work at these sites, and others with population age structure data, would help identify areas where *A. islandica* are thriving and where they are dying out – if the underlying reasons behind such information could be identified, it may help to provide an insight into other factors influencing shell growth.

Despite previous research highlighting the palaeoclimate potential of *A. islandica* (Schöne et al., 2003; 2004; 2005a; 2005b; Butler et al., 2009a; 2009b), there has been little published concerning the potential of *A. islandica* from N. W. Scotland (e.g. Stott et al., 2010). The results from this chapter indicate there is between site variability in shell growth form and rate.

6 Geochemical Analysis

6.1 Introduction

Geochemical analyses constrained by well dated shell chronologies have been used to investigate the marine ^{14}C reservoir age effect in Loch Etive, together with the effects of marine discharge from the Sellafield reprocessing plant. Radiocarbon results from Loch Etive have been compared to those from other researchers (i.e. Cage et al., 2006) to provide a better understanding of local marine ^{14}C reservoir age variability. Analysis of $\delta^{13}C$ variability can also be undertaken on shell material to examine the timing and magnitude of the ocean $\delta^{13}C$ Suess Effect (Section 1.4.5) at sites C1 and C7. Results from these sites can be compared to both marine (Butler et al., 2009a) and atmospheric (Francey et al., 1999) Suess Effect records. The $\delta^{13}C$ results are also potentially of use to investigate whether there is an ontogenetic growth trend present in the $\delta^{13}C$ record as has been demonstrated elsewhere (e.g. Butler et al., 2011). If there is a trend present in the data then this must be accounted for to remove any bias that it would introduce to any material sampled from periods of early shell growth.

Both the marine and terrestrial ^{14}C records are miss-matched due to two main factors; (i) the exchange of gases across the ocean-atmosphere boundary is restricted and therefore limits ^{14}C exchange rates, and (ii) upwelling/mixing within the oceans leads to ^{14}C depleted water being introduced to the surface ocean which alters its ^{14}C signal (Cage et al., 2006). The result is that marine organisms have different ^{14}C ages when compared to terrestrial organisms with the same calendar age (Cage et al., 2006). This offset in ^{14}C values between contemporary marine and terrestrial material is known as the marine ^{14}C reservoir age; the global marine ^{14}C reservoir age is 402 years (Stuiver and Brazinuas, 1993). However, there is great variability, both spatially (Stuiver and Brazinuas, 1993; Cage et al., 2006) and over time (e.g. Austin et al., 1995). Therefore, where possible, a local marine ^{14}C reservoir correction should be applied to material from the marine environment. Around the Northeast Atlantic, for example, there are a variety of marine ^{14}C reservoir corrections applied; these are summarised in Cage et al. (2006) and show a range of ΔR values from -107±24 years in the Baltic Sea and 279 years in Danish fjords while the ΔR for Scotland has been reported as -79±17 ^{14}C years (Ascough et al., 2004). The investigation of the marine ^{14}C reservoir age of Scottish fjords has previously been undertaken for Lochs Fyne and Creran by Cage et al. (2006). Adding data from Loch Etive (Figure 2.1; Section 2.1.1.1) to this dataset would allow further testing of the hypothesis proposed in Cage et al. (2006), that the restricted exchange between coastal and fjordic waters (as outlined in Section 1.4) may result in lower fjordic reservoir ages. Correctly dated, well placed, mollusc chronologies can theoretically be used to calculate the marine ^{14}C reservoir ages as part of a wider geographical network.

Marine organisms, such as *A. islandica*, with the potential for a high ^{14}C sampling resolution, can also be used to investigate the timing of the ^{14}C bomb peak in the marine environment. During the 1950s and 1960s there were a series of nuclear weapons tests carried out which profoundly influenced the atmospheric ^{14}C signature, leading to a significant peak in values in the early 1960s (Levin and Kromer, 1997). In the northern hemisphere the timing of the bomb-peak is 1963 (Goslar et al., 2005), while it dates to 1965 in the southern hemisphere (Currie et al., 2006). The timing of the bomb-peak in the marine environment has the potential to be used as a tracer of localised ocean-atmosphere exchange processes and also to investigate ocean circulation (Weidman and Jones, 1993). This is done by determining the offset in the timing of the bomb-peak between a marine sample and the equivalent atmospheric age. Data collected from Loch Etive can be compared to ^{14}C records from elsewhere to see how the timing of the bomb-peak differs to those from Loch Creran, the North Sea, the Labrador Sea and the Scottish west coast.

Marine calcite/aragonite organisms derive their ^{14}C signature from two sources; dissolved inorganic carbon (DIC) and metabolic carbon (Ascough et al., 2005). When choosing a species to work with it is important to determine the nature of their food source, as this impacts on the ^{14}C age of the metabolic carbon source. Research has shown that deposit feeders, which consume food on the sea bed of different ages, do not grow in equilibrium with the surrounding seawater geochemical signature (Hogg et al., 1998). However, filter-feeders (Chapter 1) mainly rely on suspended food sources such as phytoplankton which generally have the same ^{14}C signature as the water in which they grow, and therefore the animals eating them can be considered as growing in equilibrium with the surrounding water (Hogg et al., 1998). During the calcification process marine calcite/aragonite organisms draw on the seawater DIC pool making it an important source to consider. As *A. islandica* is a filter-feeder it is considered a reliable recorder of seawater $^{14}C_{DIC}$. *A. islandica* growth increment-resolved ^{14}C data from Loch Etive can therefore potentially be used to investigate the marine ^{14}C reservoir age in the loch, as well as the timing of the ^{14}C bomb peak.

The $\delta^{13}C$ Suess Effect (see Chapter 1; Section 1.4.5) causes a change in $\delta^{13}C$ values of both the atmosphere and marine environment due to CO_2 released from fossil fuel combustion (Bacastow et al., 1996), a process that has greatly accelerated since the start of the Industrial Revolution (Baxter and Walton, 1970). This occurs because fossil fuel-derived CO_2 has a ^{13}C depletion (Cage and Austin, 2010) and therefore as more fossil fuel has been burnt, atmospheric and marine $\delta^{13}C$ values have decreased. Within the marine environment the strength of the Suess Effect differs depending on exchange rates with the atmosphere; however ^{13}C in the oceans can also be influenced by changes in primary production (Brandes, 2009). When the $\delta^{13}C$ of dissolved inorganic carbon (DIC) of water is calculated these various influences must be considered. Anthropogenic influences over $\delta^{13}C$-DIC, caused by CO_2 released by burning fossil fuels, has been proposed as leading to a 1.0‰ shift towards lighter values over the last 30 years (Brandes, 2009). In order to accurately measure changes in the ocean $\delta^{13}C$ Suess Effect signal there are two main sources of information, marine sediment cores (e.g. Cage and Austin, 2010) and sclerochronological records (e.g. Butler et al., 2009a). The advantage of using $\delta^{13}C$ from *A. islandica* is the ability to provide annually-resolved records of changes over time. However there are multiple sources influencing the shell ^{13}C signature which must be accounted for when analysing the $\delta^{13}C$ record obtained (see Figure 6.1). It is important to note that there are very limited direct observations of coastal ocean seawater $\delta^{13}C_{DIC}$ values available. In Figure 6.1 kinetic effects concerns the rates of diffusion and chemical reactions between isotopically light and isotopically heavy elements (Sharp, 2007). A kinetic effect causes an enrichment of the lighter ^{12}C and ^{16}O due to fractionation during the calcification process (Butler et al., 2011).

Food supply $\delta^{13}C$ signal and metabolic carbon effects can cause the isotopic signal of the shell material to become lighter (Butler et al., 2011) and can be accounted for using a model concept after McConaughey et al. (1997 in Butler et al., 2011). There is some debate in the literature as to whether the ontogenetic growth effect in the GI series also influences shell $\delta^{13}C$. If this is the case then it should be clear in the records presented in Section 6.3.2, and can be accounted for by excluding data from the early portions of shell growth. There is also the possibility of a kinetic effect on the $\delta^{13}C$ shell signal which must also be considered. As this kinetic effect fractionation process influences both the $\delta^{13}C$ and $\delta^{18}O$ signature of the aragonite shell, it is possible to use the $\delta^{18}O$ values (not affected by metabolic influences) to determine if there is a kinetic effect during fractionation by determining if the $\delta^{18}O$ is being deposited in the shell in equilibrium with the surrounding sea water (Butler et al., 2011). Significant positive relationship between $\delta^{18}O$ and $\delta^{13}C$ can also be indicative of a kinetic effect (Butler et al., 2011).

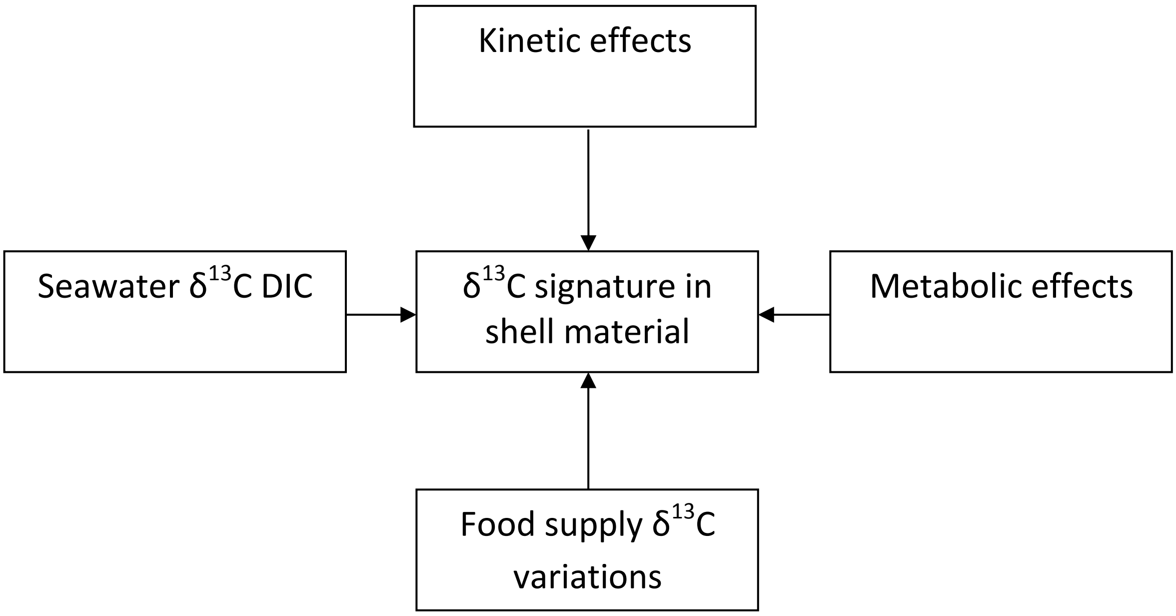


Figure 6.1: Main influences on the $\delta^{13}C$ signature recorded in marine shell material (Information taken from Butler et al., 2011).

6.2 Methods

Shells were selected for isotopic analysis based on the biometric databases created for each site (Chapter 5). Using specimen weight and height data, shells were chosen with a range of predicted ages. This was done in an attempt to ensure that sampling for radiocarbon analysis was undertaken on shells from a spread of ages. Such a methodology was used to try and ensure that samples were taken from a range of calendar ages, thus ensuring that the ^{14}C bomb-peak would be captured when samples were analysed. For the $\delta^{13}C$ samples the same sampling strategy was used for the site C7 data, this is because the samples run for $\delta^{13}C$ from the C7 shells were undertaken on material left over from the ^{14}C analysis. The $\delta^{13}C$ samples for site C1 were chosen based on targeting those shells already crossdated by Stott et al. (2010) from the site. The methods used for geochemical analysis differ for ^{14}C and ^{13}C, depending on the source of the data. The site C7 ^{14}C sampling methodology is outlined here, while those used for site C2 and the North Sea are outlined in Table 6.1 (the results for these were originally published in Stott et al., 2010). These methods primarily differ concerning the sampling site; C2 shell material was drilled from the outer shell after sectioning, while the North Sea samples were taken from a shell slice 2mm thick, and the outer shell layer was then sub-sectioned into samples comprising one or more annual bands (Stott et al., 2010). Data for the ocean $\delta^{13}C$ Suess Effect investigation comes from two sites, C1 (Daniels, 2010) and C7 (this research) (see

Figure 2.1); both used the same material collection methods. The common sampling methods are summarised in Figure 6.2 with more detail outlined in Sections 6.2.1 and 6.2.2 for radiocarbon (^{14}C) analysis and stable isotope analysis respectively.

Table 6.1: Sampling techniques applied to shells from site C2 and the North Sea (from Stott et al., 2010; 1606)

Site	**Collection method**
C2	The National Museum of Scotland (NMS) sample NM921-415 (named C2-MS1 for analysis at University of St Andrews) was live-collected from site C2 in 1968 (Gage, 1972a, b) and archived at the NMS. The shell was sampled for AMS radiocarbon analysis (AMS ^{14}C) to investigate the marine ^{14}C radiocarbon reservoir effect in Scotland by drilling nine samples from the outer periostracum layer. Out of the nine shells samples, two sample weights were under 4 mg and therefore did not yield useable results. Despite this, the advantage of using this sampling technique is that it permits sampling of a single GI during the early period of shell growth (where GIs are wider than those deposited in later life), allowing for an exact calendar age to be assigned to samples from the juvenile period, with an error of one to two years for later life (where smaller GIs mean that sampling resolution can cover a several years), e.g. on Figure 6.5, these sampling errors are illustrated with horizontal error bars. The standard used for this analysis was PDB.
North Sea, German Bight	Shells from the North Sea were live-collected in 1990 using dredge hauls from the German Bight (54'N 6'E) at a water depth of approximately 37 m and were analysed by: 1) Sectioning along the axis of maximum growth and removing a 2mm slice of shell 2) Sampling the outer layer sectioned to produce samples of one or more GIs 3) Creating a GI chronology using photographs of shell thin-sections 4) AMS ^{14}C analysis - shell samples were etched in 10% HCl for 30 seconds (to remove contaminants from the surface of the sample) before conversion of the sample to CO_2 and then graphite, ready for AMS ^{14}C analysis (Gagon and Jones, 1993). The AMS ^{14}C analyses were carried out at the National Ocean Sciences AMS Facility (Woods Hole Oceanographic Institution) and samples were normalised following the methods in Stuiver and Polach (1977) using PDB.

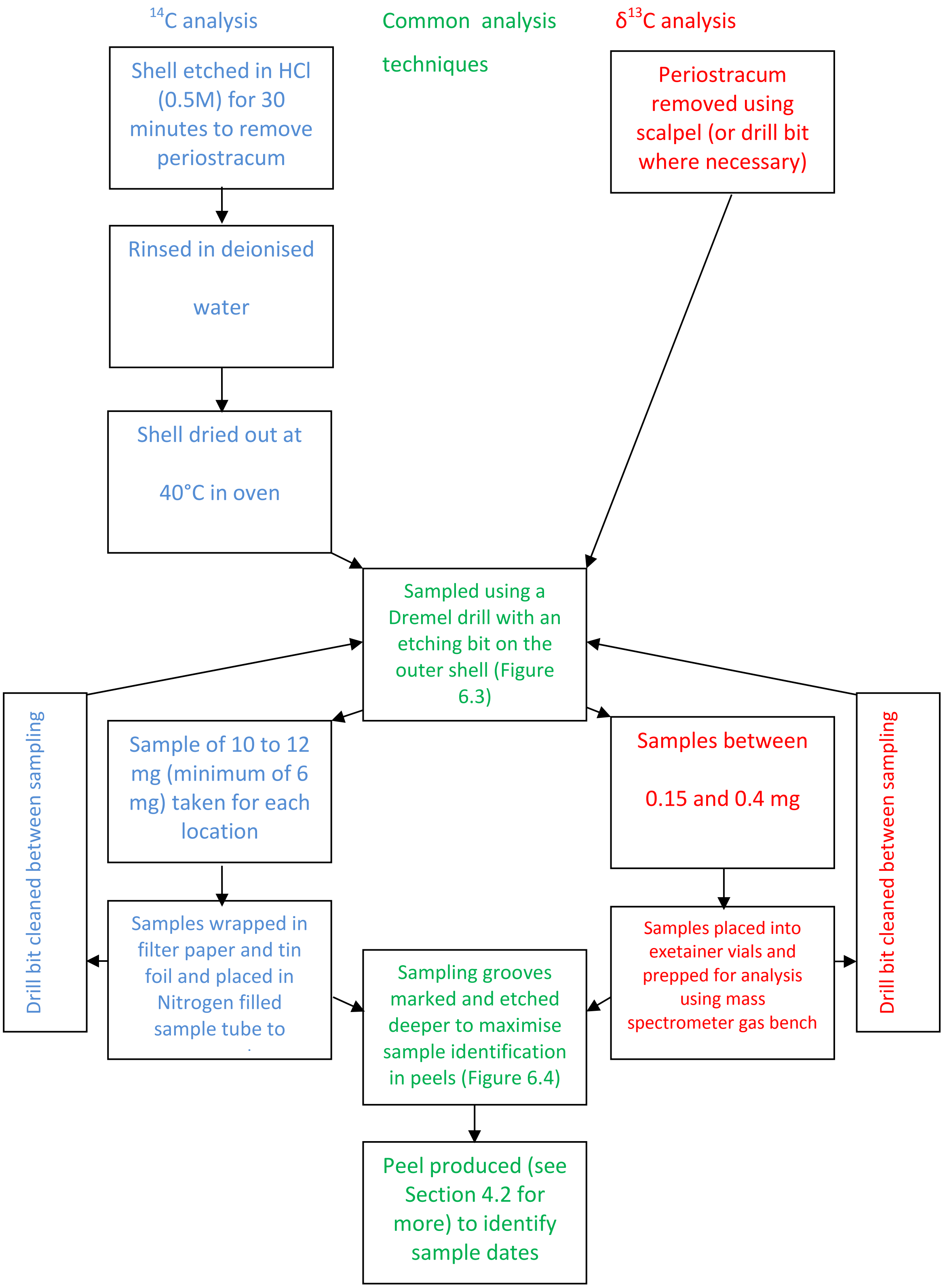


Figure 6.2: Summary of sampling techniques used for geochemical analysis

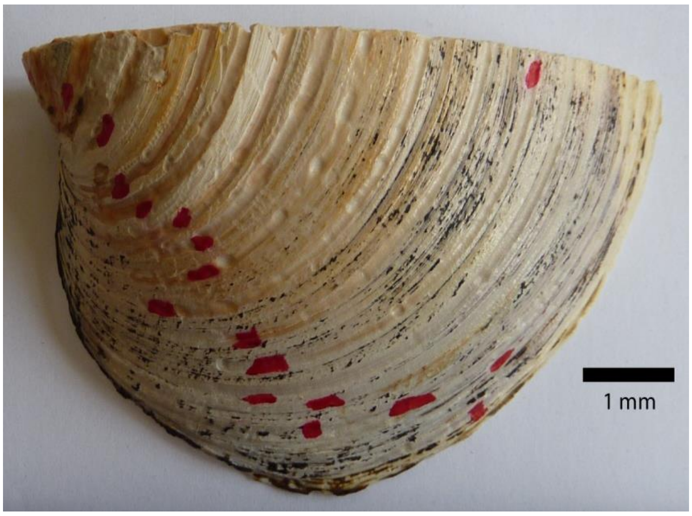


Figure 6.3: Example of sampled shell – each red mark represents a sampling location

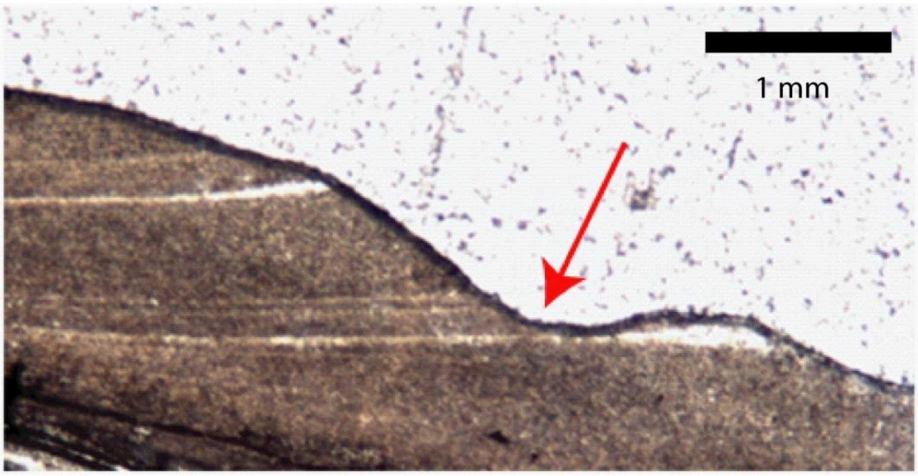


Figure 6.4: Example of a sample site on an acetate peel with red arrow indicating the sample location.

6.2.1 Radiocarbon (^{14}C) Analysis

6.2.1.1 Site C7 shells

Samples for radiocarbon analysis at site C7 (Figure 2.1) were taken from the outside of three shells (C7-L48(2), C7-L127 and C7-L104) - this sampling was undertaken on shells not crossdated into the site C7 master chronology, which has implications for the dating control of the radiocarbon and stable isotope results, this is considered in the discussion of the results later in this chapter.

It is perhaps worth highlighting that it is not unknown in sclerochronological literature for radiocarbon dating to be undertaken on shells where GI calendar age determination is undertaken by increment counting without crossdating support (e.g. Weidman and Jones, 1993; Scourse et al., 2012).

Previous research by Daniels (2010) was used to ensure sampling did not go too deep into the shell, thereby ensuring that adjacent, older material from lower down in the shell was not sampled. Where feasible, sampling was carried out on the left-hand valve, though if this valve had already been sampled for growth increment analysis then the right hand valve was used (see Figure 6.2 for more details). To check for contamination associated with the sampling method (e.g. contamination by atmospheric radiocarbon signal due to incorrect storage after sampling) a piece of Icelandic Spar Calcite (ISC) was also sampled and prepared in the same way in the laboratory and analysed at the same time. The data generated from analysis of the ISC can be used as a standard to check for ^{14}C contamination introduced in the laboratory.

All ^{14}C samples were analysed at the NERC radiocarbon facility at East Kilbride in 2010 and 2011 as part of a NERC radiocarbon grant facility award. Once samples were received by the laboratory they were removed from the nitrogen-rich atmosphere and prepared for analysis by graphitisation reduction (no pre-treatment was required at the laboratory, due to the earlier removal of the outer portion of the shell using HCl). Although best efforts were made to ensure that all samples were of a suitable weight, some were too small to be run on the conventional sample wheel and had to be analysed on a small wheel at the same facility.

Once the shells had been sub-sampled, they were mounted as outlined in Section 4.2. Through careful examination of the peel it was possible to determine which calendar year(s) each sample came from (with as much accuracy as possible, but without any crossdating being undertaken), thus providing a calendar age to compare with the ^{14}C age and potentially provide a means to determine the marine ^{14}C reservoir effect. Ideally, crossdating of growth increments should be undertaken to provide confidence in the dating control. However, this is not always achievable using this method (see Section 6.4 for a discussion on the limitations of this sampling methodology).

6.2.1.2 Marine ^{14}C Reservoir Age Analysis

The marine ^{14}C reservoir age (R(t)), a term used to describe the offset in ^{14}C values between contemporary marine and terrestrial ages, is calculated using Equation 6.1 (adapted from Cage et al., 2006):

$$R(t) = {}^{14}C_M(t) - {}^{14}C_T(t) \qquad \text{Equation 6.1}$$

Where R(t) is the marine ^{14}C reservoir age

$^{14}C_M(t)$ is the marine ^{14}C age from the sample

$^{14}C_T(t)$ is the contemporaneous ^{14}C terrestrial age and is determined using the IntCal09 terrestrial radiocarbon calibration curve (Reimer et al., 2009).

Applying the marine ^{14}C reservoir correction to a sample takes into account the fact that it grew in a non-terrestrial setting and thus has a different ^{14}C signal to contemporaneous terrestrial material obtaining ^{14}C directly from the atmosphere. To compare radiocarbon data from this thesis to that collected elsewhere from the marine environment it must be converted to ΔR values using Equation 6.2. ΔR is used to investigate how the $^{14}C_M(t)$ differs from the marine radiocarbon calibration model curve (Cage et al., 2006).

$$\Delta R = {}^{14}C_M(t) - \text{Marine09}(t) \qquad \text{Equation 6.2}$$

Where $^{14}C_M(t)$ is the measured ^{14}C value from the sample

Marine09(t) is the contemporaneous marine calibration curve ^{14}C age using the Marine09 curve (Reimer et al., 2009)[1].

[1]Since the preparation of this thesis chapter there has been an update to this curve which has been published (Reimer et al., 2013)

ΔR values for the Loch Creran and Etive samples can be compared to those from the North Sea, Australia and the Irvine Bay on the Scottish coast (Stott et al., 2010, Duffel and Griffin, 1995 and Foster, 2007 respectively). These datasets have been chosen due to their shallow, shelf sea settings. Comparisons of these datasets allows for the exploration of differences in the timing and magnitude of the ^{14}C bomb-peak in the different locations.

6.2.2 Stable isotope (^{13}C) analysis

Isotope data are available from two sites – C1 and C7 (Figure 2.1). The C1 data comes from Daniels (2010) and the C7 data was specifically run for this research. At C1, data was collected from five shells; C1-L2, C1-L4, C1-L14, C1-L17 and C1-L19, while at C7 three shells, C7-L48(2), C7-L104 and C7-L127, were sampled for $\delta^{13}C$ analysis. Out of the five shells sampled from site C1 data for C1-L4 and C1-L14 have been omitted because these two shells yielded highly variable data, suggesting an unusual level of 'noise' in the mass spectrometer analysis of these samples, meaning that there is no confidence in the data and therefore it has not been used. However, this data can be seen in Appendix 16. As the C7 shells were initially sampled for ^{14}C radiocarbon analysis, the samples are larger in weight than those required for $\delta^{13}C$ analysis, therefore fewer samples (with a higher age range) are available from these three shells compared to site C1. Excluding C1L19, all samples were run at the University of St Andrews (Daniels, 2010); C1L19 analyses were out-sourced to Cambridge due to analytical problems at the time of study.

Sampling methods are outlined in Figure 6.2. Once samples were collected and weighed they were prepared for analysis in the gas bench section of the mass spectrometer. This was done by placing the sample at the bottom of an exetainer vial where, after being left to dry out at 40°C overnight to remove any moisture present, it was flush filled with helium gas to remove any modern CO_2 present in the vial and thus remove this source of contamination. After successful flush filling, each sample had approximately 8 drops of orthophosphoric acid (H_3PO_4) added to it by injection through the vial septum. The acid reacts with the sample to release CO_2. After being left for 24 hours in the auto sampler for the reaction to complete, the CO_2 was then analysed in the mass spectrometer. Alongside the samples being analysed, one blank is run at the start and samples with known values of $\delta^{18}O$ and $\delta^{13}C$ are included as standards. The primary standard used is Carrara marble which is run in sample pairs, with two standards run for every 10 samples. These standards should be of varying weights which encompass the weights of the samples run to help determine the accuracy of the corrections after analysis. In addition to the Carrara marble, NBS-19 standards were also analysed. These were not used for standardisation directly; rather they were used to validate the standardisation to see how well these values are replicated.

A Thermo Finnigan™ Delta Plus XP IRMS with a Thermo Finnigan™ GasBench II was used for all isotope analysis carried out in house (with the exception of the C1-L19 samples. To run samples a standard run practice was adhered to (outlined in Appendix 17). Once sampling was underway the running of the machine was checked occasionally to ensure that for each sample the needle was piercing the septum on each vial. After analysis each output file was examined to ensure there were no air leaks and that there were 10 peaks present for each sample so that there is confidence in the data generated.

The raw data from runs were exported into Excel™ spreadsheets and then corrected for linearity and drift by regression, using the results generated from the 'standard' samples. This is done by analysing how the output values for the standards compare to the known true values. Some of the samples analysed were run as part of an undergraduate dissertation (Daniels, 2010); these are from shells C1-L2, C1-L17 and C1-L19.

6.3 Results and discussion

It is important to highlight that the results presented in this chapter are not based on successfully crossdated shells that form part of a site master chronology, therefore the dating control of the associated radiocarbon and stable isotopes are not verified. In an attempt to overcome this issue, counts to determine the calendar age of the samples were undertaken by several individuals (see section 6.3.1 for more about this method).

6.3.1 Radiocarbon (^{14}C) analyses

The results for sites C7 and C2 (published in Stott et al., 2010), together with those from the North Sea (Stott et al., 2010), Irvine Bay in the UK (Foster, 2007) and Australia (Druffel and Griffin, 1995) are presented in Figure 6.5. From Figure 6.2 it is possible to see that the pre-bomb ^{14}C results for sites C7, C2 and Australia are very similar, while the Irvine Bay pre-bomb values are higher and the

North Sea values lower. The rise in values at site C7 lags those seen in all the other records by up to approximately 20 years. This later rise in ^{14}C values at site C7 does not fit with the expected timing of the ^{14}C bomb-peak in the marine environment and suggest a possible problem with the shell chronology and requires further investigation.

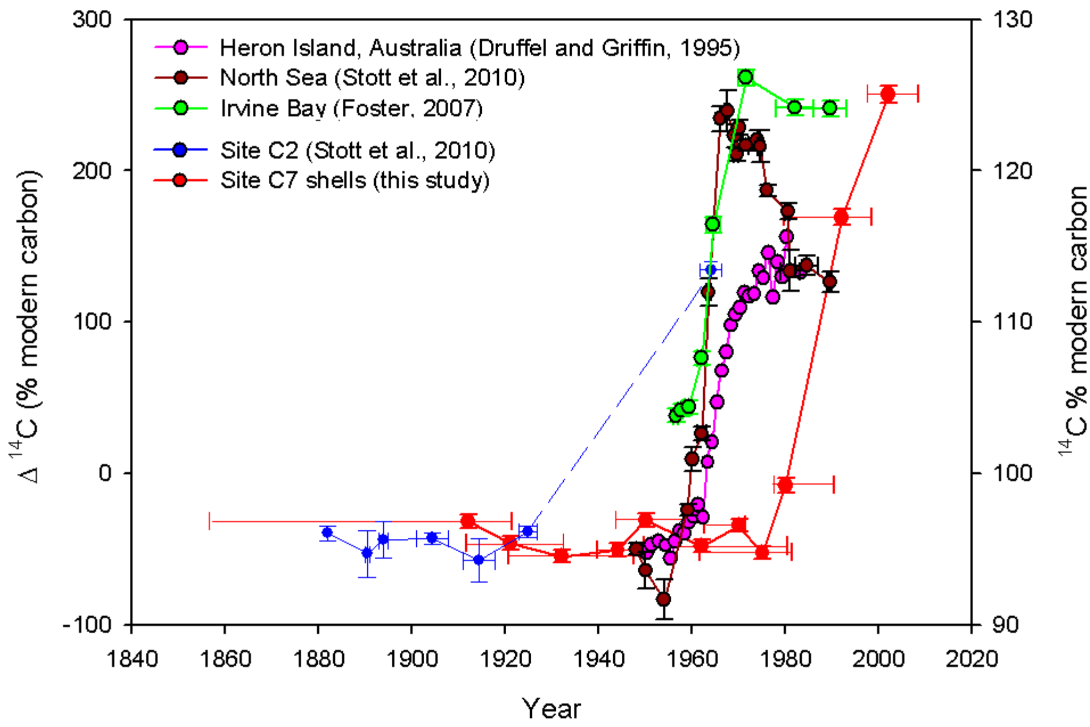


Figure 6.5: ^{14}C percent modern carbon values for sites C7 (red) C2 (blue) and Irvine Bay, Scotland (green) and $\Delta^{14}C$ % modern carbon values for the North Sea (dark red) and Heron Island, Australia (pink). The 1 sigma ^{14}C error is illustrated for both datasets, as are the associated dating errors for the calendar ages for each sample. Dating errors for the site C7 samples were generated using three counts: 'standard' – which provides the point plotted, all growth increments counted – providing a minus error bar, and minimum error was generated through only counting those growth increments that were very clear. It should be noted that the dashed blue line present for the Site C2 dataset is there to highlight the presence of the final sample, it is not there as an attempt to predict how the ^{14}C values between the two final samples would lie.

Out of the three shells sampled for ^{14}C analysis from site C7, it was not possible to crossdate their GI chronologies into the master chronology (see Chapter 4). Therefore, in order to determine the year from which a sample was taken GI counting alone had to be undertaken. To minimise the potential for errors this was undertaken three times for each shell: (1) conservative count – only very clear GIs were counted, (2) 'normal' count – only GIs normally counted for GI measurements were included, and (3) generous count – all bands however faint were counted. These counts were then compiled to create the error bars in Figure 6.5. The lack of crossdating of GIs in the three shells from site C7 means that any subsequent analysis of the C7 isotopic data (both ^{14}C and $\delta^{13}C$) must be analysed with caution as the calendar dates presented may not be absolutely correct.

When the site C7 dataset is compared to that from Irvine Bay (Figure 6.5), it is possible to see that the next nearest ^{14}C record has its bomb-peak in the 1960s/1970s. There are some slight offsets in the timing of the ^{14}C peaks in Figure 6.2 between the North Sea, Irvine Bay and Australian records, but generally they fall between 1967 and 1973. However, the peak for Heron Islands is slightly later (1976). The lag between the timing of the bomb-peak at site C7 compared to the other records in Figure 6.5 could be due to a dating issue, however this is unlikely, as not only would any error have to be replicated in all three shells analysed, but GI counting was carried out by several individuals for confirmation purposes. Figure 6.5 confirms that the timing of the bomb-peak in ^{14}C values at site C7 is much later than would be expected when looking at other sites. It also highlights that the values the C7 shells are recording for the late 1990s and early 2000s are higher than would be expected based on other results illustrated in Figure 6.5, with the exception of Irvine Bay. Foster (2007) proposed that the Irvine Bay ^{14}C values remain high, post bomb-peak, due to a terrestrial signal influencing the site. If this is the case then the shallow nature of sites C2 and C7 (20 m and 16-24 m respectively) could also be influenced by a similar signal. It was also proposed by Foster (2007) that the Sellafield nuclear reprocessing plant discharge influenced the ^{14}C values in the Irvine Bay *A. islandica* samples. It is clear that the pronounced rise in ^{14}C during the 1960s is absent from the C7 material, suggesting that there may be a problem with the GI chronology at this site, i.e. multiple missing GIs.

6.3.2 Sellafield ^{14}C discharge history

The Sellafield nuclear reprocessing plant (Figure 6.6) has been operating since the early 1950s (Gardner, 1993; WISE-Paris, 2001). During most of its history its atmospheric and marine discharge rates have been monitored, and several major discharge-related incidents have been reported (Simmonds et al., 1995; Greenpeace, 2012). Of interest here are ^{14}C discharge rates, how these have varied over time and how ^{14}C has been transported along the west coast to Scotland and beyond. ^{14}C discharge rates from Sellafield are illustrated in Figure 6.7, along with the C2, C7 and Irvine Bay data. Sellafield ^{14}C discharge peaked in the 1990s, early 2000s and later 2000s (Figure 6.7), which could in theory be responsible for the sustained high ^{14}C values recorded in both the Irvine Bay and site C7 post bomb-peak records. However, whether or not the Sellafield ^{14}C discharge would influence site C7 ^{14}C values requires further investigation. Moving up the west coast of N. England/ Scotland, from Sellafield to Wick (Figure 6.6), records of uptake values of various chemical discharges related to Sellafield in seaweed have been studied (RIFE, 1996 to 2009 inclusive). There is generally a lack of information concerning ^{14}C, therefore ^{99}Tc data are used and presented in Figure 6.8 for the period 1995 to 2008 (^{99}Tc can be used as it is also a recorded aqueous discharge from the Sellafield processing plant). Moving up from Sellafield there is a general decreasing trend in ^{99}Tc concentrations in seaweed, however it is important to note that Sellafield ^{99}Tc is still recorded at Cape Wrath and it can be concluded that discharge from Sellafield has a wide reach. It is likely that the ^{14}C discharge follows a similar pattern of decreasing values moving up through Scotland. While it is feasible that some of the high levels of ^{14}C discharge from Sellafield may influence the high ^{14}C values recorded in the shells at site C7 from the 1990s onwards, these data do not help to explain why there is no bomb-peak recorded in the 1960s/1970s at the site.

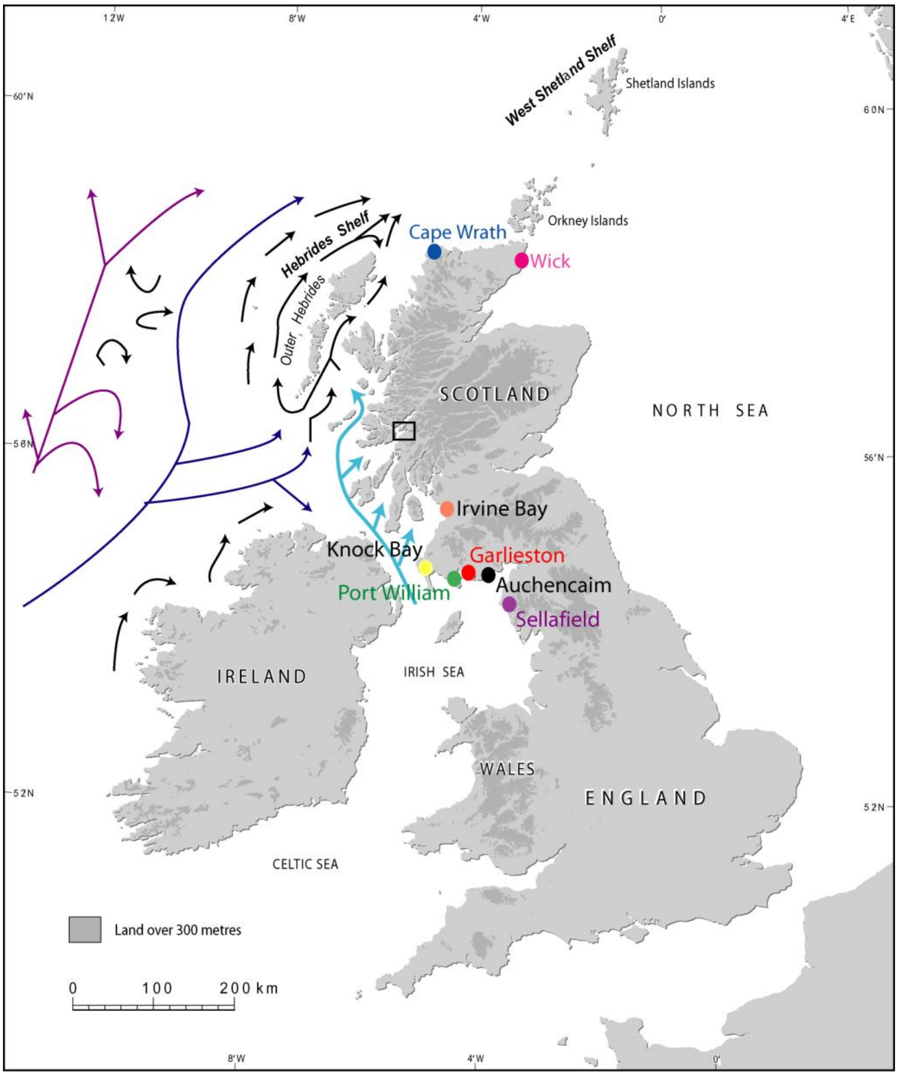


Figure 6.6: Location of Sellafield in relation to the field area (black rectangle). Also illustrated are the locations from which ^{99}Tc contamination levels of seaweed/aquatic plants has been analysed (see Figure 6.8). Also illustrated are some of the major currents present off the west coast, including the Scottish Coastal Current (light blue), North Atlantic Slope Current (dark blue) and the North Atlantic Current (purple). These currents, in particular the Scottish Coastal Current, highlight how discharge from Sellafield could easily be carried up the coast to the field area (Current information is adapted from Cage and Austin, 2010).

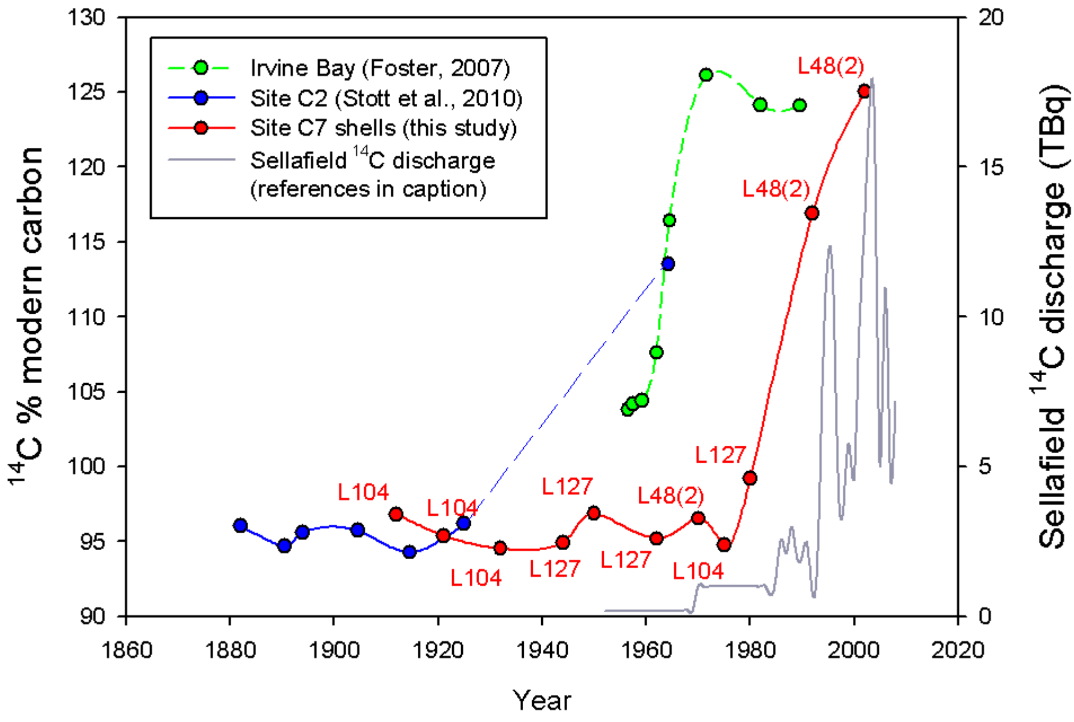


Figure 6.7: Discharge rates of ^{14}C from Sellafield from 1952 to 2008 are presented in grey along with ^{14}C data from sites C2 and C7 and the Irvine Bay location from Foster (2007). Discharge values for Sellafield come from Jackson et al. (2000) for the period 1952 to 1998, data from 1999 to 2008 comes from BNFL (2000; 2001; 2003) and Sellafield Ltd. (2008). It should be noted that the dashed blue line present for the Site C2 dataset is there to highlight the presence of the final sample; it is not there as an attempt to predict how the ^{14}C values between the two final samples would lie. As previously stated the data for site C7comes from three different shells, with each data point coming from a single sample, rather than representing a pooled value. The shell from which each sample has been derived has also been indicated on the figure. This helps to clarify that the samples from where the bomb-peak is expected to be seen onwards are not all from the same shell, therefore helping to reduce the possibility that the reason for the bomb-peak not being in the expected position is not likely down to a dating control issue.

The lack of a bomb-peak in the 1960s/1970s at site C7 is particularly unusual given that site C2, also located in a shallow water fjordic environment, shows a value plotting on the rising limb of the bomb-peak. Therefore, it seems unlikely that site C7 would not exhibit a bomb-peak due to its fjordic location. The shallow nature of site C7 (16-24 m) means that exchange of ^{14}C between the atmosphere and water should lead to the rapid uptake of the bomb-peak signal in the shells of *A. islandica* (Foster, 2007). This is clearly not the case, with the ^{14}C bomb-peak timing being out by approximately 15 years in *A. islandica* from site C7. It is unlikely that this is caused by mis-counting of GIs or multiple missing GIs, especially when it is considered that the results presented are from three different shells and therefore all three would have had to be mis-counted by the same amount or have the same amount of missing GIs.

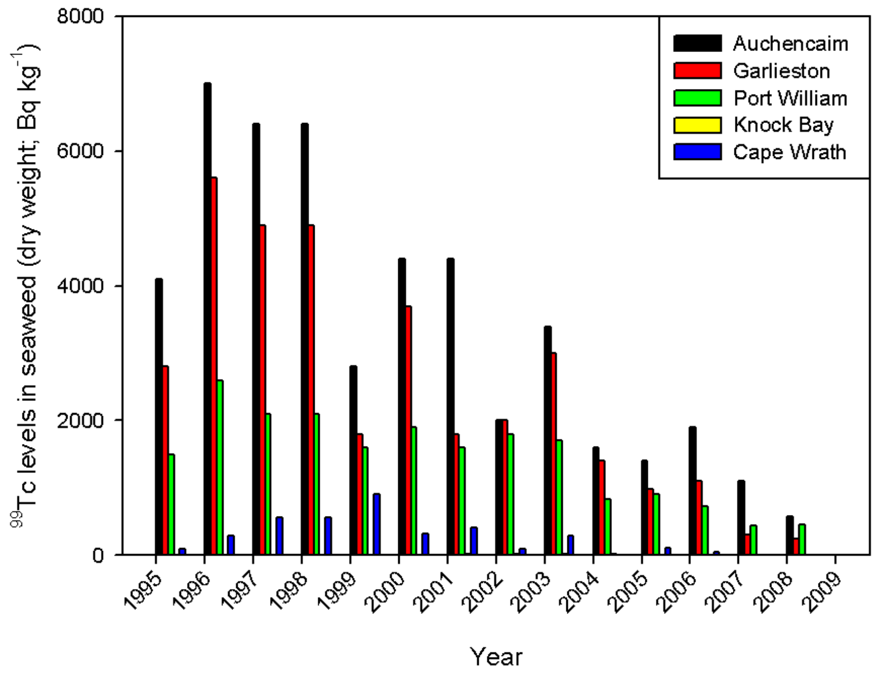


Figure 6.8: Values of ^{99}Tc recorded in various seaweed species/aquatic plants moving from Auchencaim to Cape Wrath (for site locations see Figure 6.5). Data sourced from RIFE reports from 1995 to 2008 (RIFE, 1996 to 2009 inclusive).

Weidman and Jones (1993) found a slight difference in the timing of ^{14}C bomb-peaks in various *A. islandica* records. It was proposed that this was due to differences in site type, and collection depth variations. However, these age offsets were typically only 1 to 2 years (Weidman and Jones, 1993), and thus they are not comparable to the delay in the bomb-peak at site C7. Also there is no mention of crossdating being carried out by Weidman and Jones (1993); therefore this is within a realistic dating uncertainty error. Another potential reason for the later than expected rise in ^{14}C values is that perhaps for some reason GIs in the three shells sampled at site C7 are not deposited annually. Turekian et al. (1982) found a single shell in their sample set where the number of GIs and calendar years did not match up according to ^{14}C data. They inferred that multiple GIs were deposited in a single year, although this did not fit with their ^{228}Th data which suggests annual banding in shells at the site. Turekian et al. (1982) highlighted that the shell that was apparently exhibiting non-annually resolved GIs was from a site with shallower water depths (29 m) compared to the site where no problems were found with the ^{14}C data (>55 m). It is also important to note that from the shallower site another two shells were analysed and their results were also unclear. They inferred that in the shallower site multiple GIs were deposited each year; however they offer no explanation for this, although they noted dumping in the area (Gross, 1976 in Turekian et al., 1982) which may also be a factor to consider. The results from Turekian et al. (1982) highlight that there is the potential for *A. islandica* GIs to be non-annual.

6.3.3 Stable isotope (^{13}C) analysis

6.3.3.1 Kinetic effects

Whether the *A. islandica* sampled for $\delta^{13}C$ analyses were influenced by kinetic effects deserves further investigation. The fractionation of isotopes causing an enrichment of the lighter isotopes can be investigated in two ways. The first is to test whether the $\delta^{18}O$ signal is in equilibrium with the surrounding seawater as this suggests no kinetic effect over $\delta^{18}O$, and therefore by extension $\delta^{13}C$. It can also be tested by seeing if there is a significant correlation between the $\delta^{18}O$ and $\delta^{13}C$ values recorded. Previous research (Weidman et al., 1994; Buchardt and Simonarson, 2003; Schöne et al., 2005) has demonstrated that $\delta^{18}O$ in the shell of *A. islandica* is deposited in equilibrium with seawater. Such results can be taken to indicate that there is no kinetic $\delta^{13}C$ effect in *A. islandica.* This statement is also supported by Butler et al. (2011) who found no significant relationship between $\delta^{18}O$ and $\delta^{13}C$ values in Gulf of Maine *A. islandica*. The correlations between $\delta^{18}O$ and $\delta^{13}C$ for the shells used here are presented in Figure 6.9. The site C7 shells and shells C1-L2 and C1-L19 show no significant relationship between $\delta^{18}O$ and $\delta^{13}C$, indicating there is no kinetic effect on $\delta^{13}C$ for these five shells. For shell C1-L17 (Figure 6.9) there is a significant relationship between the two variables, indicating that there may be a kinetic effect on $\delta^{13}C$ values for this shell. The caveat with all these analyses is that they were carried out on datasets with low replication, which may influence the results. Such results do not fit with the previous findings by Butler et al. (2011) and with the other shells studied here; the reason for this is not clear.

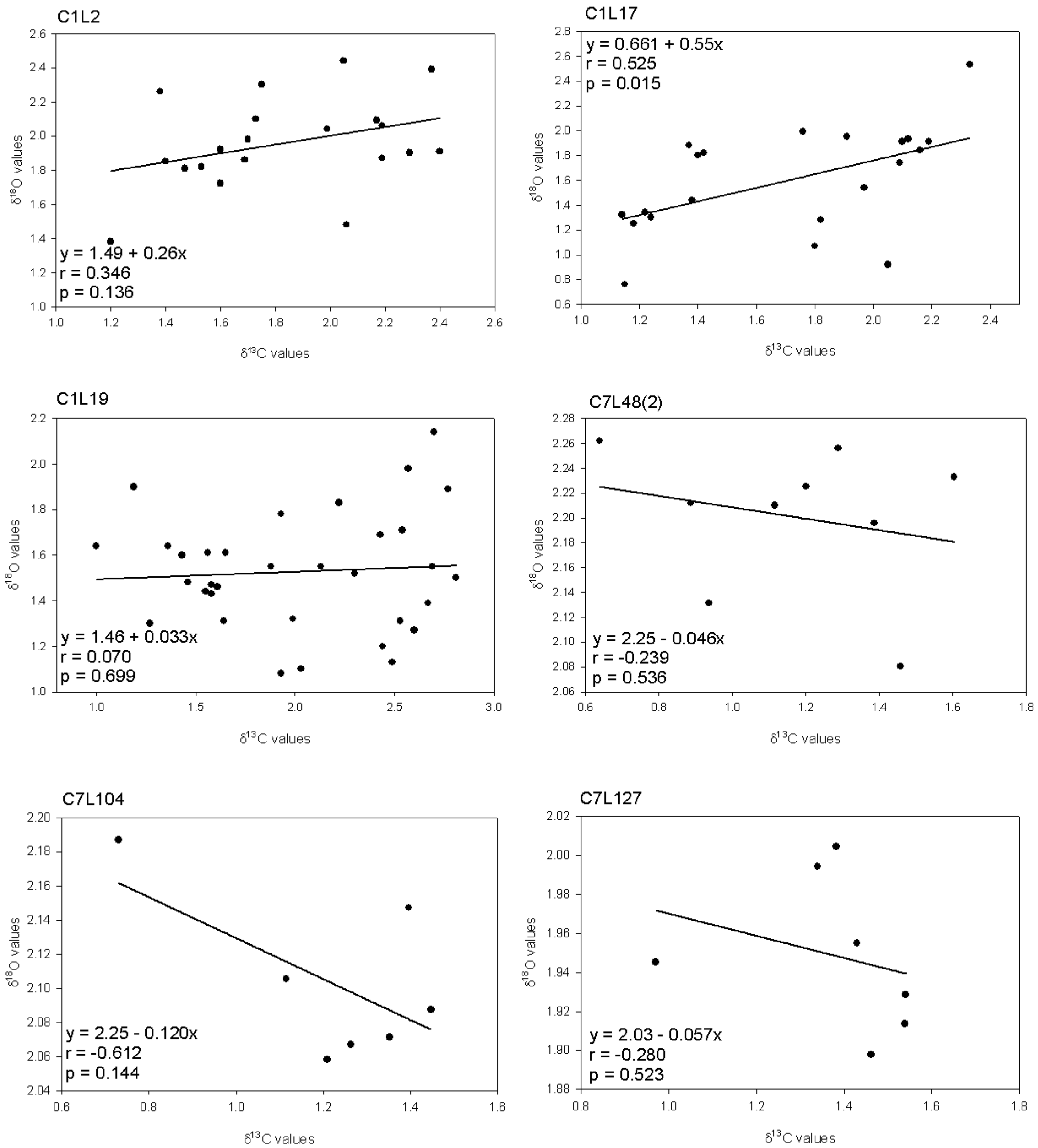


Figure 6.9: Plots of δ^{13}C against δ^{18}O values for all six shells analysed/presented here to test for the presence of a kinetic effect on δ^{13}C values in the shells. All measurements are ‰ with relation to VPDB.

6.3.3.2 Ontogenetic growth effect

A scatter plot (Figure 6.10) of samples analysed for δ^{13}C analysis, along with their age and measurement errors are presented to investigate the presence of an ontogenetic growth effect on δ^{13}C values. Shells C7-L48(2), C7-L104 and C7-L127 (Figure 6.10) were sampled specifically for this research, while shells C1-L2, C1-L17 and C1-L19 come from Daniels (2010). There is an early increase in $\delta^{13}C$ values at the beginning of all the series with the exception of shell C7-L127 (Figure 6.10). It is important to note that these results include material collected from the three C7 shells on which radiocarbon analyses were undertaken. There is the possibility that the GIs in samples C7-L48(2), C7-L104 and C7-L127, are not annually resolved as highlighted by the late timing of the bomb-peak at the site. Therefore, while they are still included here to see if they show similar results to those at site C1, they are not used for any ocean $\delta^{13}C$ Suess Effect analysis (Section 6.3.2.3).

All three site C1 shells show clear early increases in $\delta^{13}C$ values, while for the site C7 shells this increase is not as pronounced (with the possible exception of shell C7-L48(2). The data presented in Figure 6.10 also indicates a difference in the $\delta^{13}C$ value ranges between the two sites; C1 has a much larger range (0.999 to 2.63‰) than site C7 (0.639 to 1.61‰). The most likely explanation for this difference in $\delta^{13}C$ values between the two sites is that when moving from the more coastal C1 to the fjordic C7 site there is a DIC gradient moving up-fjord, which impacts on the recorded $\delta^{13}C$ values due to the importance of DIC impacting on shell $\delta^{13}C$ signal. There is evidence presented in Bouillon et al. (2008) that estuarine and mangrove creek $\delta^{13}C_{DIC}$ values are ^{13}C depleted compared to open marine $\delta^{13}C_{DIC}$. This is attributed by Bouillon et al. (2008) to be due to;

1) Freshening of the estuarine water from a freshwater source that is $\delta^{13}C_{DIC}$-depleted (see Figure 6 in Bouillon et al., 2008)
2) The input of negative $\delta^{13}C_{DIC}$ from either water column mineralisation processes or intertidal sediments sources (Bouillon et al., 2008)

When looking at global $\delta^{13}C$ values (Figure 6.11) it is possible to see great variability depending on site location and water depth. Also illustrated in Figure 6.11 are seawater $\delta^{13}C$ values recorded by Kroopnik (1985). From Figure 6.11 it can be seen that the site C1 and C7 data encompasses the average global surface water $\delta^{13}C$ value recorded in Kroopnik (1985) of 2.0‰.

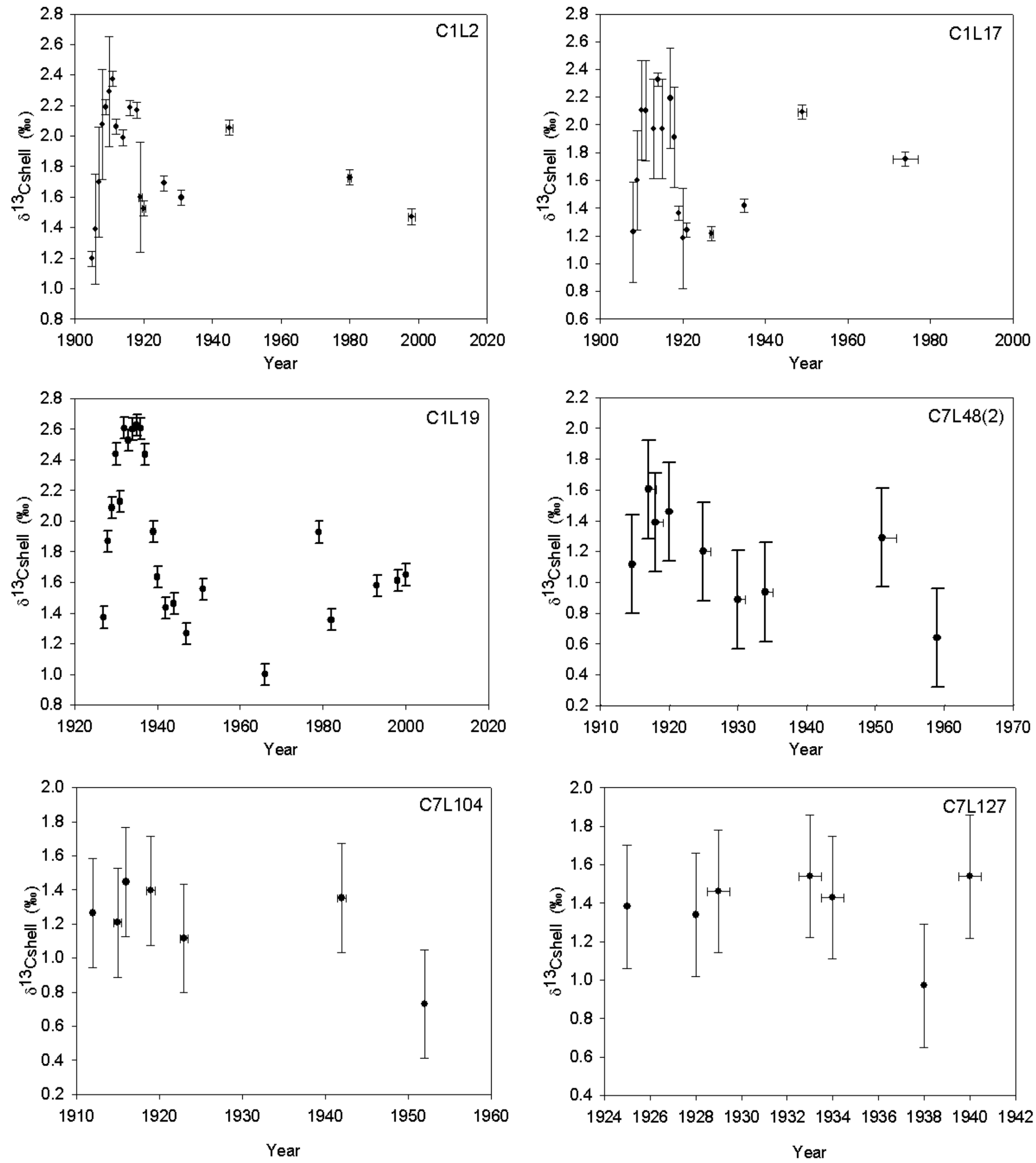


Figure 6.10: δ^{13}C results for the six shells being analysed to investigate the ocean δ^{13}C Suess Effect. All measurement errors are the SD of the standards run.

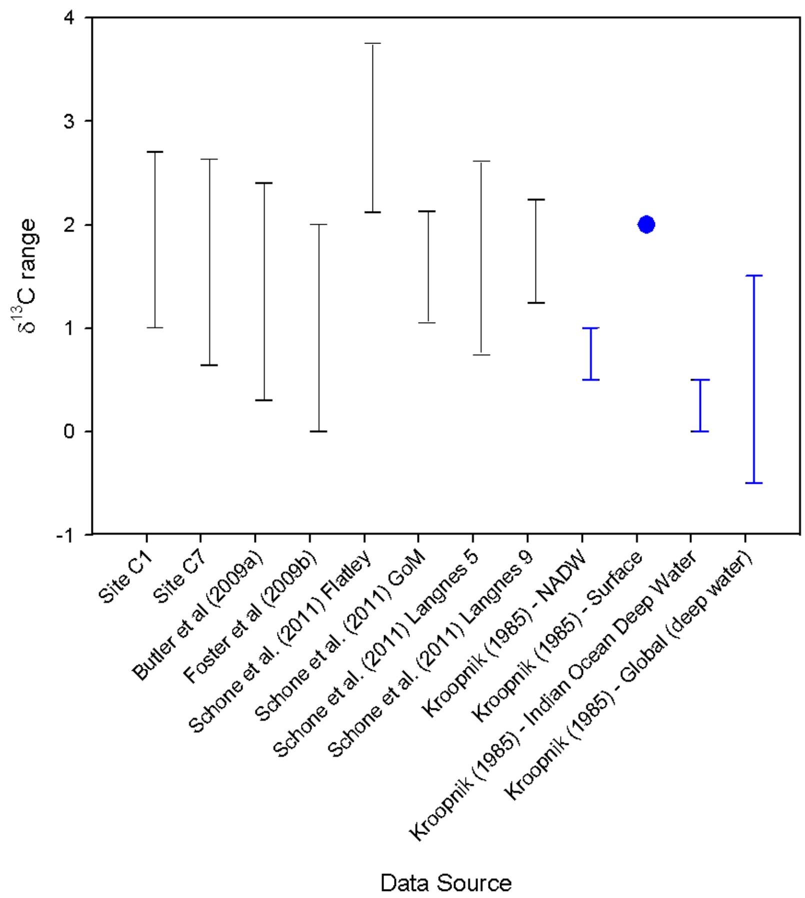


Figure 6.11: Different $\delta^{13}C$ value ranges for multiple marine sources.

When the site C1 $\delta^{13}C$ data are compared to their equivalent GI data (Figure 6.12) it is possible to see that shell $\delta^{13}C$ are most enriched after the ontogenetic peak in maximum GI widths. These offsets are 7± 3 years. The reason for this offset is not known and requires further investigation into shell biology, as well as additional shells sampled for similar analysis to see if this is a common feature at other sampling locations. No GI data was available for the shells sampled from site C7. The relationship between $\delta^{13}C$ and GI widths is also explored in Figure 6.12. For the entire period of analysis of the three shells investigated, there is a significant relationship between the two variables for C1-L19 only. However, if the period of investigation is limited to the interval over which the ontogenetic trend in the $\delta^{13}C$ values is observed (i.e. the first 40 years of growth), there is a significant relationship between GI width and $\delta^{13}C$ in shells C1-L17 ($r = 0.579$, $p = 0.030$) and C1-L19 ($r = 0.586$, $p = 0.014$); these relationships remain non-significant in the two other shells.

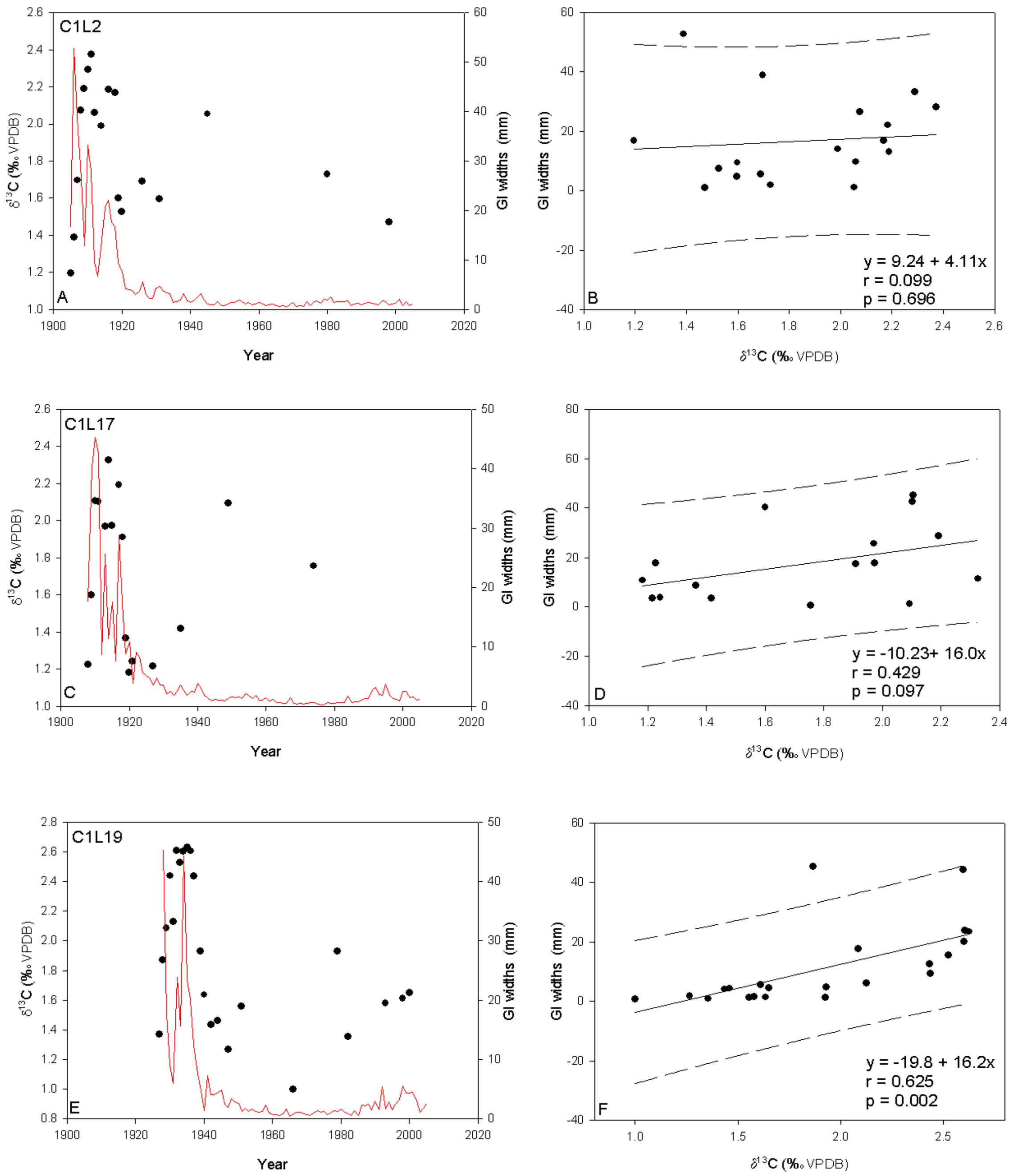


Figure 6.12: A, C and E; Relationships between raw GI rates (red lines) and $\delta^{13}C$ values (black circles) for shells from site C1 and B, D and F; the corresponding linear regressions between these values. It should be noted that after the ontogenetic $\delta^{13}C$ increase, all shell values decrease and then see a later enrichment.

To investigate the relationships presented in Figure 6.12 further, GI and $\delta^{13}C$ data for all three site C1 shells are plotted (Figure 6.13) to determine how the relationships change when the sample number is increased. From Figure 6.13 it can be seen that when all the site C1 data is analysed that the relationship between GI width and $\delta^{13}C$ values are significant.

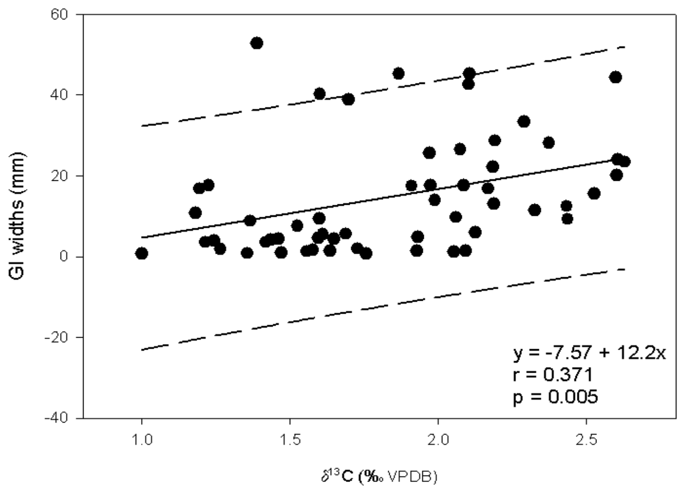
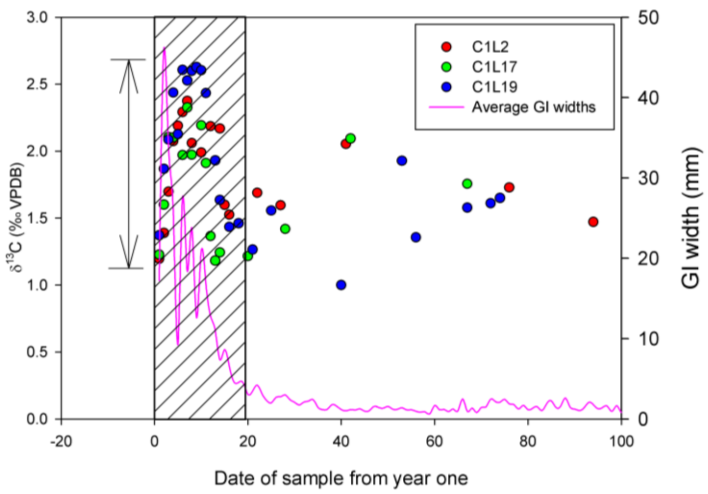


Figure 6.13: Scatter plot of all site C1 GI and δ^{13}C data to further investigate the relationship present between the two variables

If the δ^{13}C data for each shell are plotted along a common axis with each value assigned a year corresponding to the date of the sample based on GI counts from year one, then it is possible to see the relationship between ontogenetic age and δ^{13}C (Figure 6.14 and Table 6.2). This is of interest to define whether the δ^{13}C peaks are the product of either an ontogenetic influence, or some other factor (e.g. climate variability) influencing $\delta\ ^{13}$C at the sites. If the peaks are all within the juvenile period of growth, it is likely that the shells are responding to an ontogenetic effect on δ^{13}C. Alternatively, if they all have $\delta\ ^{13}$C peaks at similar calendar dates this would support the idea that they represent some sort of environmental influence on the δ^{13}C values recorded in the shells. From Table 6.2 it is clear that at both sites the δ^{13}C value peaks occur no more than 8 years after the first GI in each shell, well within the juvenile growth period (9.38 years for the Middle Atlantic Bight (Thompson et al., 1980)). These all support the idea that shells at site C1 have an ontogenetic δ^{13}C effect. Table 6.3 highlights previous research findings concerning ontogenetic influences on δ^{13}C values in several shell species, including *A. islandica*.



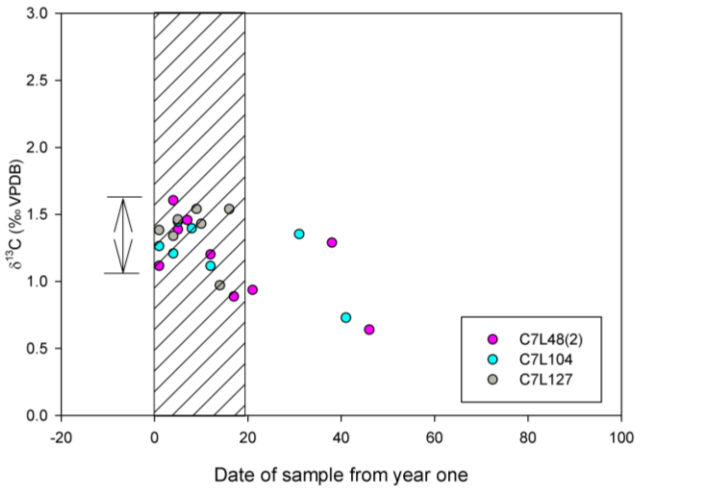


Figure 6.14: $\delta^{13}C$ values for each site plotted so that each sample is assigned a number from year 1 (first GI) to investigate the timing of the $\delta^{13}C$ peaks for each shell. The shaded area in the two graphs encompasses the first 20 years of growth and serves to highlight that the peak in $\delta^{13}C$ values for all six shells occur during this period. Also included with the site C1 data is an indication of where the final decrease in $\delta^{13}C$ values is seen after the ontogenetic peak (40 years for shell C1-L19). The average GI width for all three C1 shells is also illustrated; this clearly highlights that the peak in $\delta^{13}C$ post-dates the GI peak.

Table 6.2: Difference between year of first growth and $\delta^{13}C$ peak to investigate whether these peaks are ontogenetic, or potentially the product of an external factor

Shell ID	Year of first growth	$\delta^{13}C$ peak date	Offset (years)
C1-L2	1905	1911	6
C1-L17	1908	1914	6
C1-L19	1927	1935	8
C7-L48(2)	1914	1917	3
C7-L104	1912	1916	4
C7-L127	1925	1933	8

Table 6.3: Summary of findings from previous research concerning the presence of an ontogenetic influence over $\delta^{13}C$ values in several shell species, including *A. islandica.*

Paper	Shell type	Evidence for/against ontogenetic influence on $\delta^{13}C$ values
Jones et al., 1986	*Tridacara maxima*	Records two distinct $\delta^{13}C$ phases, the first with values from 1.2 to 2.4, then drops to a mean value of 1.1 per mille (110mm into the shell which is believed to be the size of sexual maturity). If this is due to sexual maturity, it suggests that$\delta^{13}C$ changes are ontogenetically linked.
Witbaard, 1997	*Arctica islandica*	Increasing $\delta^{13}C$ values during the first six years of shell growth – this may be the result of ontogenetic influences on $\delta^{13}C$ uptake
Schöne et al., 2005b	*Arctica islandica*	Did not find an ontogenetic influence on $\delta^{13}C$ values
Gillikin et al., 2007	*Mercenaria mercenaria*	The shells investigated recorded an ontogenetic $\delta^{13}C$ decrease – up to 4‰ over the shell lifetime. This is shown not to be the result of respired $\delta^{13}C$ changes.
Butler et al., 2009a	*Arctica islandica*	Mentions theory of $\delta^{13}C$ ontogenetic effect, but shows no supporting evidence
Butler et al., 2011	*Arctica islandica*	Found evidence of an ontogenetic impact on $\delta^{13}C$ values. On the basis of this Butler et al. (2011) suggested not using $\delta^{13}C$ values from the first 40 years of growth
Schöne et al., 2011	*Arctica islandica*	Found no ontogenetic effect on $\delta^{13}C$ values in shells from the Gulf of Maine and Iceland. However it should be noted that out of four shells analysed only one was sampled starting from ontogenetic year 1, the other three were sampled from ontogenetic years 18, 26 and 28 onwards.

Data from the site C1 shells all show a strong ontogenetic $\delta^{13}C$ signal with the presence of high $\delta^{13}C$ values followed by a decline during the juvenile period of growth (Figure 6.14). Although two of the shells have their peaks at a similar time (C-1L2 – 1911 and C1-L17 – 1914), this is because of the similar ages of the two shells. The period over which the ontogenetic influence on $\delta^{13}C$ values varies between the shells; although they all peak within the first 8 ontogenetic years of growth, shell C1-L2 values finish their initial decrease after 19 years, while for shells C1-L17 and C1-L19 this happens at 14-20 and 40 years respectively. After these initial decreases all shells then exhibit some level of $\delta^{13}C$ value increases. At site C7 all shells exhibit this final decrease in values during the first 20 ontogenetic years of growth (Figure 6.13). These results clearly indicate that there should be a truncation of the $\delta^{13}C$ data prior to analysis of the results for ocean $\delta^{13}C$ Suess Effect. However, it is not entirely clear how many years of data should be excluded. In Butler et al. (2011) it was suggested that the first 40 years of data should not be used. This is supported by the results from shell C1-L19, while the other shells analysed here suggest truncation at 20 years. For the purpose of this study the first 40 ontogenetic years worth of data was excluded from ocean $\delta^{13}C$ Suess Effect analysis based on the findings from shell C1-L19 and results presented in Butler et al. (2011). Investigation of additional shells from sites C1 and C7, with a higher sampling resolution, may clarify the exact extent of the ontogenetic $\delta^{13}C$ trend and therefore the point at which a local $\delta^{13}C$ series should be truncated. At site C7, shells C7-L48(2) and C7-L104 both show an ontogenetic $\delta^{13}C$ trend, although not as pronounced as for those shells from C1. This is likely due to the lower resolution of within-shell sampling at C7 compared to site C1 material. Again, for these two C7 shells, the first 40 years worth of samples are potentially unsuitable for ocean $\delta^{13}C$ Suess Effect work. For shell C7-L127 there is no clear ontogenetic trend in the $\delta^{13}C$ values (Figure 6.10), and because all sampling occurs within the first 40 years of growth, the data are deemed unsuitable for ocean $\delta^{13}C$ Suess Effect analysis. Figure 6.14 highlights the difference in magnitude of $\delta^{13}C$ values, and by extension ontogenetic $\delta^{13}C$ effect, between sites C1 and C7. It is likely that this is a product of terrestrial suppression of the $\delta^{13}C_{DIC}$ seawater signal at site C7 and possibly also because of an increased terrestrial (^{12}C – rich) diet and water input from the local catchment at the site.

6.3.3.3 Suess Effect - $\delta^{13}C$ value comparison with other records

Once the ontogenetically-influenced $\delta^{13}C$ values from site C1 are removed from the dataset there are 10 data points suitable for analysis (Figure 6.15) to be compared to other $\delta^{13}C$ Suess Effect records (both marine and terrestrial). One of the main restrictions with the C1 dataset in Figure 6.15 is that the timeframe over which it can be analysed is greatly restricted and does not include material from the pre-industrial period for comparison purposes (see Cage and Austin, 2010 for an example). Figure 6.15 shows that when samples from the early growth period, themselves affected by ontogenetic influences on $\delta^{13}C$, are removed, there is an overall decrease in $\delta^{13}C$ between 1945 and 2000 at site C1. As there is no data available from the pre-industrial period it is not appropriate to fit a trend line to the data. However, it is possible to compare the data in Figure 6.15 to other $\delta^{13}C$ records from both the atmosphere (Figure 6.16) and the marine environment (Figure 6.17) to see how the site C1 record compares in magnitude and trend over the period for which data are available.

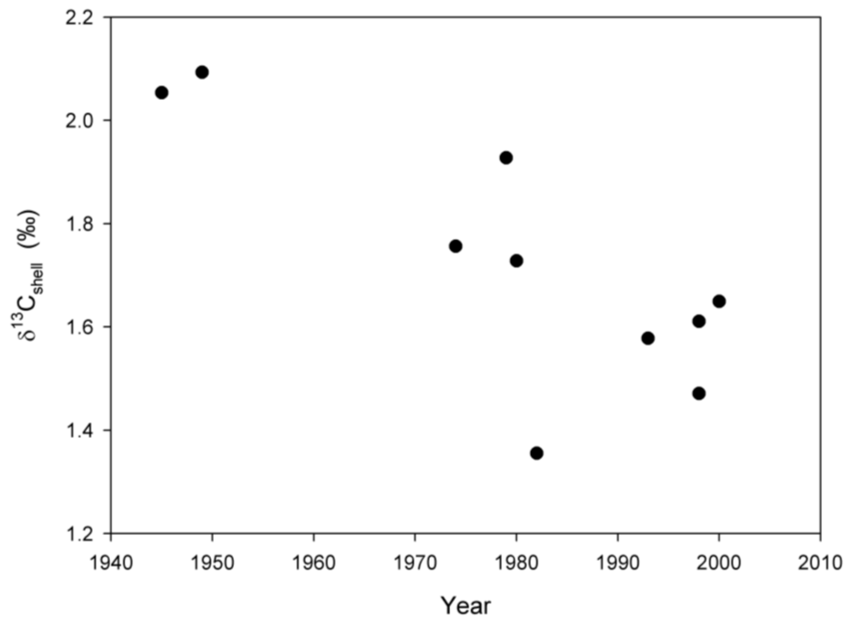


Figure 6.15: $\delta^{13}C$ values for site C1 showing data available for investigation of the oceanic $\delta^{13}C$ Suess Effect in the area. Typical $\delta^{13}C$ analytical uncertainty is ±0.07 per mille; typical age uncertainty with GIs is ± 2 years.

Atmospheric (Figure 6.16) and marine (Figure 6.17) $\delta^{13}C$ data clearly shows a $\delta^{13}C$ Suess Effect signal, with a post-industrial depletion in values after the 1840s in the atmospheric record (Figure 6.16A). The results in Figure 6.16B are in line with other ocean $\delta^{13}C$ Suess Effect data, although this is not as pronounced as in the atmospheric signal over approximately the same period of analysis; 0.037‰ per decade (1945 to 1979) at C1 and 0.16‰ per decade (1944 to 1978) in the atmospheric data (Francey et al., 1999). However, this damped $\delta^{13}C$ Suess Effect response in the marine environment compared to the atmosphere has been noted elsewhere and is likely caused by the mixing of surface water (which is sensitive to atmospheric changes) with older, deeper fjordic waters (Cage and Austin, 2010) (which is less sensitive and influenced by a larger reservoir of stable seawater $\delta^{13}C_{DIC}$).

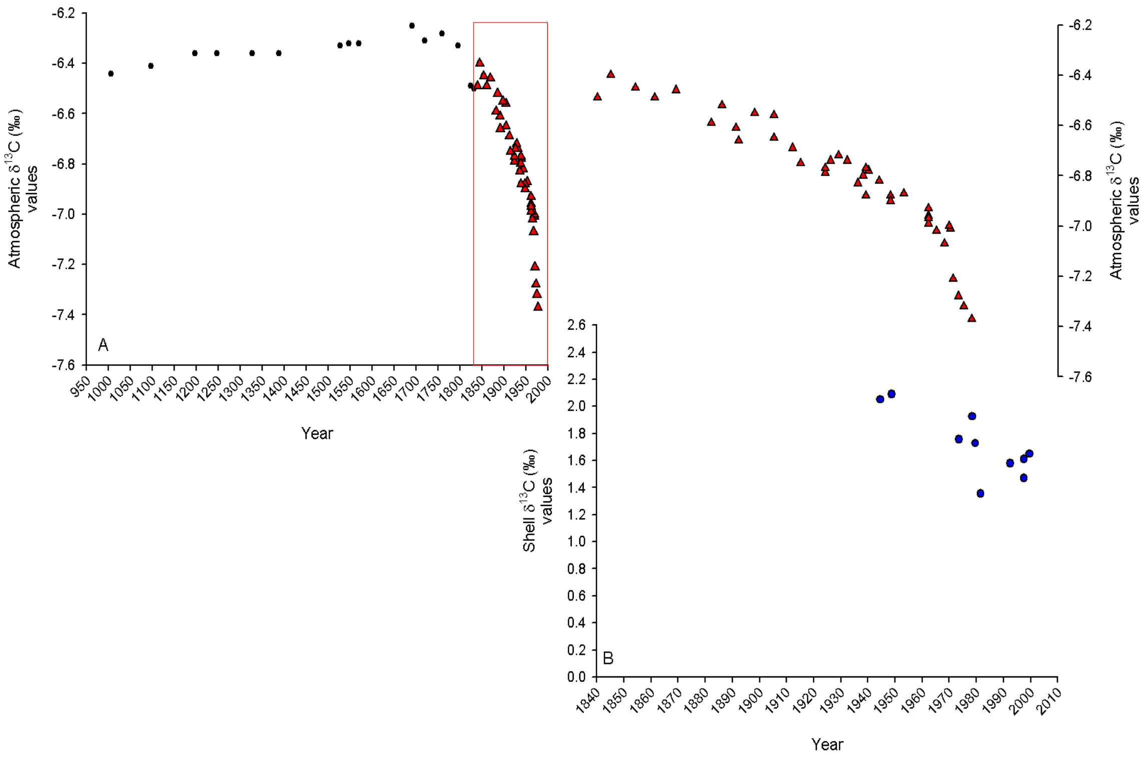


Figure 6.16: $\delta^{13}C$ comparisons between the atmospheric and marine environments. A) Shows the complete Francey et al. (1999) $\delta^{13}C$ values from the atmosphere, the red box highlights the area from which samples have been taken for direct comparison with the marine data collected from C1. B) The top portion illustrates the Francey et al. (1999) data being used for comparison with the C1 data in blue (bottom panel)

Butler et al. (2009a) (Figure 6.17B) also showed a decrease in $\delta^{13}C$ values for the Irish Sea from the 1800s onwards, which they proposed to be due to the ocean $\delta^{13}C$ Suess Effect. The range of $\delta^{13}C$ values from the Irish Sea (Butler et al., 2009a) (not including the two anomalous results) is 0.3 to 2.2‰, compared to the 1.35 to 2.09‰ range at site C1 (Figure 6.11). One potential reason for the different ranges may be the period for which samples are taken – 1945 to 2000 for C1 and ~1570 to 1980 for the Irish Sea. It is also possible that the differences are due to site-specific factors. The Irish Sea site is dominated by more coastal waters than C1 and this could influence the $\delta^{13}C_{DIC}$ values at the two sites (similar to those site differences between C1 and C7). Both the marine datasets (Irish Sea and C1) have $\delta^{13}C$ value ranges which are significantly different to those seen in the atmospheric signal of Francey et al. (1999) (Figure 6.11). Most noticeably the $\delta^{13}C$ values for the atmosphere are isotopically lighter than for both of the marine records as well as for a number of other marine $\delta^{13}C$ records from *A. islandica* for comparison purposes. This is because atmospheric CO_2 is isotopically lighter than DIC found in the marine environment as a result of isotopic fractionation at the atmosphere-marine boundary (Butler et al., 2009a) and the large marine DIC reservoir with which it mixes (Cage and Austin, 2010).

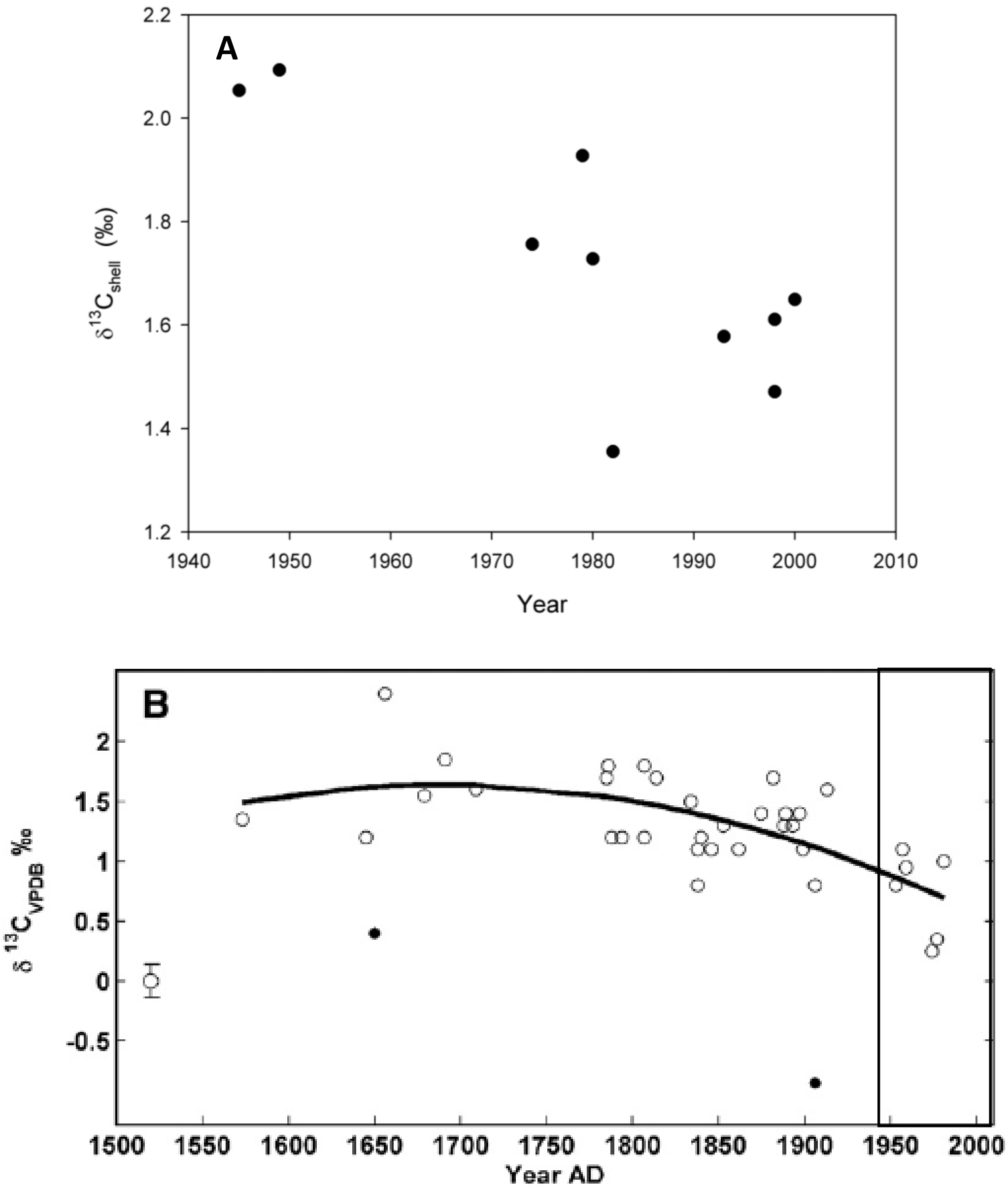


Figure 6.17: $\delta^{13}C$ comparisons between the C1 (A) and Irish Sea (B) data (Irish Sea data from Butler et al., 2009a). The two filled in circles in the Butler et al. (2009a; 238) dataset are values which were omitted from the analysis of the $\delta^{13}C$ data in their study; a second degree polynomial line was fitted to the data. The rectangle in B illustrates the common period of analysis between the two graphs.

6.4 Wider Implications

6.4.1 Sampling methods

There are some issues surrounding the use of the sampling method both in terms of sample collection and analysis that must be considered. While the sampling methods used do allow enough material to be collected from a single GI, they do not allow investigation of the internal structure of the shell peels prior to any analysis. This means it is not feasible to tell prior to sampling whether shells will produce suitable peels and whether it will be feasible to crossdate GI series from the shells. Normally, if a shell is not producing workable peels or crossdating is an issue, then other shells are sampled. As this is not possible with this method of sampling, the peels that are produced must be worked on for dating even if the peels are not optimal. Another drawback of this sampling method is that the amount of material required for radiocarbon analysis means that it is only feasible to get annually resolved sampling near the umbo where bands are larger. However, when moving towards the ventral margin the sampling resolution reduces to a minimum of five years, and this can add further uncertainty into the method. One option to remedy this sub-optimal sampling method would be to only sample shells where crossdating has successfully been undertaken.

6.4.2 ^{14}C analysis

If the *A. islandica* growth increment series are correctly dated then the ^{14}C results should clearly show a bomb-peak in the 1960s. This is not the case with the ^{14}C results obtained, indicating that the timing of the bomb-peak is late in the C7 record by approximately 20 years. Since the atmospheric ^{14}C signal is known, this potentially has something to do with the shallow nature of site C7 causing non-annual GI deposition. There are, however, some problems with this concept. In Section 6.3.1, the ^{14}C results from site C2 (water depth 20 m) indicate annual GI deposition due to the timing of the final sample being consistent with the rising limb of the bomb-peak (Figure 6.5). In addition to this, the site C1 $\delta^{13}C$ data in Section 6.3.2 also suggests annual banding at this site, which is shallower than site C7, at 11 m deep. These examples, together with the fact that the Irvine Bay site is only 5m deep and has a ^{14}C chronology indicating annual banding in the species, indicate that samples from shallow water sites do often exhibit annually-resolved GIs. It is entirely possible that the Turekian et al. (1982) example and site C7 data are anomalous in terms of annual GI deposition for some reason which may, or may not, be influenced by site-specific conditions including shallow water depth.

As previously mentioned, there is evidence of dumping (of waste from New York) in the region of the Turekian et al. (1982) site (Gross, 1976 in Turekian et al., 1982) which may have influenced shell GI deposition. At Site C7 there are several site-specific factors which make it stand out from the other sites studied (see Chapter 2). For example, site C7 has the highest sediment water content recorded, the finest grain size mode and the highest OC content values compared to the other sites. Additionally, site C7 has the lowest average shell height and average shell weight out of the six sites studied (Figure 6.18). As already mentioned, it is possible that conditions at site C7 influence the shells in such a way that they do not deposit annual GIs, indeed in this instance the shells would have to be missing approximately 20 GIs at site C7 to account for the timing of the bomb-peak at the site. Currently it appears unlikely that this is the case, therefore further investigation is required.

As crossdating has been successfully undertaken at site C7 (in Chapter 4) it has been illustrated that there is a degree of common variability in GIs, therefore it is possible to conclude that either (i) whatever factor(s) are causing the lack of annual GI deposition at site C7, all shells are being influenced in the same way, or (ii) those shells crossdated into the master growth chronology do exhibit annual banding, while shells C7-L48(2), C7-L104 and C7-L127 are the only ones studied here that are influenced by factors causing sub-annual banding. The second of these two suggestions seems unlikely, particularly when it is considered that all site C7 shells were collected from a small depth range and in close proximity. If shells were collected from different depths at the site or were influenced by localised disturbance, a limited number of shells might have been affected. However, according to the NERC SCUBA divers who collected the shells, the depth of collection at site C7 ranged from 16-20 m. It is remotely feasible that the three shells from which samples were taken for ^{14}C analysis came from the shallower collection depths, while those crossdated into the site chronology came from the deeper end of the range; there are, however, no constraints in our available sampling information to test this possibility.

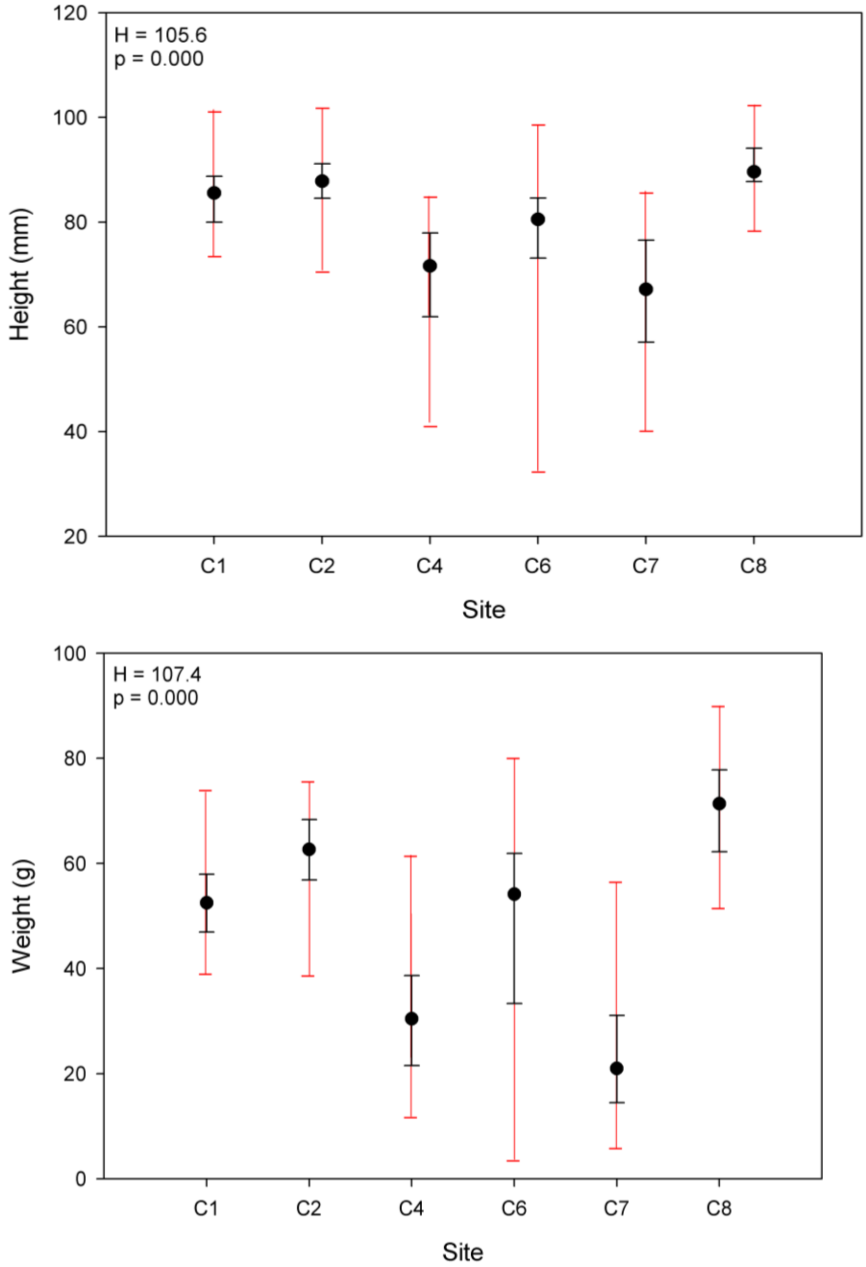


Figure 6.18: Median and IQR values for height and weight data from each site in black. Also included is the range of the data in red with the maximum and minimum values indicated. The H and p values included in the figure relate to the Kruskal-Wallis analysis undertaken on the datasets. The n-values are as follows:
Height: C1 = 15, C2 = 30, C4 = 38, C6 = 35, C7 = 34, C8 = 30
Weight: C1 = 15, C2 = 24, C4 = 37, C6 = 35, C7 = 33, C8 = 25

To calculate the marine ^{14}C reservoir age it is necessary to establish a known calendar age (Equations 6.1 and 6.2). Due to some uncertainty concerning the dating control for the site C7 ^{14}C data it was not possible to establish with sufficient confidence the calendar age of each sample in Figure 6.5. As a result of this calendar age uncertainty, the marine ^{14}C reservoir ages for the samples have not been calculated and any such calculation should be considered unreliable at this time.

6.4.3 $\delta^{13}C$ analysis

The work presented in Figure 6.14 of this thesis indicates that during the juvenile period of growth $\delta^{13}C$ values increase to a peak before decreasing again; this occurs before the shells reach the age of approximately 20 years old. The timing of these changes is similar for all six shells analysed, and for site C1 where clear GI data are available, fits within a juvenile interval of distinct high growth rates in the raw shell data. Due to these similarities, this trend is interpreted as an ontogenetic/juvenile effect on shell $\delta^{13}C$ values lasting approximately 20 years. There is mixed opinion within the sclerochronological literature regarding whether there is indeed a juvenile effect on the isotopic records in shells, and if there is what causes it. Analysis of *A. islandica* by Schöne et al. (2005b) found no ontogenetic impact on the $\delta^{13}C$ record of the shells. Similarly the work by Schöne et al. (2011) on *A. islandica* from the Gulf of Maine and Iceland showed no ontogenetic trend in the $\delta^{13}C$ values of four shells analysed. It is important to note that in Schöne et al. (2011) only one of the shells analysed was sampled from the first year of growth, the other three were sampled from years 18, 26 and 28 onwards. Therefore, it is possible that the ontogenetic trend was present in these three shells, but was simply not captured within the low sampling record which missed the critical, juvenile period of growth.

Conversely, work by Witbaard (1997) on *A. islandica* $\delta^{13}C$ lends support to the theory that there is an ontogenetic trend present in $\delta^{13}C$ values with an increase in $\delta^{13}C$ during the first five years of shell growth. As Witbaard (1997) did not sample after the fifth year of growth it is not possible to conclusively say whether this is an ontogenetic trend, but it does help support the concept of a juvenile effect on $\delta^{13}C$ values. Butler et al. (2011) tested to see whether $\delta^{13}C$ values in the shell of *A. islandica* do exhibit an ontogenetic trend using isotopic and biological age data from specimens collected at four sites. Butler et al. (2011) found that in juvenile *A. islandica* $\delta^{13}C$ records decreased during the first 40 years of growth, Foster (2007) also reported a decline in $\delta^{13}C$ during juvenile *A. islandica* growth, which they linked to declining GI width values. Foster (2007) suggested that their findings indicate an ontogenetic influence on $\delta^{13}C$ values.

It was also suggested by Foster (2007) that differences in the habitat or shell growth rates may cause different $\delta^{13}C$ signals within the shell of *A. islandica*. One potential reason proposed by Butler et al. (2011) for shells exhibiting this ontogenetic trend in $\delta^{13}C$ values is that there is a sensitivity to growth rates and a relationship between the amount of shell material deposited and metabolic carbon availability, which in turn impacts on the $\delta^{13}C$ value. Butler et al. (2011) suggested that this means that as GI growth rates decrease so do $\delta^{13}C$ values. However, Klein et al. (1996a in Foster, 2007) found that at lower GI growth rates $\delta^{13}C$ values were higher (see Figure 6.10 for how this compares to findings from this research). Currently, there is much conflicting evidence within the sclerochronological literature as to whether *A. islandica* exhibits an ontogenetic $\delta^{13}C$ trend. From the new evidence presented within this thesis and the data in Foster (2007), Butler et al. (2011) and Witbaard (1997), it is possible to suggest that certain specimens of *A. islandica* do exhibit $\delta^{13}C$ ontogenetic trends. Taking into account the work of Schöne et al. (2005b; 2011) it should be noted that it is possible that not all *A. islandica* specimens have an ontogenetic $\delta^{13}C$ trend. Further work should focus on analysing shells with a range of ages from a variety of environments to determine if either variable has an impact on the presence of an ontogenetic $\delta^{13}C$ signal.

In Butler et al. (2011) an ontogenetic trend was observed during the first 40 years of growth, while in this study the period over which the effect is seen varies from 14 to 40 years. Therefore, the suggestion to exclude data from the first 40 years of growth for ocean $\delta^{13}C$ Suess Effect investigations (Butler et al., 2011) seems broadly valid, although perhaps slightly over-cautious in some of the cases presented here. As a result of the strong ontogenetic effect on shell $\delta^{13}C$ values, the data available for investigating the ocean $\delta^{13}C$ Suess Effect in the field area was limited. This data, however, (Figure 6.13) does appear to indicate the expected decrease in values during the 20th century. Unfortunately, no firm conclusions can be reached concerning the ocean $\delta^{13}C$ Suess Effect at site C7 until additional data is collected extending measurements back into the 1800s. This would not only indicate pre-industrial $\delta^{13}C$ levels for the site, but also provide a chronology for the noted decrease in values at around AD 1850. The $\delta^{13}C$ values recorded in *A. islandica* shells from these fjordic sites may reflect the exchange history and differences in balance between fjord and coastal ocean water masses (Figure 6.19). Cage and Austin (2010) proposed their foraminiferal $\delta^{13}C$ record from Loch Sunart could also be interpreted as a product of exchanges between coastal and fjordic waters.

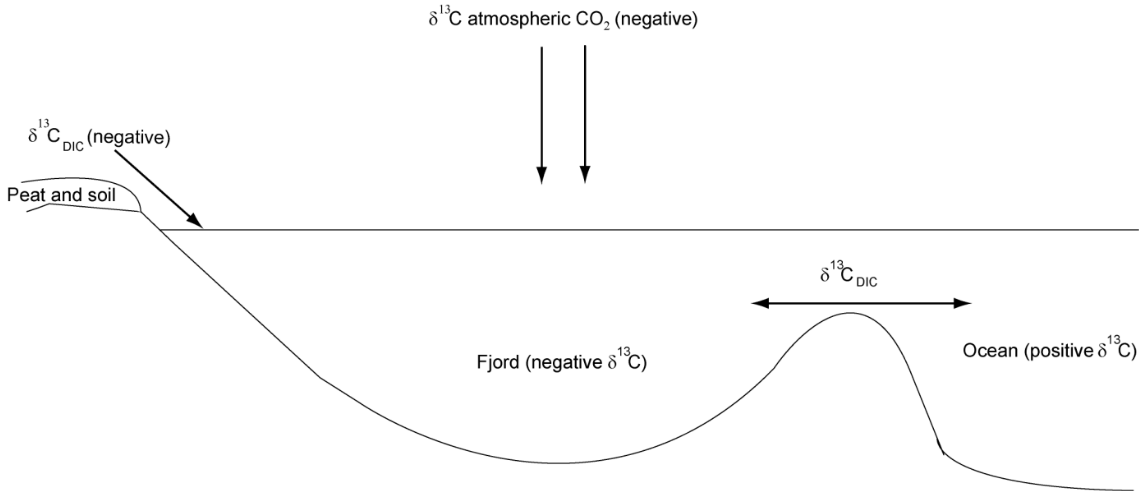


Figure 6.19: Schematic of different $\delta^{13}C_{DIC}$ values affecting fjordic values; the conceptual model suggests that fjordic environments might exhibit strong spatial and temporal $\delta^{13}C_{DIC}$ gradients

7. Synthesis and Conclusions

7.1 Introduction

The North Atlantic Ocean is important for both global and regional European climate variability due to the influence of the North Atlantic Current/Gulf Stream, and the NAO (e.g. Hurrell, 1995). To fully understand past North Atlantic variability it is important to produce long, high-resolution climate proxies capable of capturing the effect of these changes. However, a lack of high-resolution marine proxy data in the north-east Atlantic sector (Cunningham et al., 2013) must be addressed to fully understand past marine climate variability for this region. Scotland is in a sensitive location to study past North Atlantic Oscillation (NAO) and North Atlantic water mass variability. The fjords of North West Scotland present an excellent opportunity to study marine climate change on a range of Holocene timescales.

Fjordic environments are situated in a unique position with inputs from both marine and terrestrial sources (Hjelstuen et al., 2009). This means that fjords can be used to investigate a range of past changes, including variability in pollen from the catchment area (Cundill and Austin, 2010) and westerly air stream variability (Gillibrand et al., 2005). Previous studies have already indicated the potential of fjords as sources of palaeoclimatic proxy records through the use of benthic foraminifera records (e.g. Cage and Austin, 2010), which are of a higher resolution compared to the open ocean records due to the higher sedimentation rates (e.g. for Loch Sunart sedimentation rates are up to ~1 cm a year (Cage and Austin, 2010)). As well as having the potential to record changes in the NAO (e.g. Gillibrand et al., 2005) and westerly air stream variability (Austin and Inall, 2002), it is this dual ability of fjords to provide records for both marine and terrestrial climate change that makes them important for advancing palaeoclimatic research.

Due to the importance of fjordic environments as potential sources of palaeoclimatic records, a major goal in current research has been to supplement the existing lower resolution sedimentary records with annually resolved records (e.g. Reynolds et al., 2013); something that this thesis aimed to address using the marine bivalve *A. islandica*.

A. islandica was chosen for this study as previous research had already established that the growth increments (GIs) are annually resolved (Ropes, 1988 in Scourse et al., 2006; Weidman et al., 1994) and show common variance and response to factors influencing growth, which allows crossdating of GIs to be undertaken (e.g. Schöne et al., 2005a). The species has also been shown to have potential as an annually-resolved palaeo-proxy for climate variability and anthropogenic activity using GIs and shell geochemistry (e.g. Butler et al., 2009a; 2010; Schöne et al., 2009b). However, there is currently little known about the application of this proxy archive in fjordic environments, which deserves investigation given that fjords in the NE Atlantic realm have already been shown to be sites sensitive to NAO variability (e.g. Nordberg et al., 2000 in Sweden; 2001 in Sweden; Gillibrand et al., 2005 in Scotland). This study aimed to investigate the potential of fjordic *A. islandica* as palaeoclimatic proxies as well as analysing $\delta^{13}C$ and ^{14}C variability within shells to evaluate their potential as archives of the ocean $\delta^{13}C$ Suess Effect and marine ^{14}C reservoir age effect/^{14}C bomb-peak timing, respectively.

It is important that when selecting a proxy for climatic research that the growth variability is mainly driven by a single variable (e.g. SST). Where this is the case, annual growth rates from individuals collected at a single sample site should share this common variability, therefore allowing them to be crossdated. It has also been argued that regional chronologies can be constructed from multiple sites when shells display common variability (e.g. Butler et al. 2009b). Taking this earlier work into account, six sites were sampled and intra- and inter-site common variability assessed.

The results of this study highlight that there is no common signal between the sites, and the intra-site signal is weak at best. These results, coupled with the lack of a common signal between GI growth rates and the instrumental datasets means that specimens from this study should be considered as a poor proxy for marine environmental changes. This chapter aims to explore the reasons for these weak/non-existent relationships through bringing together the analyses from previous chapters.

7.2 Chronology construction

The chronology construction methods (See Chapter 4), involved a range of techniques, including the important step of detrending the raw GI growth rate data to remove the ontogenetic growth trend present. A number of underlying factors underpinning these methods require clarification; even using a NE function to detrend, the amount of long-term information contained in the master chronology is still determined by the mean length of the samples. This is commonly referred to in dendrochronology as the “Segment Length Curse” (SLC) and many more samples will be needed for this project before information can be obtained at time-scales longer than the mean length of the samples (Mitchell, 1967; Briffa et al., 1992; Cook et al., 1995; Esper et al., 2003).

In this project the potential information captured by the site chronologies is a function of the various detrending methods used. Those detrended using either NE or Hugershoff functions will have a bias based on the mean length of the samples (SLC), while the use of a 10 year smoothing spline removes potential lower frequency information at time-scales > 10 years. Theoretically this bias can be overcome using Regional Curve Standardisation (RCS) detrending. RCS has the potential to preserve information at time-scales that are larger than the mean sample length by applying a common detrending curve to all samples at a site (Cook et al., 1995). The samples presented in this thesis (see Chapter 4) do not have a strong common signal, therefore, at the moment the use of the RCS is not possible, however it should be considered in the future at sites with high sample replication where crossdating works.

Until it is clear what is controlling inter-annual variability in the shells there is little point in trying to capture mid to low frequency variability, pending a fuller understanding of the controls over shell GI growth rates within an environment then the focus should remain on researching the influences on year to year variability and then move to considering the lower frequency trends. Prior to the 1990s no dendrochronological research attempted to capture centennial variability, rather they focused on the decadal and higher. For any future work is undertaken on *A. islandica* from shallow water sites it is therefore important not to focus on the SLC issue, rather the emphasis should be on investigating the controls on the high frequency.

To investigate why *A. islandica* from the field area studied here are not exhibiting a clear common response the relevant results from the previous chapters have been compared using correlation analyses (Table 7.1). Only those results that can potentially contribute to furthering our understanding about the drivers behind *A. islandica* from the field site not showing common GI variability. The results being investigated are site-specific factors that may be influencing the crossdating success rate and RBAR values at the six sites and therefore be used to determine what site variables are important to consider for site selection. Out of the results presented in Table 7.1 only two are statistically significant at the 95% confidence level; average sediment grain size mode and crossdating success rate, and clay percentage and crossdating success rates. These two results are summarised in Figures 7.1 and 7.2 respectively.

	Crossdating successrate (%)[1]	RBAR
RBAR	0.429 0.396	
Sediment water content	-0.401 0.431	0.124 0.815
OC content	-0.296 0.569	0.205 0.697
Sediment grain size mode	0.867 0.025	0.260 0.619
Clay %	0.953 0.003	0.635 0.176
Silt %	0.627 0.183	0.572 0.235
Sand %	0.720 0.106	-0.606 0.202
Min site water depth (m)	-0.314 0.544	-0.284 0.586
Max site water depth (m)	-0.546 0.262	0.006 0.991
Average site water depth (m)	-0.487 0.327	-0.190 0.718

Table 7.1: Results of correlation analyses between the results from chapters 2, 4, 5 and 6. Results that are statistically significant at the 95% confidence level are highlighted. For each of these datasets df = 6.

[1] The crossdating success rate was worked on in Chapter 4 by comparing the number of samples processed at each site compared to the number that made it into the final master chronology.

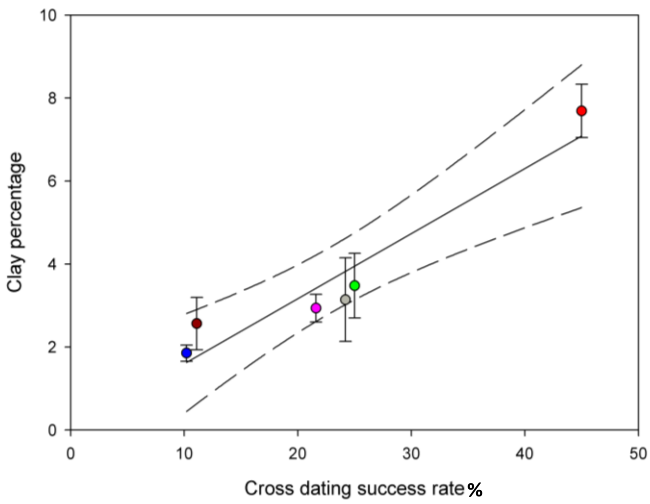
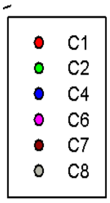


Figure 7.1: Relationship between crossdating success rate and average sediment grain size mode



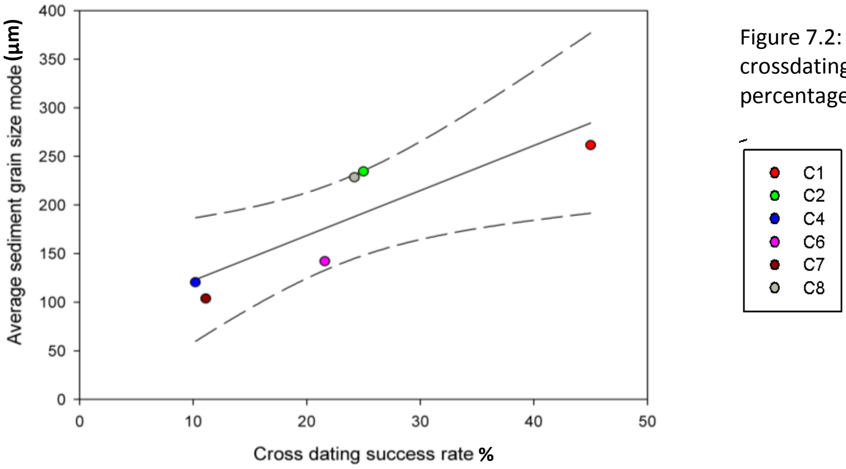


Figure 7.2: Relationship between crossdating success rate and clay percentage

The relationships in Figures 7.1 and 7.2 indicate that sites with higher crossdating success rates have higher clay content levels and higher average grain size mode values. These results suggest that it may be important to focus on sites with higher levels of clay in the sediment or with higher average grain size mode values. For this to be possible site surveys would have to be undertaken prior to analysis to determine the type of sediment present at the site.

Further research investigating the potential number of additional shells required to reach an EPS ≥0.85 for all six master chronologies has also been undertaken, using the crossdating success rate and the theoretical number of specimens required to reach the required EPS value as worked out in Chapter 4. These results (Table 7.2) indicate that potentially another 3443 samples would have to be analysed to reach the required EPS of 0.85 or greater at all six sites. Such findings support the idea that working on *A. islandica* from shallow water fjordic environments with the aim of generating robust chronologies may not be realistic.

Site	WC (U)	PMR (U)	WC (FD)	PMR (FD)	Highest
C1	8 → **18**	21 → **47**	90 → **200**	31 → **67**	**200**
C2	17 → **68**	20 → **80**	25 → **100**	18 → **72**	**100**
C4	15 → **148**	5 → **50**	259 → **2540**	4 → **40**	**2450**
C6	51 → **237**	N/A	48 → **223**	N/A	**237**
C7	17 → **154**	10 → **91**	18 → **163**	14 → **127**	**163**
C8	49 → **203**	40 → **167**	26 → **108**	15 → **67**	**203**
				Total	**3443**

Table 7.2: Estimates of the potential number of additional shells required to reach an EPS value ≥0.85 for each of the chronologies for both the whole chronology (WC) and the period of maximum replication (PMR) for the six sites. The first number represents the number of shells required to gain the n-value outlined in Figures 4.7 to 4.12, while the second is the number that may be required to be processed to gain this number of additional shells in the master chronology for each site (based on the crossdating success rates outlined in Table 4.2.

The sampling to crossdating success rates presented in Table 4.2 is similar to those found elsewhere for this species (Reynolds pers. comm., 2012). However, the inter-series correlation RBAR values for the site master chronologies are low compared to those reported for *A. islandica* from the Irish Sea(e.g. Butler et al., 2009a; 2010) and other species (e.g. Black et al., 2008 – yelloweye rockfish; Helama and Nielsen, 2008 – river pearl mussel). One of the reasons for this is the low signal strength between the individual shells at the sites, it is also important to understand why the individuals at the sites studied are portraying different signals.

There are statistically significant relationships between RBAR values and shell median age, as well as between crossdating success rate and grain size mode/clay percentage. This is something that is observed in trees with juveniles expressing a weaker common signal. If this is also the case in the *A. islandica* studied for this project then it is possible that the younger shells analysed may have a different responses to climate and this is something that requires further investigation for the species and is something already being considered in dendrochronology (e.g. Wilson et al., 2004). To fully investigate the reasons behind these relationships future research should focus on investigating the hypothesis that sites with higher clay content in the sediment and a greater grain size sediment mode value lead to a higher crossdating success rate.

Another factor which may be influencing signal strength is the shallow nature of the sites. Although there is no significant relationship between depth and RBAR in Table 7.1, the maximum site depth is 24 m, and research by Epplé et al. (2006) noted how inter-series correlations decrease between *A. islandica* shell interannual variability sampled from shallow settings (15 to 20 m) in the inner German Bight (North Sea). This apparent lack of synchronicity was attributed by the authors to the conditions in which the shells had grown, including the site temperature, turbidity and salinity fluctuations, which are prominent in a shallow, coastal water environment (Epplé et al., 2006). It is possible that the inherent physical, chemical and biological heterogeneity within shallow water environments provide problems for obtaining a synchronous growth signal between the shells of *A. islandica.* This could account for not only the poor signal strength, but also the poor correlations between shell annual growth rates and climate (Chapter 4). The water depth issue requires further investigation; previous work by Butler et al. (2009a; 2010) in the Irish Sea demonstrated that *A. islandica* collected from sites with water depths ranging between 30 to 70 m produce robust, crossdated chronologies with good signal strength statistics, therefore future work should focus on analysing samples from water depths within the 30 to 70 m range.

7.3 Inter-site coherence

If shells from different sites within a climatologically/oceanographic homogenous region are internally crossdated and are responding to the same environmental conditions, the resultant site chronologies should correlate with each other (e.g. Witbaard et al., 1997b; Butler et al., 2009b). Although all the chronologies have been crossdated (Chapter 4) to ensure dating control, there is no clear, common inter-site signal. To investigate whether it was a very localised climate signal being recorded in the shell GI growth rates rather than the 'regional' signal represented by the gridded datasets, the master chronologies were also compared to the two 'local' instrumental datasets (Appendix 18). Although these datasets can be considered geographically local due to their location within the field area, they are not representative of all six sample sites due to the complex nature of the fjordic hydrography. As with the regional dataset correlations, these results didn't indicate a common relationship between the results at the six sites, lending support to the idea that factors other than climate have the dominant influence over shell GI growth rates at the sample sites.

Witbaard et al. (1999) noted that temperature is not always the primary influence over annual growth rates and those other environmental factors can dominate. It is likely that this is the case here as there are many non-climatic influences acting in the region that have the potential to affect shell GI growth rates from year to year. These include the anthropogenic influences outlined in Chapter 4 such as fish farming and industrial activities in the area. To minimise the impact of such activities and their added influence to annual growth rate variability, future sites must be chosen in locations with minimal anthropogenic impacts.

In addition to anthropogenic influences food cannot be discounted as a reason for the shell growth records not recording changes in temperature. Several other studies have discussed not only the importance of food supply (e.g. Witbaard, 1997; Witbaard et al., 1999), but also how the abundance of other fauna higher up the water column can influence food availability e.g. copepods (Witbaard et al., 2003). Currently there is insufficient information for the field area to determine how phytoplankton/copepod abundance influences *A. islandica* GI growth rates and how this may be modulated by climate variability. There is a repository of available Continuous Plankton Record (CPR) data which can be used as a proxy for available food over time. Using this dataset could aid with selecting future sample sites by ensuring there is adequate data to test the hypothesis that in years with higher copepod abundance shells experience lower annual growth rates due to less food reaching *A. islandica* on the bottom. This would then allow for direct comparison with the work of Witbaard et al. (2003) who reported that copepod abundance influenced *A. islandica* growth at the Fladen Ground (northern North Sea). They found a negative correlation between shell GI growth rates and copepod abundance (lagged by 6 months), such that during periods of high shell GI growth rates, copepod levels are low and vice versa. Witbaard et al. (2003) suggested that this negative relationship indicates that *A. islandica* and copepods are competing for the same food source, therefore at times of high copepod levels they intercept primary productivity (PP) food, leaving *A. islandica* with a much depleted food reservoir and reduced annual growth rates.

The shells studied here likely reflect local conditions that mask larger-scale climate processes. For example, renewal events in fjords change bottom water conditions on a range of time scales (Austin and Inall, 2002; Inall and Gillibrand, 2010); however the influence of such events on *A. islandica* GI growth rates and GI deposition is not known and requires further investigation as it is possible that at some fjordic sites live specimens could be stuck in 'old' bottom water and thus be removed from the climate signal until a renewal event introduces fresh water to the site.

7.4 *Arctica islandica* as a climate proxy

The Correlation Response Function Analyses (CRFA) Chapter 4 indicated few statistically significant relationships between the six master chronologies and the instrumental datasets. Those that are present are ambiguous at best and serve to highlight that shell growth chronologies from the field area cannot currently be used as proxies for marine climate variability. This is partly because none of the chronologies have EPS values greater than 0.85 for both their whole chronology and period of maximum replication. Until replication and EPS values are increased at all the sites these results can only be considered as preliminary. The results do suggest is that there may be many factors (climatic and non-climatic) other than just temperature influencing annual shell growth rates and inter-annual response, and at times these factors dominate the signal recorded in the shells. This is best highlighted by the lack of a time-stable relationship between the master chronology for site C1 and the HadSST2 temperature record (Figures 4.16 and 4.17) (Stott et al., 2010). Research into *A. islandica* as a marine climate proxy from a variety of sites have previously indicated that the species has potential to produce annually-resolved records for past climate and environmental changes (e.g. Weidman et al., 1994; Witbaard et al., 2005; Schöne et al., 2005b). The results presented within this thesis appear to indicate that A*. islandica* from shallow water fjordic environments are unsuitable as proxies for both marine and terrestrial climate change. These findings have important implications for the future of sclerochronological research in fjordic environments, suggesting that *A. islandica* are not a suitable proxy for examining past environmental and climate change in shallow water sites in fjords. While research has been published elsewhere indicating that shallow water environments can be problematic when analysing shell GI growth rates in *A. islandica* (e.g. Epplé et al., 2006; Butler, 2008), no work has been published about shallow water fjordic research for climate reconstructions with the exception of Stott et al. (2010) the results of which are included in this thesis. As a result it is important to understand what site specific factors may be leading to the poor results presented in Chapter 4.

7.5 Biometrics and morphology

Sediment grain size appears to be a primary driver of shell growth at the six sites with significant correlations present between specimen height and weight and the sediment grain size mode data, with height and weight being higher at sites with a higher sediment grain size modal value (Figure 7.3). Previous research has shown the importance of secondary food supply in supporting shell growth; this secondary food supply proposed by Witbaard (1997) for *A. islandica* is material not consumed by other fauna which has subsequently settled on the sea/fjord bed, only to be resuspended and eaten at a later date. Duineved and Jenness (1984 in Witbaard, 1997) also reported that the echinoid *Echinocardium cordatum* showed higher growth rates in coarser sediments which they attributed to the resuspension of food. De la Huz et al. (2002) found significantly higher growth rates in coarse sand compared to gravel for the bivalve *Donax trunculus* also lending support to this “resuspension” hypothesis.

These relationships further suggest that in the study area temperature is not the primary driver behind shell growth rates; rather it is sites with larger grain size mode values and therefore a greater supply of secondary food that influences the coherence of shell growth rates. It is therefore even more important to consider the sediment properties of future sample sites due to the influence of the sediment grain size mode on shell growth.

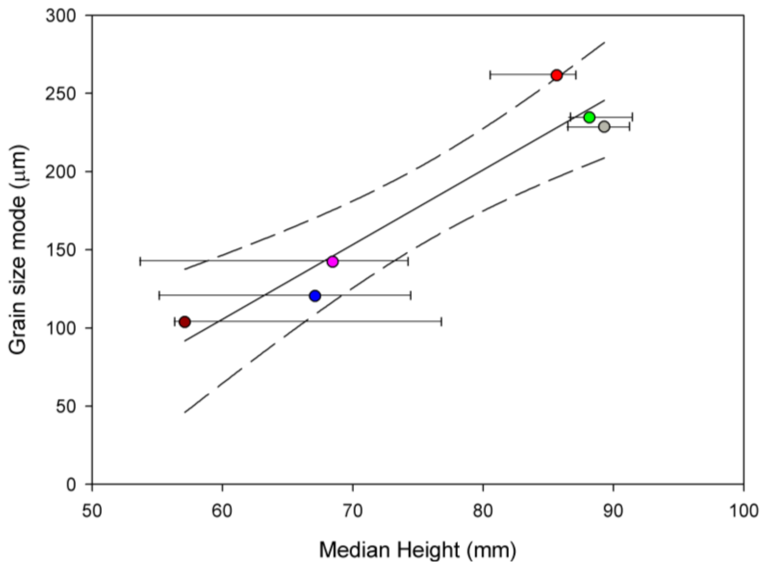
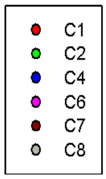
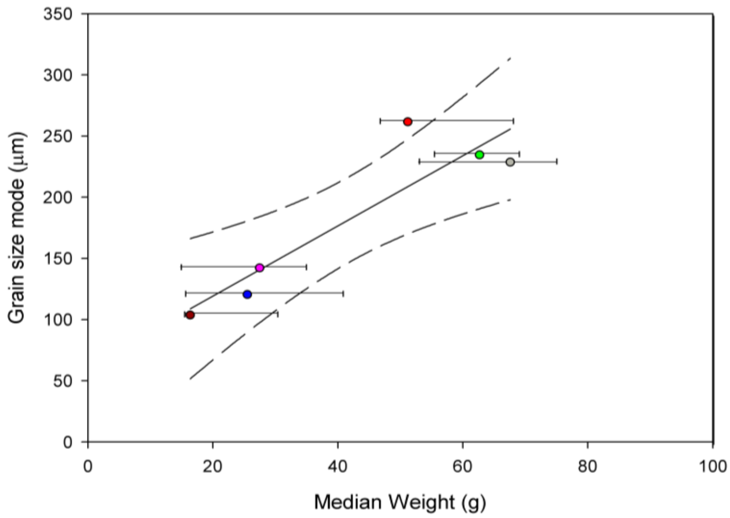


Figure 7.3: Relationship between median height and grain size mode - r = 0.956, p = 0.003 (top panel), and median weight and average grain size mode – r = 0.915, p = 0.011 (bottom panel)





7.6 Shell growth rates

A. islandica shells are obviously being influenced by a range of different factors within the fjordic environment studied for this research (Figure 7.4). It is possible to see in Figure 7.4 just how complex the growth of *A. islandica* in fjords actually is. Therefore, it is of little surprise that when attempting to use shell GI growth rates as a proxy for marine environmental/climatic changes that there is not a clear signal in the shell master chronologies.

Despite previous research highlighting the palaeoclimate potential of *A. islandica* (Schöne et al., 2003; 2004; 2005a; 2005b; Butler et al., 2009a; 2009b), there has been little published concerning the potential of *A. islandica* from N. W. Scotland (e.g. Stott et al., 2010). The results presented herein, unfortunately indicate that *A. islandica* chronologies from Scottish fjords have limited potential as palaeoclimate proxies.

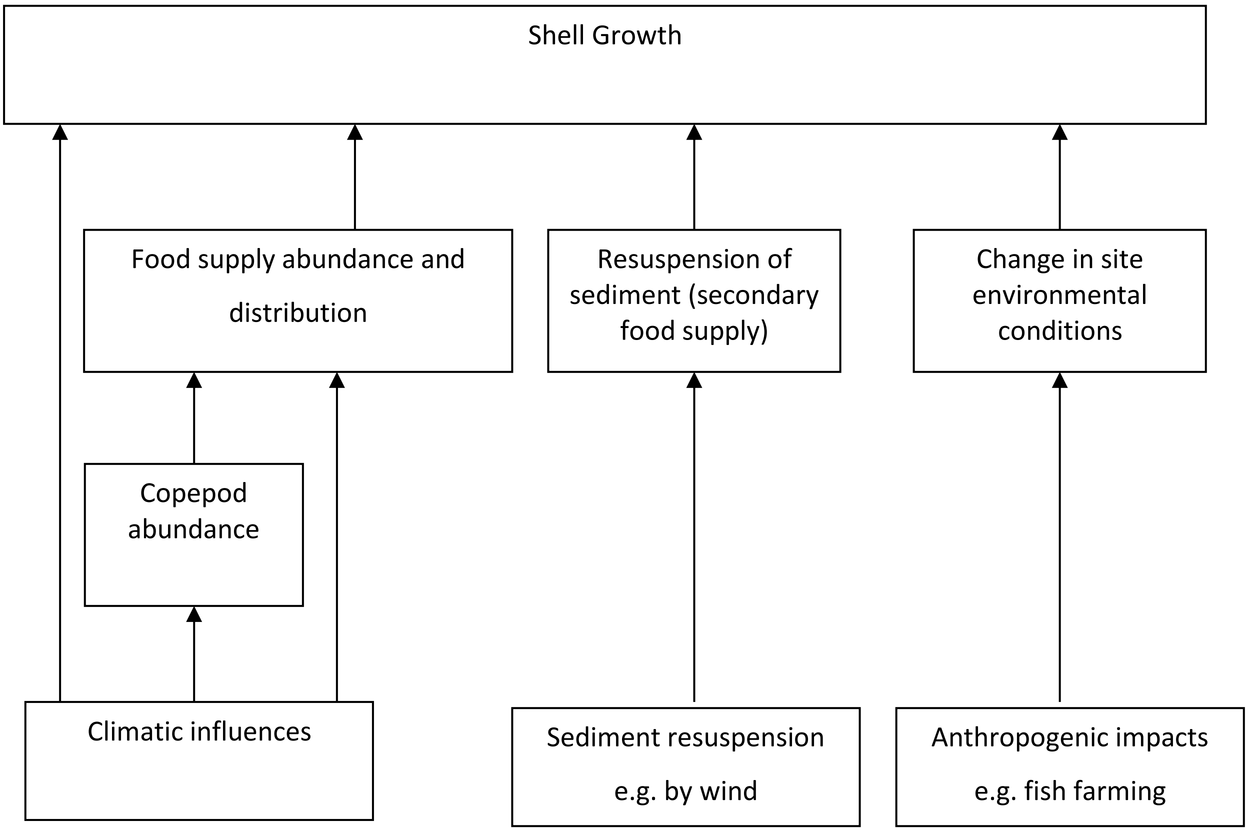


Figure 7.4: Summary of processes that influence shell growth rates as discussed in this chapter

7.7 Conclusions

7.7.1 Site Selection

The findings of this thesis clearly highlight that within fjords there are many variables influencing shell annual growth rates (Figure 7.4). Therefore, *A. islandica* from shallow fjordic environments should not be considered as suitable candidates for marine climate/environmental proxies. It is also questionable whether specimen annual growth rates from deeper fjordic sites can be used as climatic proxies due to the mixture of marine and terrestrial influences on fjords as outlined by other researchers (e.g. Hjelstuen et al., 2009). As a result of these findings it is recommended that future research using *A. islandica* as a climatic/environmental proxy focuses on non-fjordic environments as fjords are too complex to provide a clear signal using GI growth rates.

The results concerning the lack of inter- and intra-site coherence in annual growth rates and the lack of a clear climate signal being recorded in the shells of *A. islandica* from the field sites are not clear. However, there are some useful findings for moving forwards with the use of the species as a climate proxy regarding site selection. Research undertaken elsewhere has already shown that *A. islandica* prefer sediment conditions that are sandy mud/mud (Liehr et al., 2005) and medium to fine grained sands (Thórarindóttir et al., 2008) – similar sediment types were found at the six sites studied here. This project however takes the importance of sediment type a step further by investigating whether there are links between the sediment in which specimens are growing and the site RBAR and crossdating success values. Through examining these results (see Section 7.2) it is apparent that sites which have higher clay percentage content and higher grain size sediment mode values have higher crossdating success rates. Based on these findings it is therefore recommended that where possible future research focused on undertaking analysis on *A. islandica* that involves crossdating should include a site survey to determine the clay content of sites and sediment grain size profiles to aid with site selection. These should then help researchers focus on sites that have the higher clay/sediment grain size values.

7.7.2 Geochemical analysis

There is a potential problem associated with the sampling techniques applied for collection of material for ^{14}C and $\delta^{13}C$ analysis (see Section 6.2). As sampling is undertaken on the outside of the shell prior to sectioning it is not possible to target certain calendar ages for sampling; the date of samples can only be determined once sectioning of the shell has been undertaken. This also means that it is not known whether a workable peel can be produced for a shell until after sampling for geochemical analysis has been undertaken. To address this sub-optimal sampling in the future, only shells that have been successfully crossdated into a master chronology should be analysed as material could be taken from the other valve in the knowledge that dating should work, therefore allowing accurate dating of the sample sites.

7.7.3 Future Directions

To continue investigating the six sites researched here a potential further 3443 shells would be required. This level of sampling would not be cost effective considering the amount of time required to analyse such a volume of shells. If research into the use of *A. islandica* as a palaeoclimate proxy for NW Scotland is to be continued then lessons must be learnt from this study. From a palaeoclimate proxy point of view the findings presented in this thesis have been disappointing and suggest that the future of *A. islandica* sclerochronological research in Scotland may be best focused outside of fjordic environments towards deeper environments. Other studies from deeper water locations have shown the potential of *A. islandica* as a proxy for reconstructing past climate variability with stronger inter-series signal strength than for the master growth chronologies presented here (e.g. Butler et al., 2010). The fjordic location of the sites with the associated restricted exchange of water between the coast and fjord plus complex renewal event history, combined with the shallow nature of the six sites, likely cause the lack of climate signal in shell growth increment variability. For this reason it is suggested that future research investigating the potential of *A. islandica* as a marine climate proxy should focus on deeper water sites, including the west coast of the Scottish islands and the Faroe Islands. Both these sites are ideally located within the North Atlantic to capture any NAO and Gulf Stream variability and have known *A. islandica* populations present (Figure 1.8). It may also be of use to ensure that any future sampling locations have suitable existing food availability datasets (i.e. Continuous Plankton Record datasets), or have the potential for such data to be collected, to aid with the identification of the role of food on the interaction between shell GI growth rates and the climate/environment.

Further, $\delta^{13}C$ analysis at the Loch Etive sites, including C/N analysis of sample soft tissue should be undertaken to investigate the different $\delta^{13}C$ ranges recorded between the outer and inner fjord sites. This would allow the determination of how diet, and by extension terrestrial material, influences $\delta^{13}C$ values. Undertaking this analysis along the length of Loch Etive should make it possible to investigate how terrestrial and dietary influences change moving up fjord.

Over the last 90 years thousands of tree-ring chronologies have been sampled over the whole planet (ITRDB, 2012), and this extensive sampling means dendrochronologists have developed a good understanding and knowledge of tree growth response to climate as a function of site. Similar large scale, multi-site sampling is required for *A. islandica* for a full understanding of site-specific response of the species to climatic/environmental factors. Currently, the site specific response of *A. islandica* is not yet fully understood and this study may help to highlight the difficulties of working at shallow sites.

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Appendix

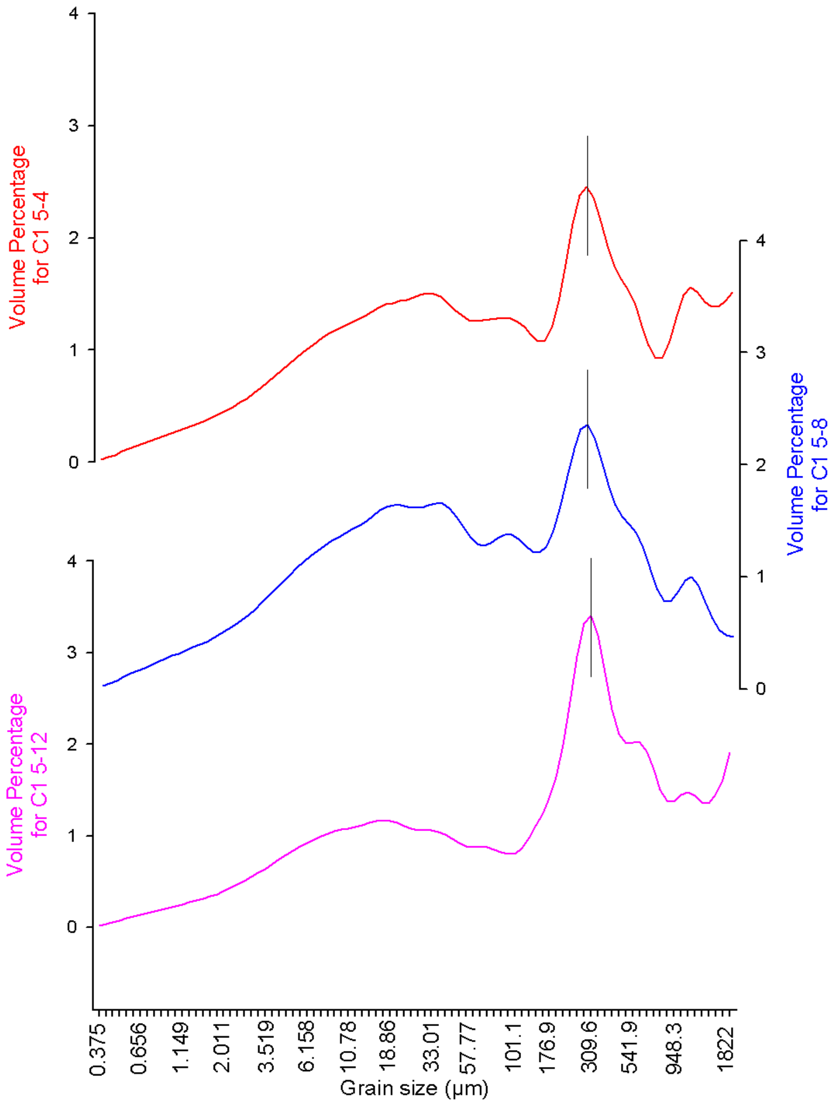
Appendix 1: Summary of the definition of habitat type SS.SMu.VirOphPmax (Connor et al., 2004). This habitat type is present at site C1.

Salinity	30-35
Wave Exposure	Moderately exposed, sheltered/very sheltered
Substratum	Sandy mud, shelly/gravelly mud
Depth Band	5-10 m, 10-20 m, 20-30 m

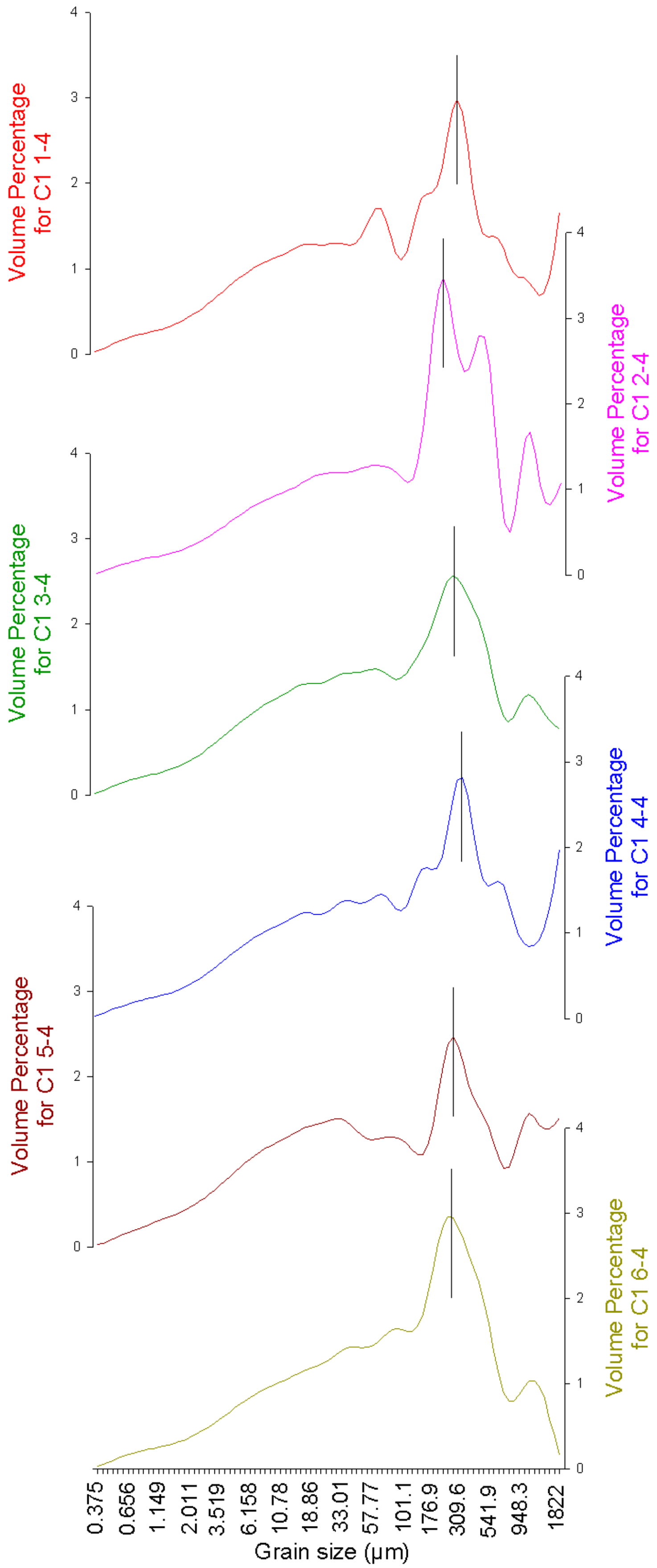
Appendix 2: Normality test results for sediment water content data.
To determine what statistical tests were appropriate for analysis of the sediment water content data at each site normality tests were undertaken and the results of these are presented here.

Site	Anderson-Darling value	p-value	Normally or non-normally distributed?
C1	0.199	0.864	Normally distributed
C2	0.848	0.023	Non-normally distributed
C4	1.443	<0.005	Non-normally distributed
C6	0.386	0.350	Normally distributed
C7	0.973	0.011	Non-normally distributed
C8	0.949	0.013	Non-normally distributed

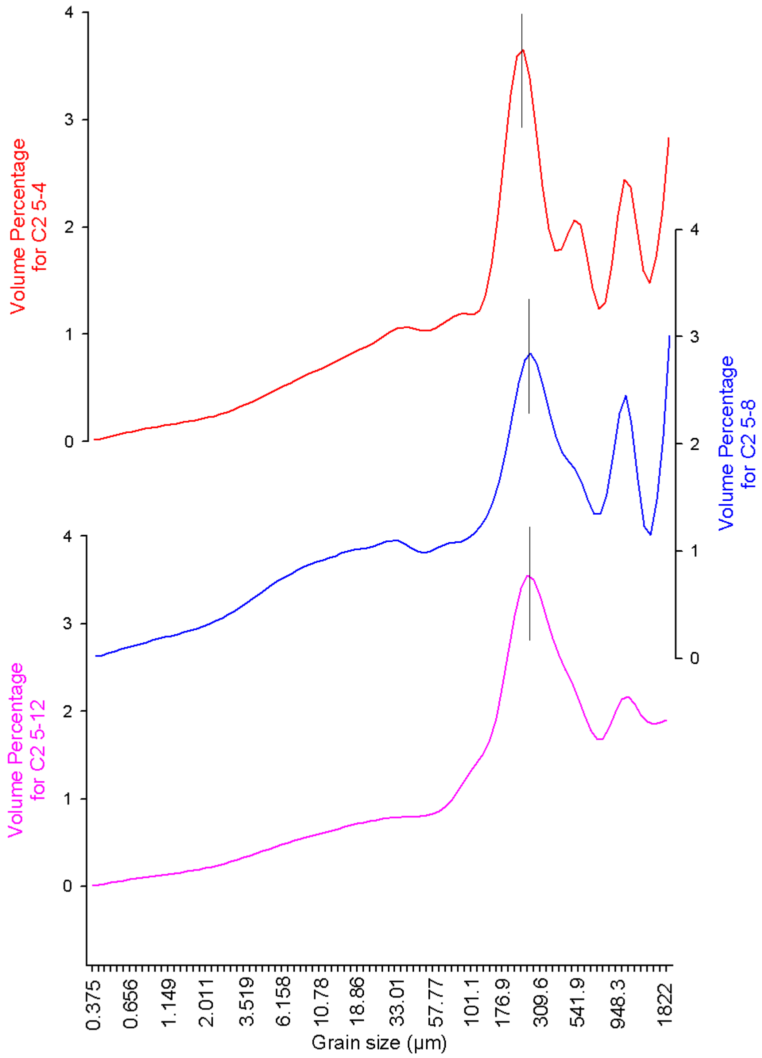
Appendix 3: Grain size distribution graphs for all six sites illustrating down core and core top data. On each graph the mode of the distribution is highlighted using a vertical line. All data were tested at the 95% confidence level for significance. These graphs help to illustrate how grain size distribution varies at the sites and supplement Figures 2.6, 2.8 and 2.9.



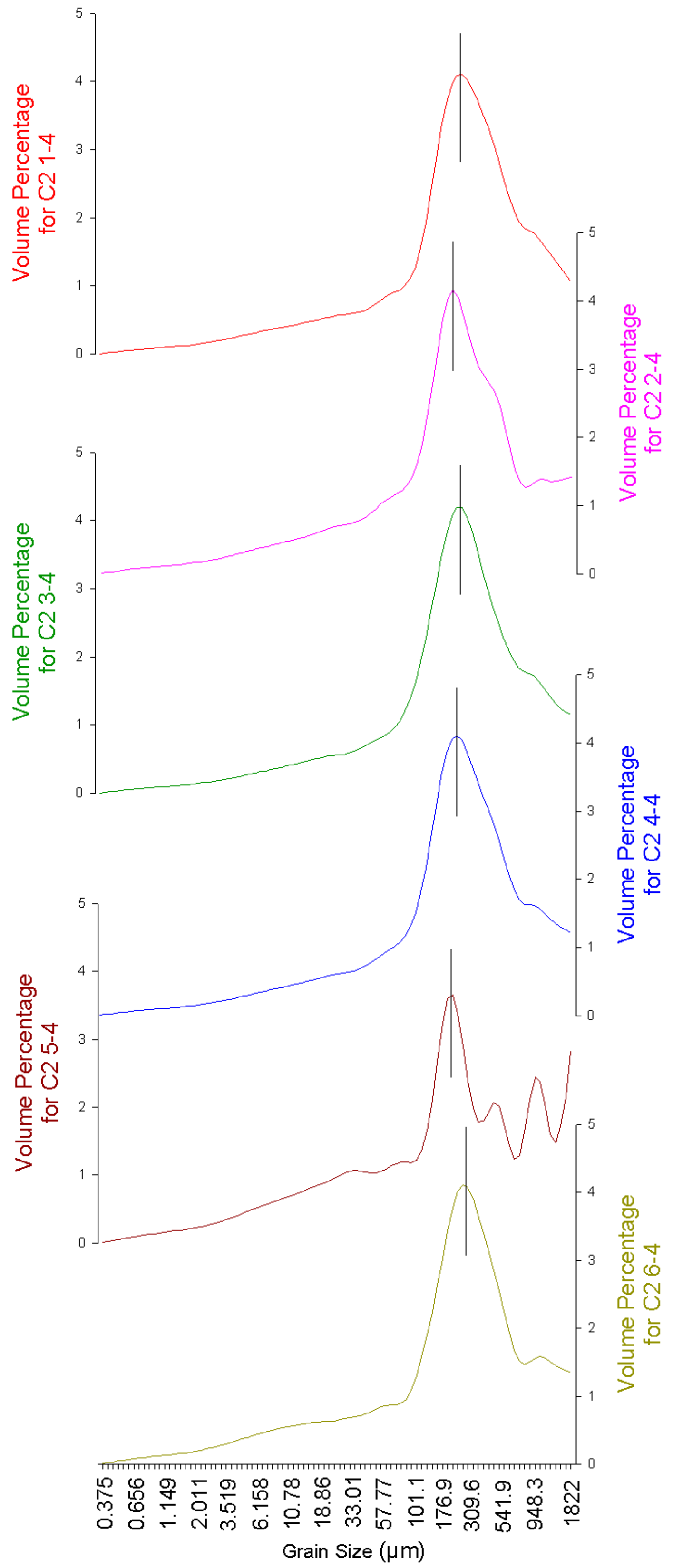
Appendix 3A: Down core grain size distribution graphs for site C1, core 5
Chi-squared analysis results: Not significantly different



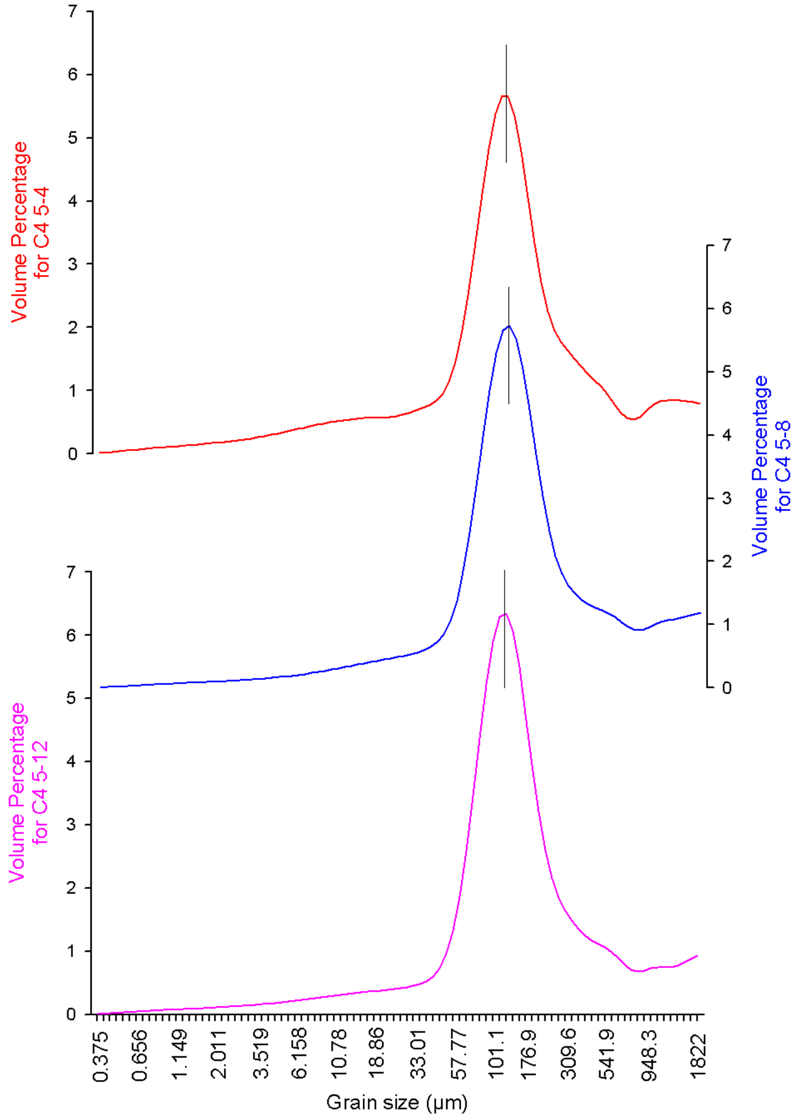
Appendix 3B: Site C1 top core grain size distribution graphs. Chi-squared analysis results: Significantly different



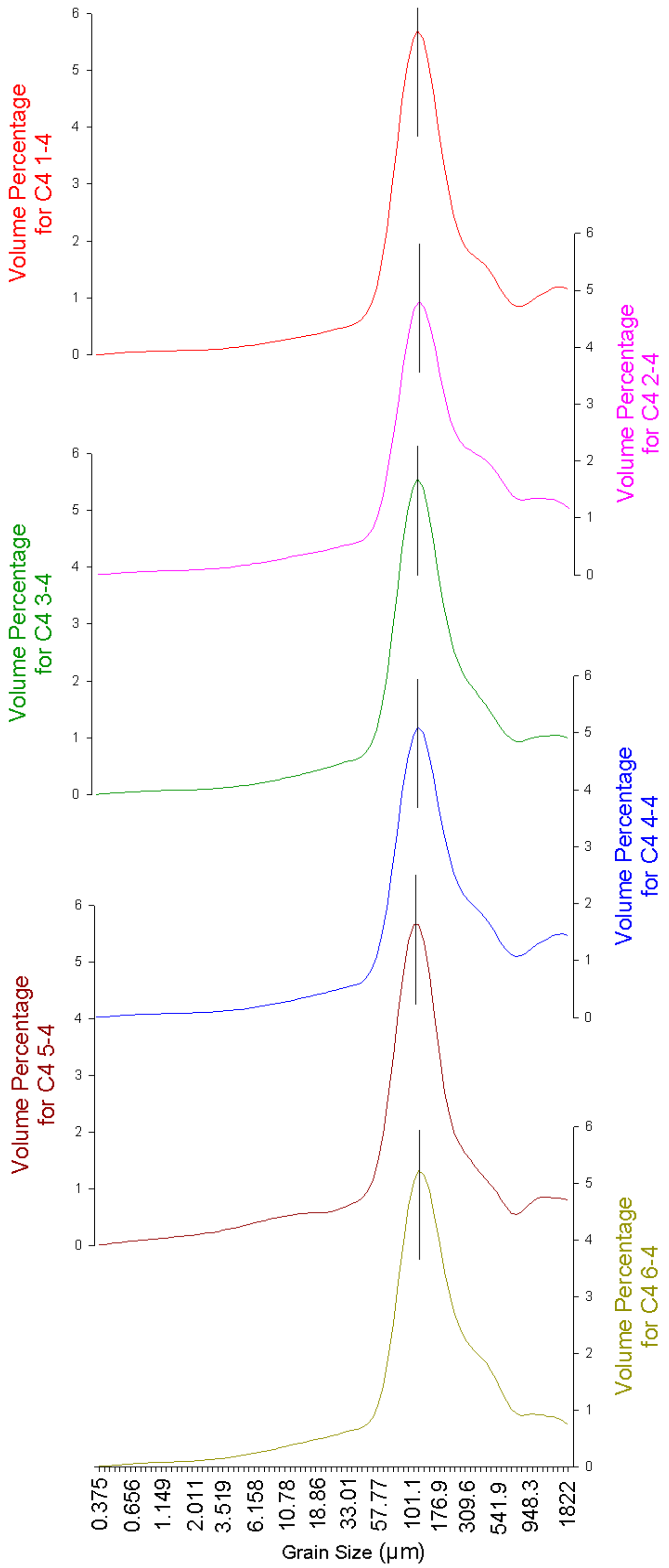
Appendix 3C: Down core grain size distribution graphs for site C2, core 5
Chi-squared analysis results: Significantly different



Appendix 3D: The six top core grain size distribution graphs for site C2
Chi-squared analysis results: Not significantly different

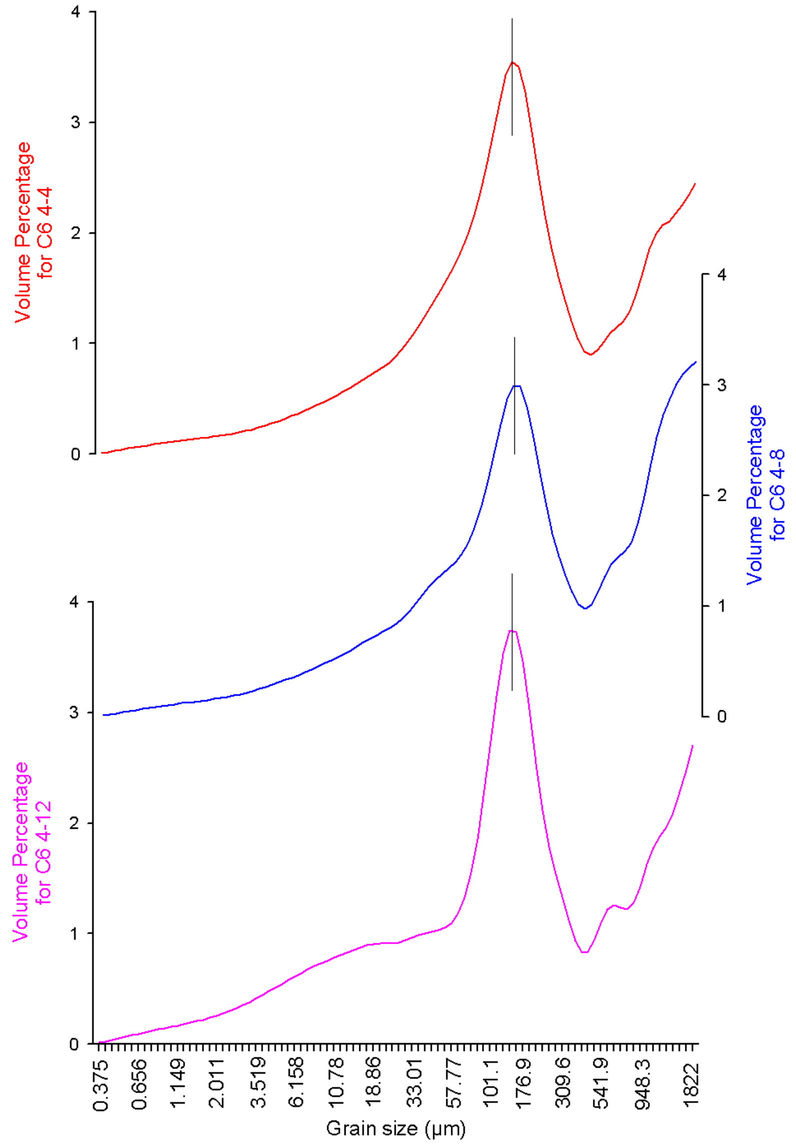


Appendix 3E: Down core grain size distribution graphs for site C4, core 5
Chi-squared analysis results: Not significantly different

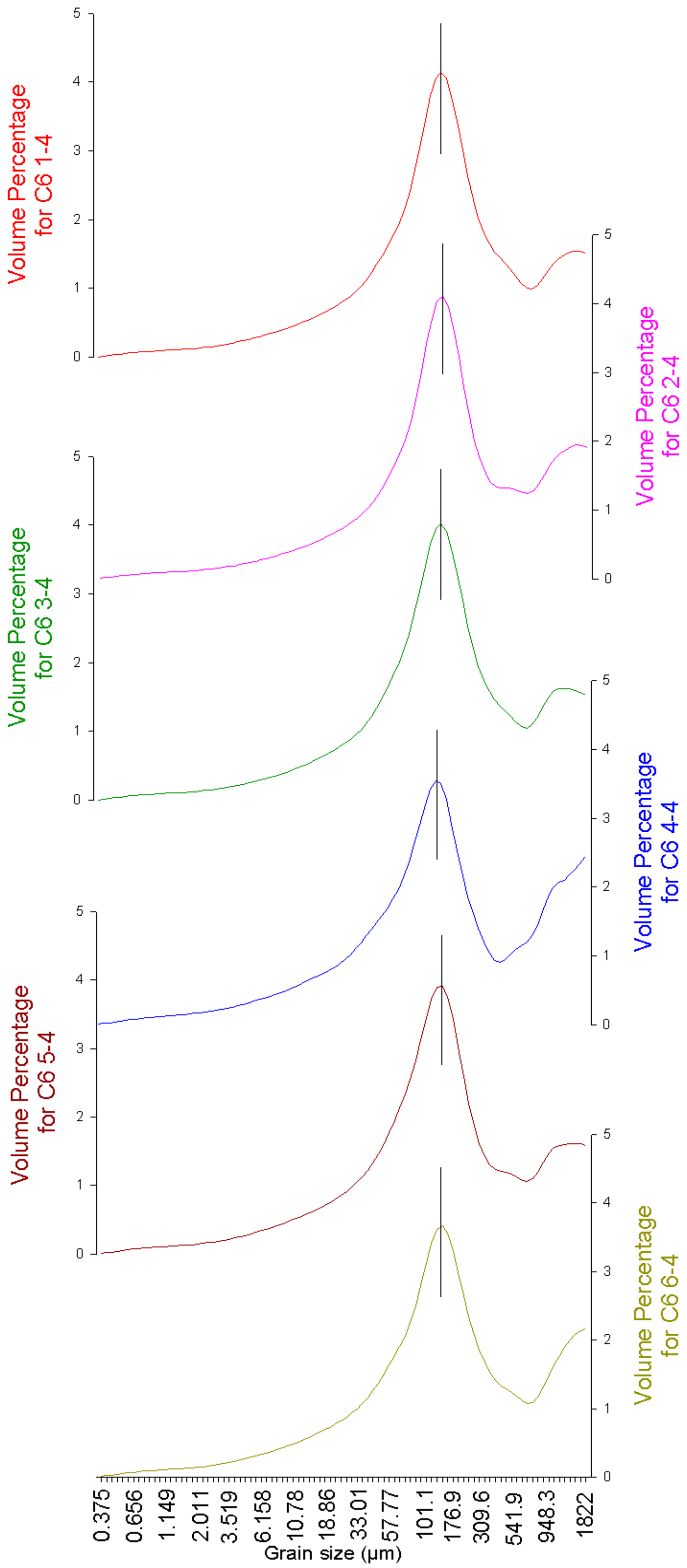


Appendix 3F: Top core grain size distribution graphs for site C4

Chi-squared analysis results: Not significantly different

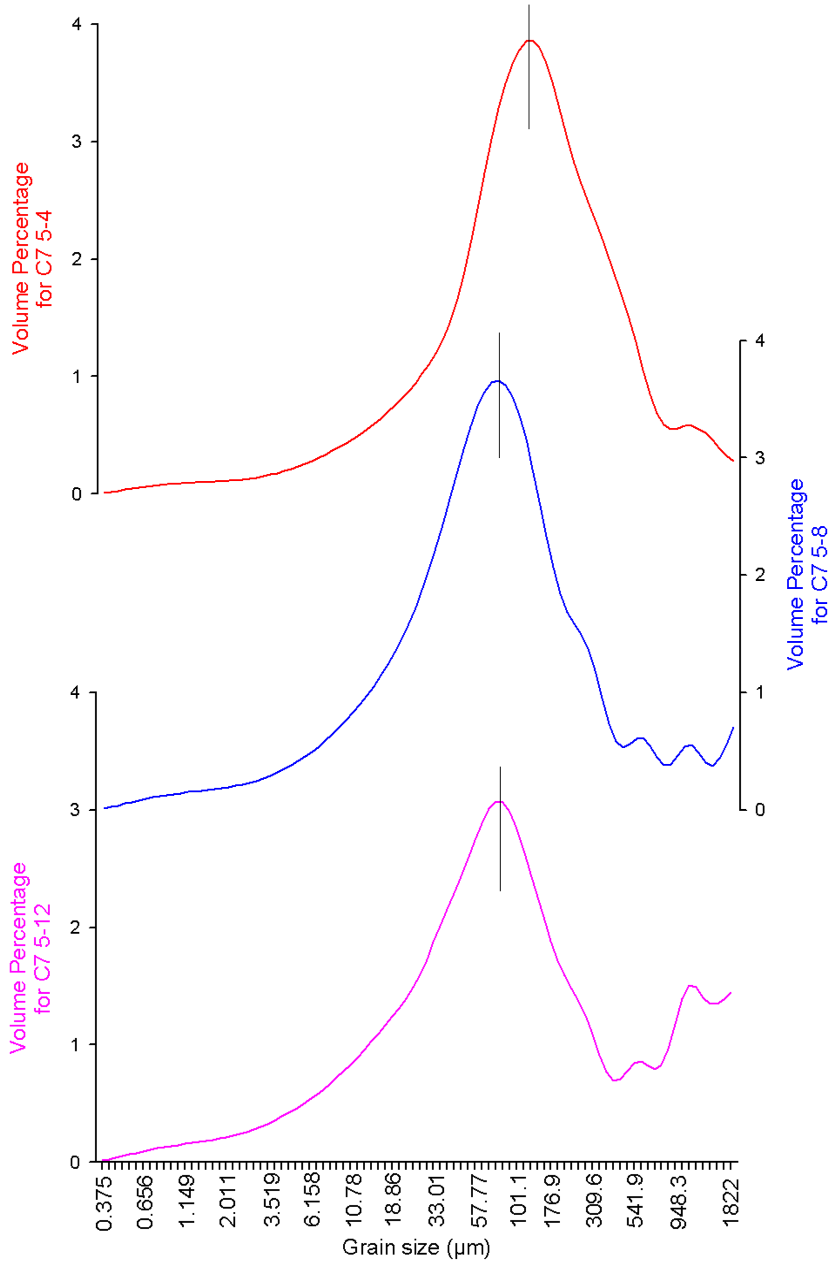


Appendix 3G: Down core grain size distribution graphs for site C6, core 4
Chi-squared analysis results: Not significantly different



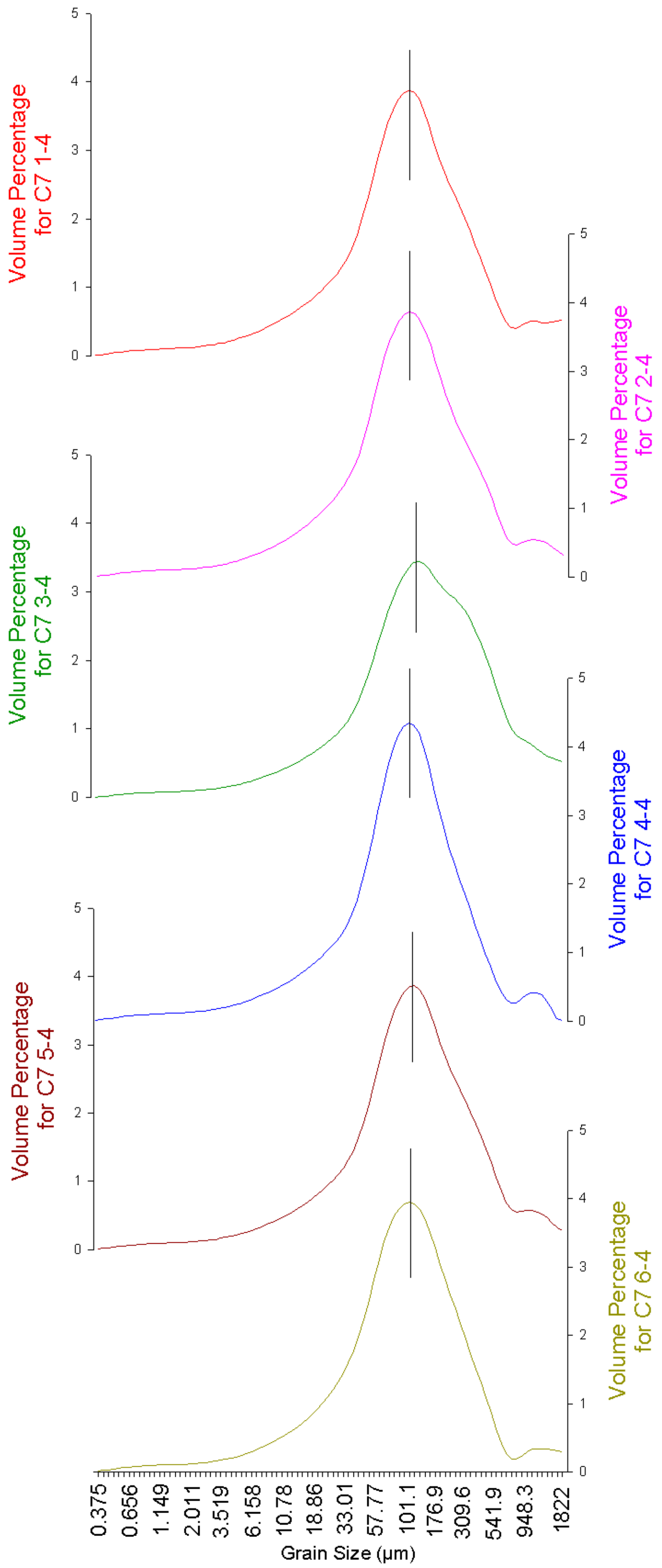
Appendix 3H:Top core grain size distribution graphs for site C6

Chi-squared analysis results: Not significantly different

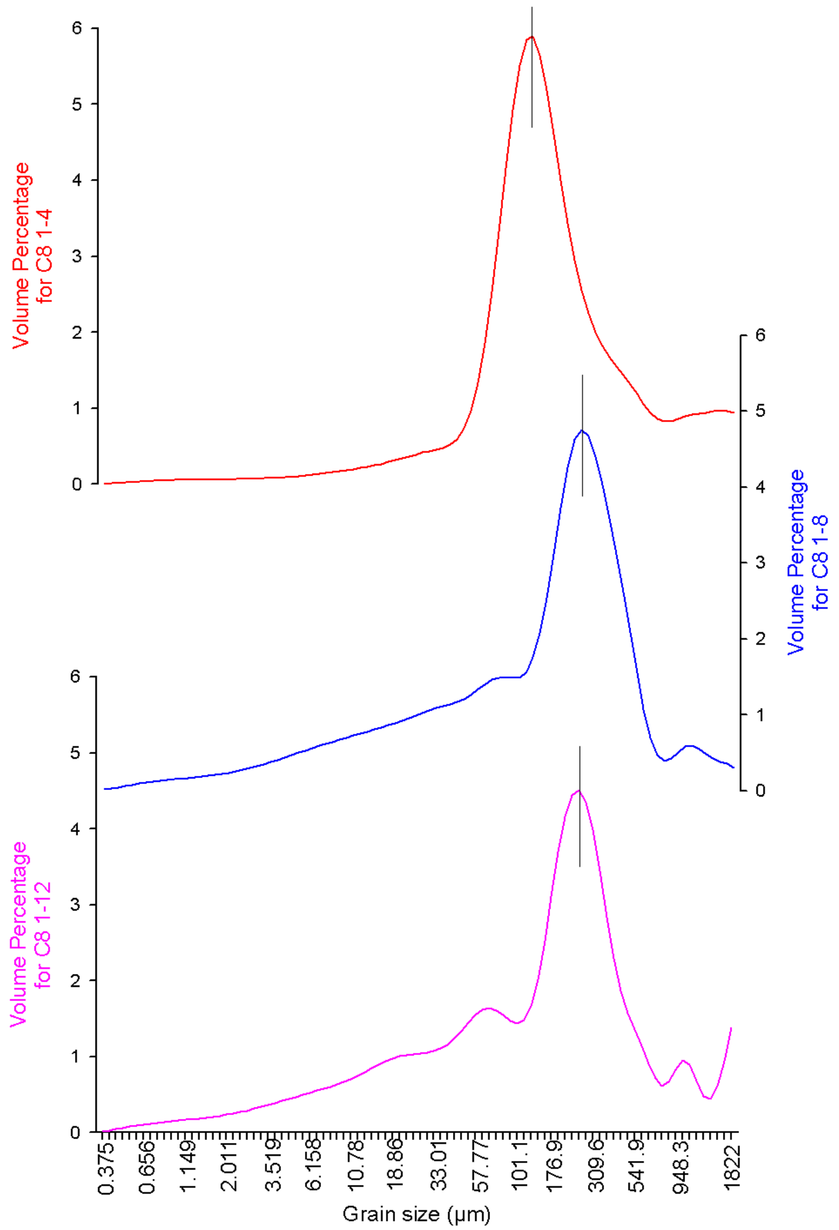


Appendix 3I: Graphical representation of the grain size distribution results for the three down core sections of core number 5 from site C7

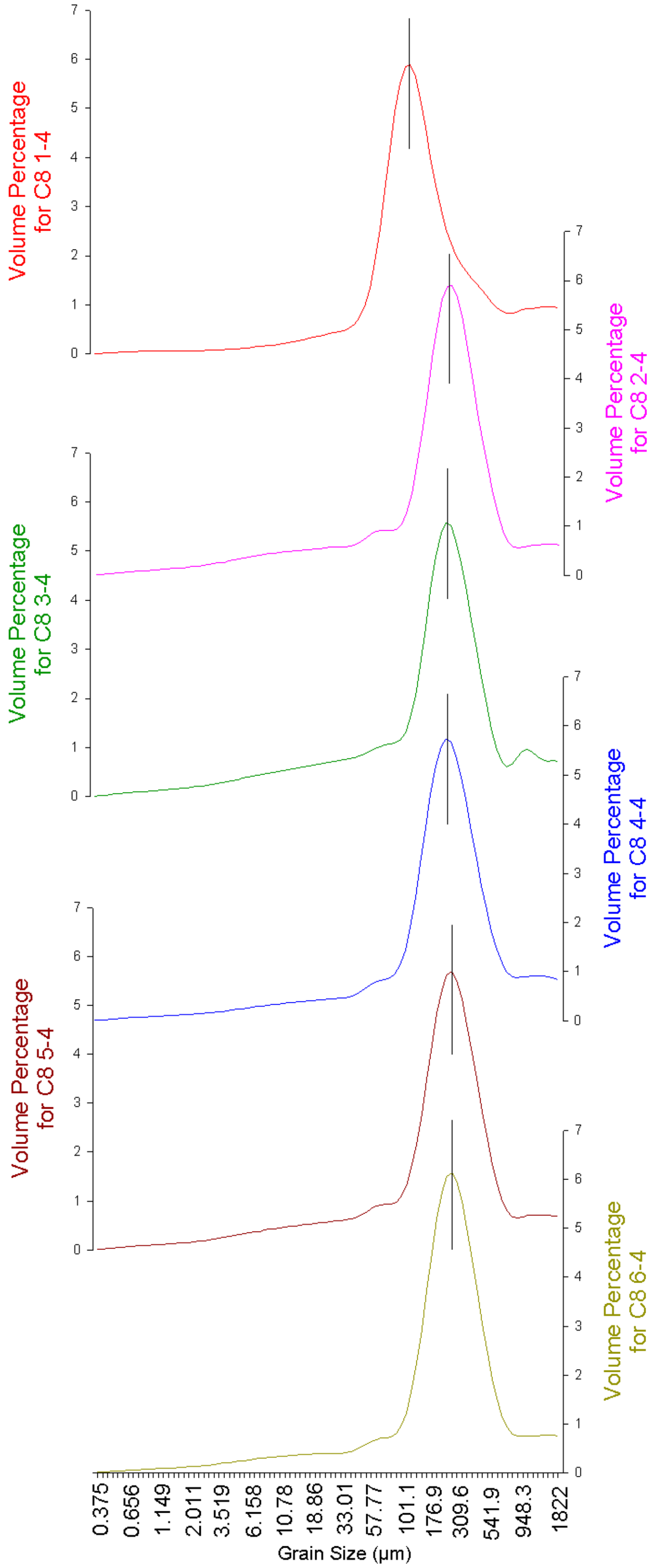
Chi-squared analysis results: Significantly different



Appendix 3J: Core top grain size graphs for the six cores from site C7
Chi-squared analysis results: Not significantly different



Appendix 3K: Grain size distribution graphs for down core sections from core 1, site C8
Chi-squared analysis results: Significantly different



Appendix 3L: Core top grain size distribution graphs for the six cores from site C8 Chi-squared analysis results: Significantlydifferent

Appendix 4: Sediment grain size series correlation data for all six sites. Where the sample size was too low to allow a meaningful correlation to be undertaken an N/A was put into the p-value column to highlight that the corresponding r-value is of no use.
Correlations were undertaken between sediment grain size data for each site taking into account AC. Those results that are not signification are presented here; the significant results are in Table 2.5.

Appendix 4A: Site C1 Sediment grain size series correlation

Core 1	Core 2	N' (From Equation 2.2)	r	p
5-4	5-8	3.75	0.895	>0.05
	5-12	3.28	0.886	>0.05
5-8	5-12	3.28	0.740	>0.05
1-4	2-4	3.75	0.869	>0.05
	3-4	2.81	0.958	>0.05
	4-4	3.75	0.974	>0.05
	5-4	3.75	0.902	>0.05
	6-4	3.28	0.929	>0.05
2-4	3-4	2.81	0.935	>0.05
	4-4	3.75	0.849	>0.05
	5-4	3.75	0.855	>0.05
	6-4	3.28	0.936	>0.05
3-4	4-4	2.81	0.941	>0.05
	5-4	2.81	0.929	>0.05
	6-4	2.33	0.981	>0.05
4-4	5-4	3.75	0.907	>0.05
	6-4	3.28	0.893	>0.05
5-4	6-4	3.28	0.862	>0.05

Appendix 4B: Site C2 Sediment grain size series correlation

Core 1	Core 2	N' (From Equation 2.2)	r	p
5-4	5-8	4.29	0.965	<0.05
	5-12	1.39	0.949	N/A
5-8	5-12	4.76	0.943	<0.05
1-4	2-4	0.92	0.976	N/A
	3-4	0.92	0.994	N/A
	4-4	0.92	0.995	N/A
	5-4	2.82	0.884	N/A
	6-4	0.92	0.994	N/A
2-4	3-4	0.92	0.988	N/A
	4-4	2.82	0.992	N/A
	5-4	0.92	0.921	N/A
	6-4	0.92	0.978	N/A
3-4	4-4	0.92	0.999	N/A
	5-4	2.82	0.898	N/A
	6-4	0.92	0.992	N/A
4-4	5-4	2.82	0.904	N/A
	6-4	0.92	0.993	N/A
5-4	6-4	2.82	0.888	N/A

Appendix 4C: Site C4 Sediment grain size series correlation

Core 1	Core 2	N' (From Equation 2.2)	r	p
5-4	5-8	1.86	0.993	N/A
	5-12	1.86	0.996	N/A
5-8	5-12	1.86	0.997	N/A
1-4	2-4	1.39	0.984	N/A
	3-4	1.86	0.999	N/A
	4-4	1.86	0.994	N/A
	5-4	1.86	0.983	N/A
	6-4	1.86	0.993	N/A
2-4	3-4	1.39	0.987	N/A
	4-4	1.39	0.996	N/A
	5-4	1.39	0.994	N/A
	6-4	1.39	0.989	N/A
3-4	4-4	1.86	0.994	N/A
	5-4	1.86	0.980	N/A
	6-4	1.86	0.997	N/A
4-4	5-4	1.86	0.960	N/A
	6-4	1.86	0.992	N/A
5-4	6-4	1.86	0.967	N/A

Appendix 4D: Site C6 Sediment grain size series correlation

Core 1	Core 2	N' (From Equation 2.2)	r	p
4-4	4-8	2.34	0.952	N/A
	4-12	2.34	0.974	N/A
4-8	4-12	3.75	0.938	>0.05
1-4	2-4	1.39	0.989	N/A
	3-4	0.92	0.998	N/A
	4-4	1.86	0.946	N/A
	5-4	1.39	0.991	N/A
	6-4	1.39	0.986	N/A
2-4	3-4	1.39	0.994	N/A
	4-4	2.33	0.975	N/A
	5-4	1.86	0.990	N/A
	6-4	1.86	0.994	N/A
3-4	4-4	1.86	0.960	N/A
	5-4	1.39	0.995	N/A
	6-4	1.39	0.991	N/A
4-4	5-4	2.33	0.973	N/A
	6-4	2.33	0.981	N/A
5-4	6-4	1.86	0.988	N/A

Appendix 4E: Site C7 Sediment grain size series correlation

Core 1	Core 2	N' (From Equation 2.2)	r	p
5-4	5-8	0.92	0.871	N/A
	5-12	1.39	0.836	N/A
5-8	5-12	1.39	0.948	N/A
1-4	2-4	0.92	0.999	N/A
	3-4	0.92	0.948	N/A
	4-4	0.92	0.995	N/A
	5-4	0.92	0.996	N/A
	6-4	0.92	0.997	N/A
2-4	3-4	0.92	0.949	N/A
	4-4	0.92	0.995	N/A
	5-4	0.92	0.997	N/A
	6-4	0.92	0.996	N/A
3-4	4-4	0.92	0.923	N/A
	5-4	0.92	0.970	N/A
	6-4	0.92	0.927	N/A
4-4	5-4	0.92	0.989	N/A
	6-4	0.92	0.996	N/A
5-4	6-4	0.92	0.989	N/A

Appendix 4F: Site C8 Sediment grain size series correlation

Core 1	Core 2	N' (From Equation 2.2)	r	p
1-4	1-8	1.86	0.610	N/A
	1-12	1.86	0.640	N/A
1-8	1-12	1.86	0.982	N/A
1-4	2-4	1.86	0.540	N/A
	3-4	1.86	0.557	N/A
	4-4	1.39	0.557	N/A
	5-4	1.86	0.542	N/A
	6-4	1.86	0.523	N/A
2-4	3-4	1.86	0.997	N/A
	4-4	1.39	0.995	N/A
	5-4	1.86	0.999	N/A
	6-4	1.86	0.997	N/A
3-4	4-4	1.39	0.993	N/A
	5-4	1.86	0.996	N/A
	6-4	1.86	0.992	N/A
4-4	5-4	1.39	0.995	N/A
	6-4	1.39	0.996	N/A
5-4	6-4	1.86	0.978	N/A

Appendix 5: Normality test results for grain size data. These tests were carried out on the grain size data to determine the statistical tests to use on the data.

Appendix 5A: Core top data: Data highlighted in yellow are non-normally distributed

Site	Clay		Silt		Sand	
	Anderson-Darling value	p-value	Anderson-Darling value	p-value	Anderson-Darling value	p-value
C1	0.205	0.766	0.189	0.822	0.198	0.790
C2	0.388	0.260	0.517	0.110	0.476	0.143
C4	0.954	0.006	0.656	0.043	0.713	0.029
C6	0.236	0.644	0.172	0.873	0.169	0.883
C7	0.539	0.095	0.525	0.104	0.562	0.081
C8	0.306	0.439	0.366	0.301	0.293	0.477

Appendix 5B: Down core data: Data highlighted in yellow are non-normally distributed

Site	Clay		Silt		Sand	
	Anderson-Darling value	p-value	Anderson-Darling value	p-value	Anderson-Darling value	p-value
C1	0.190	0.627	0.205	0.562	0.199	0.587
C2	0.338	0.201	0.190	0.628	0.200	0.581
C4	0.379	0.141	0.289	0.302	0.343	0.193
C6	0.463	0.070	0.194	0.608	0.271	0.350
C7	0.351	0.180	0.255	0.393	0.281	0.323
C8	0.448	0.080	0.442	0.083	0.457	0.074

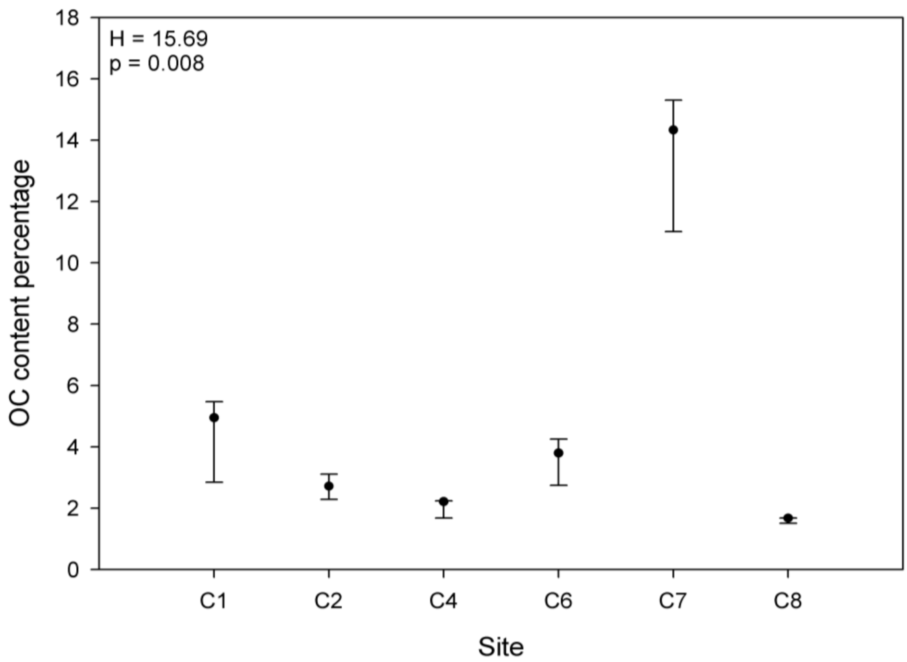
Appendx 5C: All data analysed: Data highlighted in yellow are non-normally distributed

Site	Clay		Silt		Sand	
	Anderson-Darling value	p-value	Anderson-Darling value	p-value	Anderson-Darling value	p-value
C1	0.365	0.340	0.265	0.585	0.261	0.599
C2	0.485	0.159	0.443	0.210	0.429	0.228
C4	1.137	<0.005	0.805	0.021	0.890	0.012
C6	0.847	0.016	0.130	0.967	0.234	0.699
C7	0.889	0.012	0.607	0.074	0.652	0.055
C8	0.254	0.624	0.523	0.124	0.459	0.188

Appendix 6: OC content normality test results. These tests were undertaken on the data to determine what test to use to analyse the data.

Site	Anderson-Darling value	p-value	Normally or non-normally distributed?
C1	0.312	0.249	Normally distributed
C2	0.190	0.628	Normally distributed
C4	0.438	0.086	Normally distributed
C6	0.248	0.420	Normally distributed
C7	0.292	0.294	Normally distributed
C8	0.482	0.059	Normally distributed

Appendix 7: Non-parametric analysis of OC content data. Due to the small n-values of the OC datasets both parametric and non-parametric tests were carried out on the data. The tests presented here were compared to those in Figure 2.14 and the results discussed in Section 2.3.2.3.

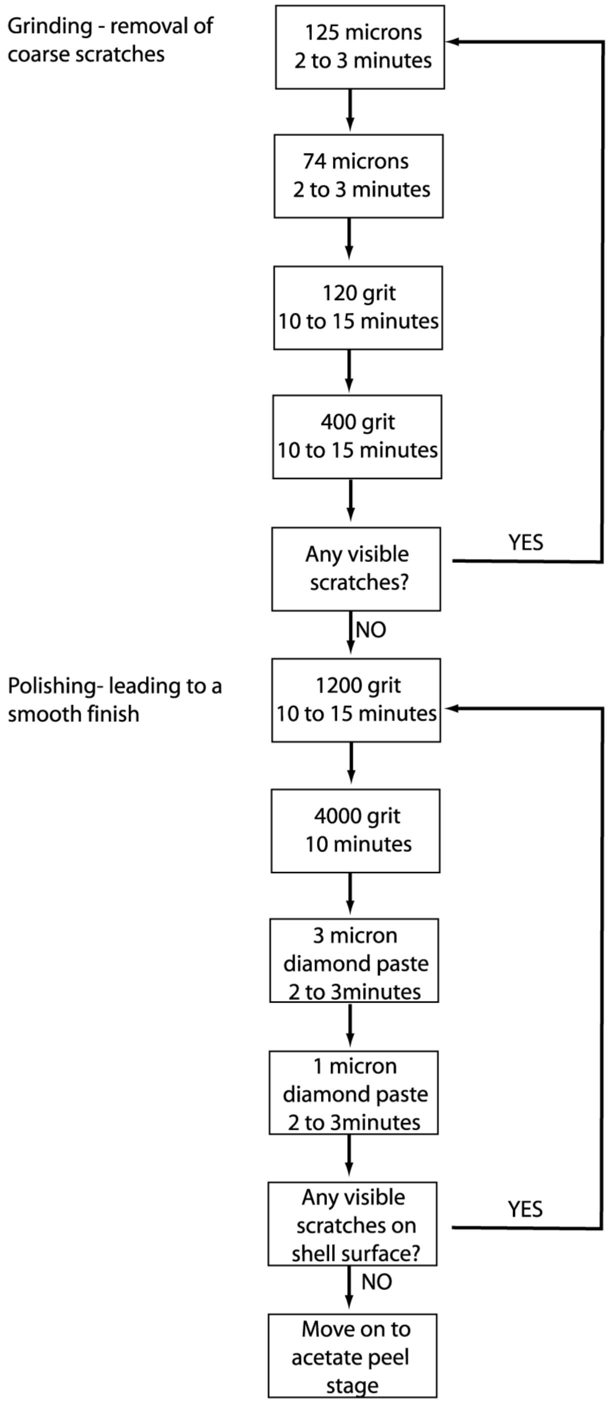


The results in the graph above as well as the Kruskal-Wallis analyses of the OC content datasets indicates that the parametric analyses carried out on the same dataset in Figure 2.14 are correct and that the data at site C7 are significantly different from that at all the other sites. Data presented as the median and IQR of the values.

Appendix 8: Data collection methods.
To fully understand each instrumental dataset investigated in Chapter 3 their data collection methods are considered here.

Dataset	Collection methods
Saulmore	Diver –deployed temperature loggers at 10m below chart datum recording temperature every 12 minutes. Since 2007 two loggers have been used due to previous breakages, data from these are averaged to generate daily data. From this monthly, seasonal and annual average data can be generated. Over time the logger temperature resolution has gone from 0.12 to 0.01°C, the divers test the loggers against water of known temperature to check for problems. (Sayer, pers. comm., 2010)
Dunstaffnage and Tiree	Both datasets are collected using Met Office weather station equipment – there is little information on how this has changed over time or what exactly is currently being used at each site. At Tiree the station is at 12m above mean sea level (amsl) while at Dunstaffnage it is at 3m amsl. (Met Office, 2011d, Met Office, 2011a).
Millport	Temperature taken from samples collected off Keppel Pier using a bucket and then measured using a mercury thermometer to 0.1°C. This method has been used since records began in the 1950s. Samples are measured at approximately 10am each morning. (Stevenson pers. comm.)
HadSST2	Data are taken from records collected by ships and buoys – this comes from two databases. These are ICOADS (1850 to 1997) and NCEP-GTS (1998 to present). The data used are converted to anomalies and gridded; there is a need to correct the data to remove any bias introduced due to changes in collection methods before 1942. (Met Office, 2011b)
CRUTEM3	CRUTEM3 is made up from a variety of monthly mean temperature sources. For the grid being used for analysis here there are four datasets: Stornoway Fort William Ben Nevis Tiree. The fact that the Tiree series is included in the CRUTEM3 dataset explains the high correlations between the two series as seen in Chapter 3. The data used to create the CRUTEM3 dataset are turned into anomalies – relative to 1961 to 1990 (UEA, 2011)

Appendix 9: Grinding and polishing techniques for resin mounted shell blocks.
This figure outlines the processes/stages involved in the grinding and polishing of the resin mounted shells to prepare the surface for acetate peel production by minimising the number of scratches present.



Appendix 10: Table highlighting some key papers and the location in the shell analysis was undertaken. N.B. (G) denotes that some form of geochemical analysis was undertaken as part of this research. This information highlights the split between where analysis is undertaken on the shells and the need to investigate growth rates between the umbo and outer sections.

Umbo	Outer	Both
Stott et al., 2010	Witbaard, 1997 (older shells only)	Weidman and Jones, 1994
Wanamaker et al., 2008	Witbaard et al., 2003	Butler et al., 2009a
Witbaard et al., 1996; 1999; 2005	Schöne et al., 2004; 2005b	Daniels, 2010
Witbaard, 1997 (younger shells only)	Wanamaker et al., 2007 (G)	Schöne and Fiebig, 2009
Kilada et al., 2006	Weidman and Jones, 1993 (G)	Ropes, 1988, 1989
Liehr et al., 2005 (G)		

Appendix 11. Raw GI data for all shells measured whether dated into the master chronology or not. All measurements are in microns.
This data has been obtained through GI measurements of those shells clear enough to faciliate this stage of the analysis process. Also included in appendix 11 are the outer vs. inner shell detrended GI measurements for the comparison work undertaken in Chapter 4.

Appendix 11A: Raw GI data for site C1

Year	L5	L10	L14	L4	L2	L15	L19	L20B	L17
1843				0.84					
1844				0.632					
1845				0.53					
1846				0.299					
1847				0.305					
1848				0.255					
1849				0.156					
1850				0.064					
1851				0.096					
1852				0.049					
1853				0.097					
1854				0.104					
1855				0.053					
1856				0.06					
1857				0.142					
1858				0.111					
1859				0.127					
1860				0.074					
1861				0.054					
1862				0.047					
1863				0.052					
1864				0.06					

1865		0.115
1866		0.109
1867		0.095
1868		0.141
1869		0.153
1870		0.117
1871		0.112
1872		0.072
1873		0.036
1874		0.065
1875		0.065
1876		0.096
1877		0.048
1878		0.077
1879		0.039
1880		0.041
1881		0.044
1882		0.053
1883		0.044
1884		0.08
1885		0.035
1886	0.73	0.03
1887	0.711	0.042
1888	0.329	0.037
1889	0.257	0.042
1890	0.211	0.036
1891	0.184	0.031
1892	0.114	0.027

1893		0.161	0.017			
1894		0.196	0.027		0.889	
1895		0.197	0.035		1.087	
1896		0.104	0.02		0.852	
1897		0.114	0.024		0.35	
1898		0.146	0.021		0.225	
1899		0.071	0.026		0.18	
1900		0.102	0.025		0.526	
1901		0.083	0.034		0.416	
1902	0.666	0.067	0.037		0.816	
1903	0.741	0.058	0.042		0.441	
1904	0.784	0.093	0.076		0.309	
1905	0.609	0.005	0.027		0.212	0.906
1906	0.394	0.04	0.059		0.175	0.691
1907	0.277	0.065	0.036		0.017	0.182
1908	0.247	0.062	0.034		0.092	0.198
1909	0.147	0.067	0.038		0.053	0.367
1910	0.147	0.035	0.021		0.123	0.159
1911	0.119	0.045	0.077		0.05	0.263
1912	0.086	0.036	0.028		0.084	0.604
1913	0.103	0.096	0.019	0.472	0.112	0.344
1914	0.123	0.097	0.02	0.45	0.069	0.337
1915	0.089	0.102	0.025	0.433	0.129	0.313
1916	0.106	0.075	0.016	0.582	0.102	0.408
1917	0.101	0.061	0.026	0.415	0.054	0.311
1918	0.125	0.048	0.027	0.386	0.048	0.318
1919	0.037	0.045	0.016	0.252	0.088	0.268
1920	0.019	0.054	0.009	0.185	0.043	0.198

1921		0.054	0.075	0.015	0.148	0.166		0.117	1.429
1922		0.047	0.037	0.016	0.131	0.131		0.193	1.11
1923		0.079	0.032	0.019	0.148	0.051		0.09	0.931
1924		0.074	0.063	0.052	0.11	0.043		0.195	0.869
1925		0.051	0.066	0.019	0.128	0.066		0.227	0.487
1926		0.044	0.073	0.025	0.182	0.138		0.209	0.226
1927		0.067	0.03	0.017	0.096	0.032		0.165	0.295
1928		0.059	0.053	0.028	0.112	0.034		0.143	0.133
1929		0.068	0.05	0.012	0.099	0.084		0.112	0.227
1930		0.042	0.093	0.034	0.12	0.028		0.158	0.242
1931		0.047	0.079	0.043	0.15	0.042		0.112	0.208
1932		0.05	0.012	0.022	0.119	0.032		0.093	0.176
1933		0.055	0.019	0.033	0.101	0.035		0.076	0.162
1934		0.053	0.025	0.029	0.112	0.052		0.088	0.134
1935		0.028	0.012	0.022	0.053	0.043		0.041	0.168
1936		0.06	0.013	0.035	0.052	0.023		0.083	0.15
1937		0.069	0.023	0.024	0.064	0.0865		0.125	0.134
1938		0.054	0.026	0.02	0.112	0.022		0.116	0.062
1939		0.016	0.005	0.017	0.065	0.0245		0.06	0.093
1940		0.037	0.013	0.012	0.047	0.019		0.078	0.065
1941		0.05	0.026	0.015	0.07	0.045		0.104	0.079
1942		0.099	0.057	0.025	0.098	0.0275		0.129	0.139
1943		0.056	0.046	0.034	0.103	0.033		0.12	0.094
1944		0.032	0.035	0.015	0.048	0.0265	1.534	0.038	0.054
1945	0.779	0.022	0.009	0.01	0.05	0.058	1.745	0.026	0.092
1946	0.783	0.022	0.006	0.022	0.035	0.042	1.49	0.014	0.077
1947	0.799	0.03	0.015	0.031	0.04	0.028	0.832	0.02	0.141
1948	0.828	0.033	0.021	0.039	0.049	0.032	0.51	0.032	0.106

1949	0.471	0.022	0.023	0.025	0.03	0.012	0.262	0.044	0.059
1950	0.366	0.025	0.028	0.011	0.034	0.013	0.237	0.043	0.042
1951	0.316	0.02	0.022	0.011	0.045	0.012	0.327	0.037	0.021
1952	0.401	0.046	0.05	0.007	0.07	0.035	0.114	0.034	0.035
1953	0.251	0.032	0.014	0.015	0.059	0.022	0.12	0.058	0.021
1954	0.293	0.041	0.017	0.022	0.061	0.025	0.099	0.071	0.038
1955	0.195	0.034	0.007	0.012	0.044	0.013	0.096	0.051	0.031
1956	0.232	0.044	0.02	0.009	0.036	0.032	0.063	0.043	0.049
1957	0.216	0.05	0.031	0.009	0.058	0.039	0.073	0.062	0.041
1958	0.181	0.031	0.024	0.028	0.032	0.015	0.044	0.066	0.048
1959	0.193	0.047	0.006	0.016	0.047	0.037	0.05	0.029	0.032
1960	0.122	0.018	0.004	0.027	0.032	0.017	0.032	0.059	0.027
1961	0.109	0.018	0.01	0.018	0.037	0.013	0.054	0.032	0.041
1962	0.07	0.013	0.005	0.023	0.022	0.035	0.035	0.032	0.058
1963	0.112	0.031	0.01	0.02	0.034	0.027	0.075	0.018	0.067
1964	0.105	0.031	0.007	0.019	0.046	0.016	0.033	0.032	0.106
1965	0.093	0.018	0.043	0.022	0.025	0.009	0.034	0.019	0.025
1966	0.038	0.013	0.01	0.017	0.025	0.01	0.02	0.04	0.027
1967	0.04	0.016	0.006	0.017	0.029	0.009	0.047	0.017	0.013
1968	0.039	0.019	0.008	0.007	0.017	0.009	0.026	0.02	0.025
1969	0.053	0.019	0.007	0.022	0.03	0.037	0.017	0.016	0.017
1970	0.109	0.017	0.01	0.016	0.055	0.012	0.023	0.013	0.019
1971	0.043	0.02	0.015	0.017	0.018	0.009	0.013	0.019	0.025
1972	0.055	0.016	0.014	0.007	0.024	0.01	0.012	0.025	0.018
1973	0.031	0.021	0.015	0.009	0.024	0.011	0.013	0.041	0.018
1974	0.044	0.016	0.006	0.03	0.055	0.016	0.055	0.019	0.014
1975	0.026	0.019	0.011	0.024	0.031	0.012	0.021	0.029	0.013
1976	0.033	0.014	0.01	0.012	0.055	0.026	0.023	0.013	0.059

1977	0.026	0.019	0.009	0.007	0.059	0.016	0.022	0.024	0.017
1978	0.023	0.011	0.015	0.006	0.036	0.012	0.019	0.018	0.024
1979	0.034	0.015	0.019	0.015	0.062	0.014	0.013	0.029	0.032
1980	0.023	0.012	0.017	0.007	0.061	0.01	0.015	0.029	0.022
1981	0.051	0.024	0.074	0.015	0.076	0.016	0.028	0.033	0.056
1982	0.053	0.013	0.034	0.009	0.043	0.009	0.031	0.033	0.021
1983	0.043	0.024	0.015	0.012	0.056	0.028	0.023	0.028	0.013
1984	0.029	0.015	0.015	0.012	0.052	0.012	0.023	0.025	0.013
1985	0.082	0.031	0.004	0.01	0.054	0.005	0.017	0.051	0.003
1986	0.029	0.015	0.057	0.016	0.052	0.011	0.024	0.032	0.038
1987	0.029	0.017	0.053	0.012	0.02	0.007	0.039	0.022	0.024
1988	0.033	0.018	0.048	0.009	0.019	0.022	0.007	0.035	0.014
1989	0.015	0.013	0.013	0.009	0.035	0.017	0.023	0.04	0.029
1990	0.069	0.078	0.056	0.028	0.033	0.031	0.028	0.047	0.013
1991	0.084	0.04	0.072	0.03	0.043	0.047	0.041	0.066	0.079
1992	0.076	0.039	0.056	0.028	0.052	0.025	0.045	0.071	0.065
1993	0.085	0.066	0.064	0.03	0.047	0.031	0.127	0.098	0.107
1994	0.066	0.082	0.109	0.032	0.046	0.023	0.082	0.066	0.115
1995	0.105	0.043	0.032	0.025	0.038	0.051	0.096	0.077	0.07
1996	0.053	0.038	0.023	0.023	0.07	0.027	0.161	0.081	0.095
1997	0.098	0.096	0.057	0.029	0.051	0.011	0.093	0.055	0.147
1998	0.1	0.06	0.069	0.029	0.039	0.03	0.125	0.078	0.083
1999	0.085	0.05	0.069	0.025	0.039	0.031	0.125	0.06	0.099
2000	0.091	0.049	0.076	0.028	0.047	0.038	0.095	0.079	0.037
2001	0.059	0.055	0.033	0.036	0.067	0.018	0.124	0.078	0.103
2002	0.082	0.066	0.011	0.027	0.022	0.025	0.103	0.05	0.094
2003	0.097	0.043	0.047	0.018	0.05	0.033	0.078	0.059	0.044
2004	0.078	0.035	0.03	0.025	0.03	0.033	0.048	0.036	0.058

2005	0.061	0.021	0.013	0.018	0.036	0.014	0.075	0.039	0.036

Appendix 11B: Raw GI data for site C2

Year	C2L6	C2L7	C2L8	C2L11	C2L14	C2L41	C2L42	C2L45	C2L47	C2L48	C2L48(2)	C2L51	C2L54	C2L57	C2L66	C2L68
1915			0.076													
1916			1.182													
1917			1.108													
1918			0.668													
1919			0.667													
1920			0.772													
1921			1.072													
1922			1.415													
1923			1.144													
1924			0.623													
1925			0.626													
1926			0.392													
1927			0.103													
1928			0.27													
1929			0.323													
1930			0.051													
1931			0.073													
1932			0.063													
1933			0.163													
1934			0.191													
1935			0.196													
1936			0.155					0.789			0.222					
1937			0.077					0.792			0.448					
1938			0.168					0.61			0.596					

1939			0.09					0.558			0.639					
1940			0.077				0.803	0.46			0.437					
1941			0.035				0.551	0.38			0.385					
1942	1.267		0.027	0.671			0.199	0.287			0.235					
1943	1.024		0.045	0.166			0.342	0.253		0.8	0.186					
1944	0.895		0.054	0.573			0.167	0.184		0.875	0.14		0.615			
1945	0.538		0.04	0.502			0.381	0.112		1.076	0.015		0.821			
1946	0.467		0.041	0.843			0.407	0.115		0.441	0.143	0.098	0.992	0.789		
1947	0.383		0.029	0.719			0.317	0.148		1.267	0.27	1.041	1.035	0.611		
1948	0.397		0.041	0.64			0.247	0.096		2.121	0.115	1.247	1.241	0.453		
1949	0.348		0.026	0.597			0.265	0.094		1.247	0.081	1.034	0.928	0.437		
1950	0.137		0.042	0.359			0.134	0.035		1.227	0.095	0.838	0.485	0.311		0.8
1951	0.102	1.007	0.039	0.383			0.284	0.102		0.817	0.125	1.141	0.378	0.262		1.054
1952	0.108	0.744	0.012	0.296			0.211	0.046		0.878	0.109	0.787	0.4	0.2		0.959
1953	0.17	0.76	0.014	0.291	0.628		0.267	0.103		0.838	0.027	0.577	0.246	0.163		1.071
1954	0.22	0.851	0.054	0.252	1.097		0.185	0.096		0.597	0.028	0.471	0.247	0.195		0.766
1955	0.142	0.732	0.035	0.227	0.348		0.16	0.032		0.604	0.113	0.396	0.196	0.164		0.773
1956	0.146	0.68	0.032	0.221	0.32		0.195	0.055		0.499	0.109	0.386	0.241	0.173		0.468
1957	0.159	0.471	0.024	0.155	0.336		0.14	0.038		0.492	0.138	0.345	0.223	0.137		0.37
1958	0.107	0.391	0.08	0.214	0.305		0.185	0.02		0.25	0.079	0.209	0.241	0.215		0.284
1959	0.141	0.236	0.041	0.193	0.383		0.106	0.044		0.145	0.113	0.198	0.264	0.116		0.471
1960	0.119	0.164	0.058	0.144	0.369		0.158	0.064		0.116	0.092	0.19	0.185	0.102		0.207
1961	0.13	0.213	0.024	0.163	0.263		0.098	0.064		0.142	0.086	0.21	0.211	0.077		0.262
1962	0.101	0.132	0.036	0.118	0.221		0.119	0.087		0.09	0.078	0.157	0.174	0.123		0.165
1963	0.1	0.166	0.067	0.172	0.191		0.08	0.064		0.084	0.086	0.024	0.172	0.084		0.163
1964	0.12	0.154	0.026	0.109	0.216		0.092	0.06		0.043	0.082	0.134	0.17	0.072		0.101
1965	0.093	0.132	0.02	0.17	0.196		0.092	0.048		0.07	0.07	0.108	0.147	0.095		0.13
1966	0.068	0.151	0.006	0.17	0.14		0.091	0.074		0.056	0.06	0.092	0.085	0.026		0.128

1967	0.068	0.121	0.012	0.146	0.153		0.066	0.048		0.091	0.051	0.122	0.098	0.018		0.155
1968	0.077	0.078	0.047	0.146	0.149		0.074	0.04		0.099	0.057	0.081	0.078	0.061		0.08
1969	0.086	0.077	0.017	0.12	0.084		0.063	0.084		0.084	0.073	0.102	0.103	0.061		0.073
1970	0.094	0.072	0.021	0.071	0.103	0.595	0.053	0.024		0.05	0.077	0.124	0.082	0.081		0.076
1971	0.063	0.08	0.037	0.074	0.112	0.534	0.056	0.062		0.018	0.059	0.09	0.078	0.067		0.112
1972	0.103	0.096	0.05	0.127	0.062	0.638	0.07	0.05		0.07	0.082	0.085	0.095	0.042		0.073
1973	0.053	0.045	0.019	0.077	0.046	0.498	0.064	0.05		0.059	0.045	0.025	0.095	0.064		0.061
1974	0.059	0.031	0.044	0.068	0.034	0.443	0.061	0.062		0.03	0.042	0.047	0.071	0.046		0.084
1975	0.042	0.037	0.031	0.057	0.074	0.32	0.107	0.032	0.789	0.069	0.039	0.121	0.078	0.114		0.047
1976	0.059	0.041	0.027	0.064	0.07	0.367	0.068	0.024	0.764	0.026	0.039	0.069	0.09	0.055		0.056
1977	0.057	0.045	0.03	0.058	0.069	0.327	0.055	0.032	0.839	0.048	0.052	0.022	0.08	0.054		0.061
1978	0.05	0.063	0.016	0.079	0.052	0.206	0.035	0.028	0.674	0.009	0.034	0.086	0.069	0.02		0.027
1979	0.059	0.047	0.028	0.099	0.073	0.141	0.052	0.044	0.496	0.073	0.054	0.086	0.054	0.043		0.052
1980	0.044	0.05	0.082	0.077	0.042	0.082	0.076	0.014	0.678	0.029	0.032	0.077	0.011	0.017		0.093
1981	0.048	0.047	0.048	0.053	0.051	0.135	0.067	0.03	0.622	0.028	0.046	0.097	0.012	0.014		0.015
1982	0.044	0.063	0.024	0.067	0.046	0.102	0.087	0.028	0.282	0.069	0.036	0.04	0.045	0.025		0.083
1983	0.075	0.037	0.047	0.075	0.052	0.081	0.06	0.014	0.405	0.032	0.075	0.069	0.08	0.079		0.059
1984	0.025	0.023	0.018	0.072	0.05	0.076	0.077	0.062	0.212	0.038	0.027	0.012	0.085	0.027		0.063
1985	0.054	0.066	0.033	0.082	0.07	0.088	0.093	0.04	0.273	0.077	0.031	0.043	0.06	0.062		0.031
1986	0.05	0.03	0.029	0.044	0.048	0.08	0.031	0.044	0.276	0.013	0.076	0.04	0.063	0.052		0.052
1987	0.031	0.037	0.03	0.084	0.036	0.051	0.059	0.028	0.14	0.046	0.046	0.017	0.044	0.026		0.077
1988	0.047	0.022	0.054	0.06	0.04	0.078	0.041	0.04	0.18	0.037	0.049	0.048	0.026	0.032		0.029
1989	0.065	0.032	0.04	0.032	0.052	0.052	0.044	0.038	0.199	0.016	0.031	0.035	0.045	0.029		0.07
1990	0.029	0.012	0.013	0.048	0.034	0.046	0.054	0.022	0.153	0.027	0.031	0.036	0.048	0.032		0.045
1991	0.034	0.032	0.026	0.059	0.037	0.042	0.067	0.04	0.094	0.033	0.034	0.02	0.036	0.045		0.084
1992	0.037	0.028	0.038	0.044	0.036	0.033	0.052	0.062	0.05	0.026	0.024	0.06	0.022	0.037	0.462	0.051
1993	0.02	0.012	0.042	0.034	0.042	0.022	0.046	0.02	0.024	0.029	0.044	0.047	0.025	0.042	0.527	0.046
1994	0.048	0.037	0.051	0.051	0.038	0.025	0.017	0.028	0.032	0.037	0.037	0.01	0.022	0.032	1.615	0.048

1995	0.036	0.042	0.045	0.041	0.034	0.035	0.02	0.026	0.059	0.068	0.03	0.012	0.021	0.01	0.059	0.053
1996	0.037	0.037	0.025	0.048	0.066	0.037	0.021	0.032	0.055	0.008	0.054	0.081	0.016	0.02	1.536	0.042
1997	0.059	0.024	0.018	0.027	0.094	0.053	0.024	0.036	0.056	0.009	0.029	0.062	0.022	0.011	0.92	0.053
1998	0.033	0.079	0.031	0.036	0.046	0.029	0.016	0.02	0.07	0.01	0.04	0.075	0.028	0.015	0.265	0.017
1999	0.039	0.022	0.02	0.049	0.066	0.052	0.027	0.028	0.067	0.027	0.032	0.025	0.025	0.034	0.937	0.035
2000	0.037	0.02	0.021	0.047	0.039	0.013	0.022	0.016	0.1	0.034	0.043	0.011	0.024	0.03	0.607	0.025
2001	0.044	0.035	0.016	0.031	0.066	0.009	0.075	0.014	0.032	0.019	0.062	0.07	0.014	0.04	0.573	0.045
2002	0.07	0.035	0.01	0.041	0.048	0.039	0.066	0.03	0.038	0.021	0.053	0.086	0.026	0.05	0.392	0.058
2003	0.043	0.012	0.023	0.056	0.016	0.056	0.049	0.034	0.031	0.018	0.021	0.046	0.017	0.031	0.292	0.036
2004	0.031	0.018	0.029	0.067	0.034	0.038	0.037	0.026	0.063	0.042	0.025	0.036	0.013	0.042	0.132	0.046
2005	0.071	0.019	0.016	0.065	0.018	0.026	0.02	0.022	0.065	0.026	0.035	0.034	0.019	0.034	0.299	0.026
2006	0.017	0.026	0.012	0.013	0.037	0.02	0.06	0.02	0.022	0.012	0.012	0.047	0.009	0.048	0.131	0.061
2007	0.015	0.028	0.077	0.017	0.016	0.039	0.012	0.028	0.025	0.034	0.012	0.013	0.047	0.014	0.193	0.021
2008	0.026	0.017	0.051	0.016	0.029	0.025	0.017	0.028	0.064	0.034	0.017	0.024	0.021	0.042	0.204	0.027

Year	C2L76	C2L10	C2L43	C2L3	C2L22	C2L34	C2L35	C2L53	C2L55	C2L69	C2L33	C2L46(2)	C2L101(A)	C2L101(B)	C2L102	C2L104
1875																0.75
1876																0.907
1877																0.973
1878																0.648
1879																0.526
1880																0.495
1881																0.356
1882																0.363
1883																0.378
1884																0.234
1885			0.32													0.185
1886			0.241													0.233

1887		0.25	0.145
1888		0.063	0.155
1889		0.112	0.085
1890		0.06	0.119
1891		0.033	0.12
1892		0.046	0.124
1893		0.046	0.116
1894		0.056	0.123
1895		0.091	0.059
1896		0.063	0.142
1897		0.041	0.048
1898		0.052	0.146
1899		0.071	0.059
1900		0.059	0.076
1901		0.038	0.063
1902	0.59	0.117	0.053
1903	0.739	0.114	0.042
1904	0.46	0.06	0.033
1905	0.574	0.127	0.058
1906	1.006	0.074	0.039
1907	1.225	0.084	0.031
1908	0.796	0.084	0.033
1909	0.619	0.052	0.039
1910	0.594	0.067	0.016
1911	0.458	0.022	0.026
1912	0.469	0.035	0.029
1913	0.184	0.051	0.038
1914	0.409	0.117	0.032

1915		0.241	0.082		0.032
1916		0.189	0.068		0.032
1917		0.087	0.012		0.055
1918		0.058	0.059		0.021
1919		0.044	0.068		0.041
1920		0.091	0.066		0.04
1921		0.092	0.039		0.055
1922		0.097	0.015		0.026
1923		0.068	0.052		0.021
1924		0.072	0.06		0.015
1925		0.047	0.039		0.033
1926		0.073	0.044		0.02
1927		0.084	0.029		0.015
1928		0.042	0.032		0.024
1929		0.019	0.056		0.015
1930		0.086	0.019		0.005
1931		0.038	0.023		0.033
1932		0.053	0.019		0.013
1933		0.035	0.028	1.047	0.04
1934		0.02	0.015	0.835	0.018
1935		0.036	0.026	0.439	0.007
1936		0.051	0.044	0.622	0.027
1937		0.039	0.021	0.854	0.016
1938		0.013	0.048	0.844	0.037
1939		0.028	0.028	0.636	0.02
1940		0.049	0.018	0.409	0.012
1941	2.466	0.036	0.024	0.214	0.017
1942	0.831	0.034	0.023	0.281	0.021

1943	0.773	0.056	0.098			0.132			0.957							0.009
1944	0.662	0.029	0.022			0.175	1.044		0.555							0.022
1945	0.67	0.039	0.022			0.173	1.199		0.581							0.024
1946	0.53	0.022	0.017			0.174	1.114		0.674							0.013
1947	0.314	0.046	0.015			0.169	0.695		0.587						0.584	0.013
1948	0.378	0.034	0.023			0.129	0.66		0.614						0.739	0.041
1949	0.228	0.045	0.036			0.126	0.589	1.272	0.428					0.844	0.738	0.013
1950	0.183	0.051	0.047			0.119	0.259	1.014	0.186					1.097	0.831	0.013
1951	0.148	0.033	0.029		0.84	0.115	0.286	0.822	0.139		1.139			0.825	1.035	0.02
1952	0.07	0.04	0.029		0.776	0.095	0.313	0.804	0.18		1.014			0.737	1.017	0.018
1953	0.089	0.031	0.047		0.878	0.091	0.314	0.669	0.141		0.83			0.593	0.587	0.02
1954	0.185	0.03	0.027		0.958	0.117	0.208	0.434	0.129	1.283	0.987			0.342	0.575	0.029
1955	0.175	0.013	0.022		0.675	0.106	0.208	0.333	0.105	0.939	0.765			0.243	0.416	0.021
1956	0.148	0.033	0.032		0.647	0.04	0.226	0.065	0.137	1.191	0.684			0.218	0.408	0.017
1957	0.143	0.043	0.012		0.6	0.039	0.233	0.258	0.131	1.438	0.496			0.194	0.383	0.024
1958	0.02	0.017	0.018		0.376	0.02	0.186	0.253	0.096	0.727	0.37			0.229	0.247	0.036
1959	0.057	0.014	0.037		0.341	0.05	0.144	0.205	0.105	0.742	0.232			0.193	0.233	0.026
1960	0.015	0.032	0.023		0.203	0.068	0.107	0.2	0.086	0.407	0.261			0.248	0.17	0.024
1961	0.036	0.054	0.028		0.205	0.078	0.148	0.108	0.094	0.405	0.236			0.174	0.142	0.013
1962	0.028	0.014	0.03		0.171	0.015	0.117	0.065	0.094	0.301	0.149			0.159	0.14	0.029
1963	0.019	0.013	0.024		0.157	0.022	0.102	0.143	0.078	0.335	0.094			0.163	0.105	0.02
1964	0.056	0.033	0.029		0.162	0.035	0.153	0.085	0.068	0.214	0.095			0.079	0.124	0.018
1965	0.036	0.017	0.063		0.119	0.048	0.132	0.024	0.084	0.24	0.17			0.069	0.077	0.038
1966	0.032	0.026	0.029		0.171	0.046	0.129	0.14	0.051	0.227	0.125			0.077	0.097	0.02
1967	0.033	0.028	0.038		0.097	0.037	0.08	0.1	0.039	0.168	0.096			0.096	0.142	0.013
1968	0.033	0.028	0.052		0.095	0.064	0.062	0.109	0.048	0.109	0.113			0.082	0.133	0.035
1969	0.043	0.033	0.065		0.074	0.042	0.075	0.101	0.048	0.119	0.042			0.095	0.111	0.024
1970	0.05	0.021	0.042	1.249	0.05	0.043	0.098	0.06	0.038	0.132	0.083		0.581	0.05	0.066	0.024

1971	0.054	0.024	0.035	1.166	0.082	0.017	0.059	0.055	0.024	0.115	0.111		1.091	0.057	0.038	0.018
1972	0.039	0.014	0.027	0.848	0.065	0.032	0.084	0.079	0.034	0.088	0.097	0.872	0.766	0.075	0.059	0.013
1973	0.047	0.012	0.041	0.986	0.089	0.022	0.064	0.137	0.022	0.064	0.103	0.85	1.081	0.088	0.053	0.018
1974	0.049	0.012	0.024	1.132	0.057	0.018	0.059	0.118	0.042	0.061	0.073	0.8	1.564	0.065	0.064	0.017
1975	0.062	0.007	0.056	1.033	0.046	0.016	0.056	0.09	0.031	0.07	0.072	0.736	1.037	0.088	0.056	0.028
1976	0.036	0.02	0.101	0.728	0.027	0.011	0.077	0.125	0.049	0.101	0.082	0.5	0.642	0.073	0.067	0.042
1977	0.022	0.03	0.039	0.767	0.04	0.031	0.067	0.071	0.032	0.073	0.098	0.882	0.581	0.078	0.053	0.026
1978	0.012	0.022	0.027	0.783	0.025	0.011	0.067	0.085	0.04	0.033	0.075	0.817	0.448	0.071	0.04	0.026
1979	0.008	0.029	0.032	0.503	0.047	0.026	0.058	0.066	0.045	0.062	0.084	0.849	0.532	0.052	0.06	0.023
1980	0.038	0.017	0.033	0.39	0.038	0.023	0.051	0.064	0.021	0.055	0.059	0.49	0.159	0.062	0.042	0.022
1981	0.042	0.013	0.066	0.326	0.032	0.012	0.085	0.096	0.04	0.035	0.049	0.556	0.183	0.047	0.029	0.039
1982	0.012	0.03	0.043	0.324	0.026	0.018	0.056	0.068	0.037	0.08	0.094	0.326	0.065	0.052	0.023	0.029
1983	0.043	0.031	0.058	0.287	0.038	0.011	0.059	0.097	0.049	0.095	0.067	0.437	0.146	0.062	0.042	0.051
1984	0.011	0.042	0.039	0.192	0.023	0.012	0.066	0.08	0.029	0.045	0.066	0.324	0.136	0.012	0.069	0.031
1985	0.064	0.011	0.019	0.136	0.021	0.043	0.048	0.073	0.038	0.017	0.064	0.178	0.211	0.021	0.064	0.038
1986	0.029	0.035	0.028	0.088	0.032	0.009	0.067	0.059	0.05	0.019	0.059	0.188	0.177	0.066	0.059	0.055
1987	0.031	0.028	0.019	0.044	0.035	0.073	0.046	0.051	0.029	0.03	0.072	0.126	0.18	0.061	0.051	0.018
1988	0.023	0.025	0.022	0.166	0.045	0.041	0.061	0.07	0.052	0.074	0.035	0.123	0.085	0.04	0.054	0.04
1989	0.032	0.027	0.021	0.128	0.009	0.042	0.051	0.082	0.02	0.036	0.07	0.095	0.087	0.021	0.019	0.03
1990	0.03	0.033	0.03	0.102	0.032	0.029	0.036	0.07	0.028	0.075	0.036	0.068	0.118	0.036	0.065	0.015
1991	0.019	0.018	0.041	0.141	0.03	0.026	0.042	0.088	0.013	0.075	0.039	0.064	0.101	0.034	0.038	0.021
1992	0.023	0.018	0.028	0.08	0.025	0.027	0.04	0.015	0.022	0.056	0.044	0.099	0.087	0.048	0.019	0.02
1993	0.017	0.011	0.078	0.052	0.028	0.025	0.034	0.027	0.021	0.069	0.052	0.063	0.081	0.049	0.024	0.031
1994	0.025	0.02	0.072	0.058	0.011	0.028	0.049	0.045	0.015	0.047	0.039	0.089	0.07	0.052	0.03	0.016
1995	0.022	0.016	0.045	0.06	0.031	0.033	0.03	0.064	0.026	0.029	0.055	0.079	0.109	0.063	0.021	0.019
1996	0.022	0.019	0.057	0.06	0.026	0.037	0.054	0.054	0.018	0.019	0.041	0.091	0.056	0.018	0.026	0.026
1997	0.028	0.021	0.039	0.044	0.026	0.065	0.05	0.057	0.047	0.021	0.045	0.108	0.093	0.042	0.038	0.028
1998	0.013	0.033	0.081	0.049	0.054	0.042	0.029	0.04	0.021	0.035	0.055	0.075	0.057	0.057	0.041	0.03

1999	0.029	0.019	0.073	0.084	0.051	0.04	0.035	0.055	0.023	0.032	0.036	0.068	0.06	0.049	0.053	0.02
2000	0.039	0.016	0.053	0.059	0.054	0.025	0.038	0.034	0.025	0.025	0.068	0.076	0.049	0.049	0.037	0.027
2001	0.017	0.014	0.025	0.067	0.063	0.041	0.025	0.062	0.039	0.067	0.044	0.096	0.047	0.055	0.046	0.028
2002	0.017	0.033	0.015	0.048	0.053	0.046	0.043	0.041	0.02	0.028	0.052	0.076	0.074	0.052	0.025	0.012
2003	0.015	0.05	0.021	0.044	0.05	0.036	0.035	0.047	0.016	0.015	0.057	0.051	0.047	0.045	0.045	0.035
2004	0.006	0.019	0.029	0.037	0.045	0.028	0.044	0.051	0.017	0.019	0.031	0.063	0.052	0.031	0.058	0.005
2005	0.008	0.011	0.011	0.045	0.026	0.024	0.025	0.05	0.015	0.036	0.044	0.047	0.054	0.046	0.014	0.013
2006	0.004	0.018	0.013	0.046	0.029	0.022	0.024	0.05	0.013	0.047	0.024	0.047	0.05	0.017	0.039	0.025
2007	0.003	0.04	0.019	0.033	0.016	0.015	0.023	0.022	0.015	0.024	0.04	0.028	0.026	0.018	0.015	0.015
2008	0.006	0.021	0.046	0.04	0.011	0.013		0.027	0.011	0.02	0.013	0.027	0.024		0.031	0.035

Appendix 11C: Raw GI data for site C4

Year	C4L1b	C4L4b	C4L5	C4L7	C4L8	C4L9	C4L10	C4L11	C4L13	C4L17	C4L18	C4L19	C4L20	C4L22	C4L32	C4L33	C4L36	C4L41
1851								0.453										
1852								0.322										
1853								0.716										
1854								0.561										
1855								0.154										
1856								0.495										
1857								0.46										
1858								0.326										
1859								0.207										
1860								0.113										
1861								0.304										
1862								0.127										
1863								0.084										
1864								0.135										

1865				0.072				
1866				0.144				
1867			0.274	0.175				
1868			0.614	0.103				
1869			0.4	0.097				
1870			0.413	0.087				
1871			0.252	0.132				
1872			0.501	0.117				
1873			0.091	0.129				
1874			0.097	0.094				
1875			0.111	0.075				
1876	0.242		0.061	0.072				
1877	0.346	0.415	0.111	0.065				
1878	0.189	0.489	0.04	0.047	0.674			
1879	0.229	0.355	0.057	0.019	0.356			
1880	0.308	0.829	0.058	0.007	0.245			
1881	0.367	0.108	0.051	0.028	0.301			
1882	0.455	0.077	0.033	0.021	0.139			
1883	0.683	0.281	0.043	0.06	0.138			
1884	0.263	0.1	0.037	0.05	0.076			
1885	0.433	0.322	0.03	0.043	0.076		0.225	
1886	0.277	0.087	0.028	0.052	0.079		0.258	
1887	0.309	0.066	0.015	0.029	0.096		0.522	
1888	0.218	0.278	0.054	0.07	0.066		0.725	
1889	0.402	0.076	0.021	0.041	0.118		1.104	
1890	0.044	0.117	0.033	0.039	0.069	0.13	0.363	
1891	0.059	0.089	0.063	0.033	0.085	0.062	0.753	0.784
1892	0.109	0.171	0.014	0.048	0.04	0.075	0.517	0.265

1893				0.168	0.083	0.012		0.019	0.543	0.063			0.102	0.454				0.602
1894				0.054	0.104	0.023		0.032	0.515	0.071			0.145	0.242				0.395
1895				0.022	0.061	0.078		0.016	0.212	0.02			0.027	0.674				0.449
1896				0.087	0.096	0.03		0.016	0.251	0.039			0.023	0.121				0.338
1897				0.031	0.064	0.024		0.058	0.188	0.021			0.068	0.133				0.834
1898				0.017	0.019	0.034		0.04	0.099	0.073			0.055	0.214				0.124
1899				0.079	0.111	0.022		0.018	0.118	0.016			0.116	0.067				0.12
1900				0.053	0.024	0.027		0.026	0.17	0.026		0.316	0.028	0.027				0.282
1901				0.101	0.034	0.052		0.052	0.098	0.047		0.705	0.079	0.022				0.402
1902				0.024	0.08	0.02		0.016	0.132	0.052		0.181	0.092	0.055				0.103
1903	0.369			0.025	0.047	0.009		0.013	0.169	0.038		0.242	0.041	0.019				0.146
1904	0.774			0.006	0.148	0.031		0.04	0.185	0.039		0.368	0.032	0.039				0.069
1905	0.836			0.049	0.046	0.021		0.036	0.201	0.041		0.434	0.111	0.058				0.096
1906	1.086			0.026	0.042	0.019		0.027	0.121	0.059		0.204	0.03	0.016				0.083
1907	0.126			0.013	0.017	0.021		0.028	0.18	0.058		0.182	0.026	0.054				0.209
1908	1.02		0.259	0.053	0.02	0.015		0.03	0.119	0.046		0.1	0.146	0.025				0.099
1909	0.23	0.318	0.561	0.022	0.055	0.021		0.049	0.273	0.022		0.201	0.045	0.04				0.108
1910	0.582	1.378	0.471	0.03	0.041	0.021	0.376	0.03	0.18	0.021		0.102	0.027	0.03			0.205	0.071
1911	0.354	0.685	0.452	0.056	0.125	0.021	0.468	0.056	0.095	0.016		0.052	0.046	0.025			0.205	0.076
1912	0.313	0.415	0.601	0.019	0.061	0.03	0.534	0.027	0.053	0.048		0.068	0.032	0.022			0.299	0.075
1913	0.2	0.563	0.068	0.028	0.011	0.063	0.43	0.06	0.075	0.021		0.086	0.096	0.03			0.468	0.031
1914	0.28	0.207	0.389	0.061	0.017	0.015	0.118	0.065	0.082	0.033		0.105	0.055	0.067			0.687	0.128
1915	0.051	0.347	0.067	0.01	0.073	0.016	0.184	0.046	0.055	0.051		0.06	0.031	0.026			0.732	0.026
1916	0.178	0.179	0.093	0.006	0.02	0.018	0.312	0.038	0.543	0.025		0.092	0.029	0.027			0.236	0.028
1917	0.278	0.135	0.034	0.019	0.032	0.08	0.22	0.018	0.515	0.018		0.081	0.027	0.169			0.047	0.147
1918	0.043	0.09	0.071	0.151	0.043	0.027	0.229	0.022	0.212	0.051		0.035	0.034	0.027			0.094	0.016
1919	0.112	0.237	0.132	0.027	0.04	0.026	0.133	0.017	0.251	0.043		0.058	0.061	0.018			0.075	0.027
1920	0.032	0.139	0.049	0.026	0.036	0.03	0.107	0.046	0.188	0.045		0.047	0.078	0.023			0.482	0.164

1921	0.235	0.204	0.147	0.028	0.015	0.024	0.064	0.013	0.099	0.035		0.039	0.071	0.029			0.516	0.035
1922	0.108	0.214	0.613	0.027	0.057	0.024	0.171	0.019	0.118	0.054		0.127	0.025	0.05			0.924	0.036
1923	0.075	0.109	0.075	0.036	0.012	0.049	0.049	0.021	0.17	0.057		0.077	0.055	0.048			0.611	0.03
1924	0.129	0.131	0.058	0.048	0.038	0.031	0.012	0.012	0.098	0.017		0.136	0.025	0.118			0.539	0.082
1925	0.087	0.139	0.049	0.024	0.052	0.032	0.024	0.022	0.132	0.019		0.053	0.06	0.046			0.221	0.071
1926	0.084	0.122	0.132	0.04	0.038	0.016	0.012	0.008	0.169	0.047		0.047	0.085	0.105			0.103	0.045
1927	0.063	0.131	0.124	0.018	0.038	0.02	0.013	0.017	0.185	0.019		0.049	0.104	0.075			0.23	0.04
1928	0.063	0.112	0.109	0.017	0.023	0.036	0.084	0.013	0.201	0.039		0.058	0.044	0.029			0.194	0.036
1929	0.048	0.088	0.099	0.032	0.037	0.022	0.031	0.014	0.121	0.023		0.035	0.021	0.025			0.2	0.076
1930	0.065	0.07	0.15	0.023	0.034	0.024	0.039	0.01	0.18	0.03		0.107	0.062	0.018			0.119	0.038
1931	0.064	0.099	0.118	0.025	0.025	0.021	0.026	0.012	0.119	0.035		0.047	0.082	0.046			0.028	0.034
1932	0.016	0.107	0.08	0.032	0.034	0.021	0.014	0.035	0.273	0.048		0.032	0.083	0.086			0.082	0.041
1933	0.054	0.046	0.024	0.013	0.028	0.046	0.018	0.019	0.18	0.011		0.052	0.08	0.022			0.089	0.048
1934	0.023	0.042	0.043	0.03	0.026	0.04	0.055	0.009	0.095	0.043		0.039	0.035	0.021			0.096	0.066
1935	0.135	0.029	0.07	0.069	0.059	0.036	0.022	0.024	0.053	0.023		0.029	0.049	0.029			0.075	0.091
1936	0.142	0.041	0.064	0.015	0.015	0.016	0.088	0.031	0.075	0.04		0.041	0.1	0.061			0.072	0.088
1937	0.03	0.075	0.095	0.024	0.015	0.013	0.04	0.021	0.082	0.073		0.081	0.034	0.024			0.054	0.085
1938	0.037	0.063	0.18	0.02	0.048	0.04	0.034	0.035	0.055	0.035		0.077	0.018	0.021			0.017	0.092
1939	0.072	0.021	0.094	0.039	0.053	0.039	0.037	0.018	0.543	0.081		0.072	0.025	0.01			0.02	0.044
1940	0.04	0.038	0.154	0.033	0.047	0.043	0.01	0.011	0.515	0.059		0.039	0.023	0.022			0.011	0.08
1941	0.046	0.04	0.171	0.034	0.049	0.021	0.01	0.01	0.212	0.028		0.073	0.059	0.015			0.028	0.081
1942	0.085	0.054	0.198	0.049	0.009	0.021	0.016	0.011	0.251	0.098		0.059	0.056	0.071			0.061	0.034
1943	0.043	0.035	0.214	0.022	0.011	0.006	0.03	0.025	0.188	0.024		0.085	0.035	0.043			0.021	0.041
1944	0.079	0.038	0.049	0.018	0.023	0.015	0.025	0.015	0.099	0.023		0.033	0.016	0.039			0.051	0.072
1945	0.085	0.066	0.049	0.023	0.102	0.035	0.03	0.008	0.118	0.014		0.033	0.021	0.059			0.026	0.022
1946	0.032	0.146	0.11	0.014	0.039	0.027	0.033	0.017	0.17	0.033		0.064	0.027	0.055			0.02	0.043
1947	0.035	0.065	0.285	0.015	0.012	0.018	0.024	0.02	0.098	0.025		0.069	0.066	0.03		0.183	0.026	0.033
1948	0.044	0.115	0.168	0.011	0.016	0.024	0.044	0.017	0.132	0.042		0.086	0.049	0.092		0.112	0.017	0.092

1949	0.057	0.062	0.02	0.033	0.017	0.017	0.022	0.017	0.169	0.023		0.058	0.038	0.025		0.193	0.02	0.031
1950	0.056	0.022	0.059	0.007	0.049	0.02	0.03	0.009	0.185	0.037		0.027	0.031	0.025		0.19	0.03	0.023
1951	0.05	0.019	0.029	0.009	0.033	0.016	0.015	0.005	0.201	0.016		0.022	0.043	0.016		0.14	0.028	0.014
1952	0.023	0.035	0.031	0.023	0.01	0.028	0.013	0.015	0.121	0.014		0.078	0.05	0.048		0.11	0.067	0.033
1953	0.016	0.038	0.209	0.014	0.021	0.011	0.031	0.042	0.18	0.022		0.022	0.014	0.062		0.361	0.035	0.049
1954	0.036	0.04	0.056	0.014	0.018	0.034	0.094	0.013	0.119	0.019		0.018	0.032	0.06		0.557	0.031	0.066
1955	0.076	0.046	0.059	0.029	0.041	0.016	0.023	0.027	0.273	0.015		0.019	0.077	0.021		0.636	0.012	0.074
1956	0.049	0.047	0.101	0.028	0.029	0.007	0.012	0.016	0.18	0.033		0.045	0.012	0.034		0.638	0.042	0.031
1957	0.062	0.035	0.07	0.017	0.018	0.021	0.021	0.019	0.095	0.026		0.031	0.024	0.02		0.375	0.034	0.075
1958	0.047	0.028	0.026	0.009	0.01	0.014	0.042	0.028	0.053	0.029		0.029	0.033	0.067		0.318	0.025	0.043
1959	0.044	0.031	0.026	0.043	0.015	0.018	0.03	0.008	0.075	0.01		0.021	0.022	0.047		0.248	0.023	0.043
1960	0.029	0.03	0.072	0.017	0.033	0.013	0.023	0.012	0.082	0.022		0.022	0.028	0.027		0.19	0.031	0.032
1961	0.069	0.039	0.05	0.02	0.016	0.032	0.024	0.013	0.055	0.012		0.031	0.017	0.033		0.138	0.036	0.018
1962	0.045	0.03	0.046	0.015	0.021	0.01	0.016	0.012	0.543	0.029		0.035	0.015	0.036		0.077	0.041	0.032
1963	0.046	0.048	0.042	0.009	0.016	0.008	0.022	0.018	0.515	0.011		0.023	0.022	0.033		0.101	0.041	0.051
1964	0.031	0.031	0.059	0.029	0.033	0.008	0.01	0.02	0.212	0.024		0.037	0.061	0.018		0.142	0.023	0.087
1965	0.031	0.046	0.031	0.021	0.032	0.007	0.033	0.011	0.251	0.029		0.026	0.087	0.036		0.11	0.051	0.033

Year	C4L43	C4L45	C4L72	C4L91	C4L103	C4L165	C4L75	C4L80	C4L87	C4L107	C4L73	C4L77	C4L104	C4L2	C4L48	C4L81	C4L102	C4L112	C4L113	C4L114
1863											0.554									
1864											0.52									
1865											0.081									
1866											0.25									
1867											0.202									
1868											0.2									
1869											0.27									
1870											0.172									
1871											0.172									

1872		0.125		
1873		0.19		
1874		0.043		
1875		0.114		
1876	0.365	0.076		
1877	0.395	0.03		
1878	0.254	0.064		
1879	0.588	0.025		
1880	0.422	0.042		
1881	0.369	0.074		
1882	0.278	0.065		
1883	0.258	0.041		
1884	0.266	0.041		
1885	0.103	0.064		
1886	0.095	0.068		
1887	0.178	0.151		
1888	0.038	0.067		
1889	0.043	0.041		
1890	0.089	0.054		
1891	0.09	0.051		
1892	0.104	0.023		
1893	0.113	0.106		0.235
1894	0.052	0.039		0.21
1895	0.037	0.036		0.527
1896	0.021	0.038		0.731
1897	0.03	0.024		0.799
1898	0.023	0.022		0.191
1899	0.02	0.049	0.622	0.491

1900		0.031		0.048		0.362	0.259
1901		0.051		0.05		0.441	0.133
1902		0.023		0.062		0.556	0.102
1903		0.026		0.06		0.343	0.376
1904		0.021		0.042		0.145	0.102
1905		0.023		0.03		0.461	0.139
1906		0.028		0.028		0.475	0.1
1907		0.021		0.096		0.186	0.058
1908		0.021		0.078		0.211	0.033
1909	0.694	0.04		0.031		0.164	0.063
1910	0.095	0.05		0.043		0.096	0.034
1911	0.117	0.038		0.018		0.204	0.062
1912	0.621	0.092		0.043		0.13	0.051
1913	0.426	0.034		0.04		0.076	0.04
1914	0.467	0.029		0.022		0.121	0.034
1915	0.291	0.023		0.006	0.593	0.097	0.06
1916	0.61	0.044		0.019	0.756	0.049	0.045
1917	0.092	0.02		0.018	0.394	0.122	0.075
1918	0.032	0.031		0.039	0.55	0.056	0.022
1919	0.157	0.042		0.019	0.155	0.144	0.017
1920	0.242	0.048		0.029	0.389	0.059	0.048
1921	0.095	0.034	0.587	0.028	0.452	0.054	0.087
1922	0.092	0.021	0.556	0.029	0.159	0.052	0.034
1923	0.048	0.033	0.479	0.041	0.327	0.031	0.029
1924	0.053	0.018	0.245	0.032	0.071	0.016	0.048
1925	0.058	0.05	0.355	0.037	0.081	0.067	0.043
1926	0.15	0.028	0.186	0.061	0.118	0.015	0.084
1927	0.03	0.03	0.792	0.013	0.103	0.07	0.031

1928	0.029	0.032		0.326			0.012	0.096	0.03		0.011
1929	0.061	0.015		0.234			0.024	0.103	0.012		0.08
1930	0.032	0.016		0.561			0.04	0.085	0.092		0.029
1931	0.098	0.026		0.072			0.031	0.046	0.017		0.027
1932	0.064	0.025		0.541			0.026	0.02	0.134		0.033
1933	0.081	0.026		0.438			0.048	0.031	0.045		0.04
1934	0.034	0.014		0.42			0.045	0.077	0.036		0.056
1935	0.036	0.018		0.319			0.015	0.035	0.045		0.026
1936	0.037	0.017		0.308			0.035	0.143	0.064		0.038
1937	0.068	0.029		0.162			0.043	0.041	0.015	0.46	0.031
1938	0.158	0.036		0.258			0.038	0.027	0.049	0.203	0.051
1939	0.04	0.022		0.194			0.04	0.015	0.045	1.308	0.044
1940	0.036	0.032		0.107			0.021	0.082	0.079	0.476	0.064
1941	0.083	0.044		0.075		0.506	0.018	0.049	0.051	0.425	0.029
1942	0.12	0.019		0.072		0.287	0.016	0.066	0.051	0.16	0.024
1943	0.019	0.057		0.108		0.686	0.045	0.044	0.019	0.275	0.034
1944	0.024	0.031		0.064		1	0.062	0.033	0.066	0.293	0.065
1945	0.04	0.039		0.071		0.784	0.028	0.08	0.076	0.204	0.034
1946	0.023	0.049		0.049		0.603	0.041	0.052	0.079	0.211	0.027
1947	0.027	0.045		0.054		0.442	0.03	0.041	0.018	0.167	0.022
1948	0.042	0.019		0.025	0.338	0.494	0.016	0.058	0.028	0.236	0.018
1949	0.041	0.015		0.039	0.398	0.214	0.037	0.037	0.031	0.158	0.023
1950	0.052	0.015		0.023	0.461	0.58	0.027	0.056	0.047	0.05	0.022
1951	0.059	0.031		0.017	0.197	0.428	0.031	0.063	0.058	0.127	0.076
1952	0.028	0.019		0.035	0.134	0.221	0.041	0.047	0.045	0.016	0.031
1953	0.053	0.024	0.412	0.022	0.109	0.168	0.013	0.027	0.02	0.042	0.022
1954	0.063	0.016	0.209	0.026	0.151	0.158	0.03	0.019	0.021	0.1	0.029
1955	0.019	0.021	0.21	0.111	0.135	0.18	0.021	0.053	0.012	0.033	0.043

1956	0.016	0.025	0.485		0.09		0.126			0.26	0.038			0.064	0.013	0.041				0.034
1957	0.041	0.02	0.554		0.039		0.117			0.171	0.02			0.038	0.063	0.052				0.044
1958	0.047	0.024	1.128		0.012		0.051			0.098	0.015			0.025	0.03	0.081				0.04
1959	0.085	0.017	0.194	0.152	0.013		0.096			0.17	0.012			0.025	0.033	0.07				0.023
1960	0.042	0.028	0.469	0.582	0.1		0.103			0.153	0.022			0.028	0.033	0.114				0.047
1961	0.041	0.017	0.422	0.589	0.026		0.042			0.085	0.013			0.029	0.036	0.064				0.037
1962	0.036	0.024	0.15	0.285	0.021		0.052			0.074	0.024			0.072	0.055	0.044				0.027
1963	0.039	0.009	0.22	0.254	0.012		0.031			0.044	0.03			0.022	0.041	0.076				0.026
1964	0.048	0.023	0.161	0.312	0.035		0.049			0.044	0.015			0.049	0.04	0.084				0.02
1965	0.041	0.032	0.142	0.487	0.023		0.027			0.079	0.031			0.038	0.02	0.048				0.016

Appendix 11D: Raw GI data for site C6

Year	C6L6	C6L9	C6L11	C6L12	C6L15	C6L18	C6L51	C6L52	C6L53	C6L55	C6L57	C6L60	C6L65	C6L66	C6L83	C6L85
1842						0.936										
1843						0.847										
1844						0.448										
1845						0.648										
1846						0.525										
1847						0.191		0.941								
1848						0.253		0.635								
1849						0.083		0.396								
1850			1.094			0.355		0.483								
1851			1.131			0.153		0.477								
1852			1.041			0.06		0.248								
1853			0.822			0.158		0.215								
1854			0.38			0.172		0.284								
1855			0.534			0.175		0.236								

1856		0.334		0.179	0.277		
1857		0.376		0.153	0.157		
1858		0.175		0.141	0.133		
1859		0.256		0.088	0.192		
1860		0.344		0.114	0.129		
1861		0.298		0.055	0.057		
1862		0.122		0.049	0.116		
1863		0.126		0.022	0.082		
1864		0.087		0.036	0.134		
1865		0.057		0.062	0.173		
1866		0.07		0.01	0.092		
1867		0.107		0.077	0.097		
1868		0.032		0.069	0.125		
1869		0.112		0.128	0.154		
1870		0.038		0.015	0.043		
1871		0.033		0.017	0.041		
1872		0.036		0.041	0.02		
1873		0.047		0.027	0.059		
1874		0.109		0.011	0.045		
1875		0.102		0.012	0.042	0.225	
1876		0.045		0.063	0.073	0.169	
1877		0.024		0.047	0.045	0.156	
1878		0.016		0.02	0.038	0.117	0.763
1879	0.738	0.077		0.015	0.066	0.064	0.839
1880	1.07	0.041		0.042	0.032	0.36	0.988
1881	1.133	0.077		0.016	0.02	0.336	0.407
1882	0.398	0.089		0.055	0.025	0.246	0.43
1883	0.581	0.089	0.449	0.03	0.015	0.186	0.379

1884	0.471	0.099		0.419	0.047		0.038	0.039		0.403	
1885	0.445	0.075		0.259	0.046		0.07	0.035	0.69	0.278	
1886	0.224	0.089		0.276	0.012		0.048	0.221	0.381	0.196	
1887	0.391	0.047		0.326	0.034		0.043	0.082	0.315	0.364	
1888	0.302	0.052		0.208	0.039		0.046	0.077	0.206	0.275	
1889	0.192	0.099		0.163	0.02		0.056	0.124	0.234	0.213	
1890	0.252	0.026		0.285	0.009		0.04	0.151	0.127	0.095	
1891	0.287	0.043		0.185	0.017		0.033	0.113	0.234	0.156	
1892	0.082	0.017		0.214	0.01		0.018	0.044	0.11	0.037	
1893	0.078	0.01		0.166	0.016		0.012	0.058	0.012	0.134	
1894	0.16	0.035		0.225	0.022		0.014	0.104	0.092	0.038	
1895	0.194	0.054		0.081	0.011		0.03	0.063	0.017	0.07	
1896	0.157	0.024		0.188	0.024		0.028	0.103	0.106	0.103	
1897	0.19	0.031		0.095	0.046		0.019	0.061	0.106	0.226	
1898	0.098	0.076		0.157	0.009		0.026	0.085	0.103	0.144	
1899	0.229	0.055		0.097	0.026		0.026	0.069	0.015	0.148	
1900	0.136	0.022		0.09	0.037		0.02	0.068	0.083	0.066	
1901	0.083	0.058		0.051	0.014		0.019	0.057	0.087	0.082	
1902	0.077	0.054		0.06	0.015		0.033	0.078	0.03	0.087	0.475
1903	0.053	0.052		0.055	0.017		0.029	0.052	0.027	0.166	0.438
1904	0.088	0.027		0.036	0.037	0.882	0.034	0.025	0.019	0.076	0.461
1905	0.077	0.072		0.092	0.034	0.581	0.031	0.049	0.097	0.075	0.56
1906	0.058	0.013		0.04	0.027	0.506	0.031	0.063	0.022	0.065	0.254
1907	0.021	0.016		0.096	0.018	0.483	0.015	0.025	0.022	0.059	0.254
1908	0.058	0.032		0.069	0.014	0.478	0.024	0.046	0.025	0.031	0.373
1909	0.044	0.038		0.015	0.025	0.313	0.021	0.099	0.021	0.092	0.148
1910	0.043	0.025		0.027	0.025	0.011	0.048	0.051	0.167	0.061	0.189

Year	C6L104	C6L118	C6L98	C6L103	C6L111	C6L80	C6L92	C6L97	C6L107	C6L112	C6L113	C6L115	C6L116	C6L71	C6L99	C6L5	C6L63	C6L68
1807								0.701										
1808								0.814										
1809								0.95										
1810								0.917										
1811								0.273										
1812								0.317										
1813								0.2										
1814								0.424										
1815								0.288										
1816								0.21										
1817								0.201										
1818								0.222										
1819								0.223										
1820								0.244										
1821								0.24										
1822								0.102										
1823								0.14										
1824								0.065		0.919								
1825								0.065		0.95								
1826								0.089		1.02								
1827	0.529							0.033		0.543								
1828	0.382							0.065		0.078								
1829	0.267							0.083		0.537								
1830	0.213							0.033		0.112								
1831	0.38							0.024		0.248								
1832	0.199							0.044		0.077								
1833	0.145							0.058		0.12								
1834	0.205							0.068		0.07								
1835	0.152							0.027		0.162								

1836	0.168		0.048	0.212	
1837	0.077		0.072	0.166	
1838	0.169		0.016	0.219	
1839	0.139		0.019	0.145	
1840	0.045		0.018	0.155	
1841	0.093		0.03	0.072	
1842	0.091		0.046	0.11	
1843	0.067		0.015	0.042	
1844	0.074		0.048	0.042	
1845	0.146		0.045	0.059	0.689
1846	0.077		0.036	0.06	0.956
1847	0.04		0.017	0.017	0.935
1848	0.112		0.04	0.04	0.916
1849	0.045		0.073	0.019	0.435
1850	0.089		0.044	0.021	0.126
1851	0.068		0.038	0.029	0.363
1852	0.029		0.05	0.036	0.114
1853	0.017		0.06	0.035	0.18
1854	0.061		0.048	0.05	0.172
1855	0.084		0.034	0.015	0.061
1856	0.056		0.014	0.013	0.067
1857	0.043		0.012	0.018	0.198
1858	0.033		0.019	0.019	0.116
1859	0.041		0.012	0.022	0.126
1860	0.015		0.028	0.037	0.052
1861	0.053		0.027	0.01	0.022
1862	0.043		0.019	0.014	0.123
1863	0.017	0.404	0.032	0.012	0.054

1864	0.028	1.05	0.036		0.026	0.052	
1865	0.023	0.771	0.019		0.023	0.057	
1866	0.032	0.274	0.018		0.031	0.085	
1867	0.031	0.198	0.038		0.017	0.094	
1868	0.034	0.433	0.048		0.013	0.083	
1869	0.036	0.184	0.019		0.015	0.057	
1870	0.02	0.199	0.021		0.011	0.089	
1871	0.034	0.18	0.012		0.007	0.035	
1872	0.017	0.111	0.029		0.008	0.014	
1873	0.009	0.133	0.027		0.025	0.021	
1874	0.039	0.105	0.012		0.062	0.016	
1875	0.035	0.099	0.015		0.01	0.01	
1876	0.037	0.033	0.028		0.013	0.024	
1877	0.059	0.138	0.05		0.039	0.028	
1878	0.017	0.146	0.027		0.036	0.044	
1879	0.009	0.071	0.029		0.01	0.029	
1880	0.031	0.07	0.014		0.013	0.022	
1881	0.013	0.068	0.015		0.021	0.013	
1882	0.022	0.031	0.036		0.024	0.029	
1883	0.018	0.036	0.014		0.027	0.044	
1884	0.022	0.037	0.025		0.015	0.033	
1885	0.018	0.032	0.011		0.025	0.039	
1886	0.016	0.021	0.016		0.019	0.015	
1887	0.016	0.034	0.023		0.019	0.013	
1888	0.021	0.039	0.012		0.013	0.025	
1889	0.018	0.054	0.031	0.36	0.05	0.021	0.435
1890	0.015	0.026	0.029	0.386	0.034	0.033	0.571
1891	0.013	0.049	0.019	0.635	0.011	0.023	0.594

1892	0.03	0.035	0.02	0.468	0.038	0.025	0.197
1893	0.027	0.037	0.03	0.358	0.036	0.012	0.444
1894	0.011	0.064	0.028	0.362	0.021	0.023	0.571
1895	0.028	0.025	0.026	0.598	0.01	0.041	0.443
1896	0.037	0.059	0.015	0.137	0.024	0.033	0.495
1897	0.013	0.02	0.022	0.482	0.008	0.01	0.382
1898	0.022	0.057	0.008	0.665	0.023	0.04	0.323
1899	0.031	0.032	0.014	0.471	0.012	0.021	0.246
1900	0.026	0.047	0.01	0.36	0.028	0.04	0.259
1901	0.031	0.076	0.016	0.313	0.012	0.013	0.271
1902	0.037	0.025	0.009	0.159	0.021	0.014	0.124
1903	0.017	0.012	0.009	0.052	0.012	0.016	0.224
1904	0.052	0.045	0.008	0.477	0.029	0.013	0.154
1905	0.015	0.046	0.009	0.154	0.009	0.01	0.338
1906	0.059	0.031	0.03	0.132	0.021	0.012	0.167
1907	0.02	0.028	0.023	0.128	0.008	0.029	0.06
1908	0.011	0.033	0.022	0.049	0.022	0.018	0.075
1909	0.024	0.062	0.022	0.029	0.015	0.013	0.116
1910	0.033	0.058	0.022	0.078	0.022	0.016	0.135

Appendix 11E: Raw GI data for site C7

Year	C7L136	C7L69	C7L49	C7L30	C7L7	C7L108	C7L113	C7L38	C7L103	C7L8	C7L12	C7L74	C7L92	C7L95	C7L158	C7L58
1870									0.24							
1871									0.6							
1872									0.45							
1873									0.112							
1874									0.137							
1875									0.065							

1876		0.039		
1877		0.188		
1878		0.198		
1879		0.213		
1880		0.305		
1881		0.067		
1882		0.094		
1883		0.053		
1884		0.053		
1885		0.044		
1886		0.052		
1887		0.022		
1888		0.032		0.463
1889		0.134	0.077	0.414
1890		0.046	0.449	0.73
1891		0.105	0.165	0.092
1892		0.012	0.271	0.482
1893		0.013	0.285	0.417
1894		0.048	0.353	0.193
1895		0.074	0.067	0.13
1896		0.117	0.05	0.578
1897		0.046	0.094	0.629
1898		0.102	0.11	0.706
1899		0.112	0.151	0.234
1900		0.062	0.08	0.115
1901	0.61	0.021	0.154	0.236
1902	0.48	0.112	0.142	0.163
1903	0.182	0.011	0.108	0.215
1904	0.154	0.012	0.067	0.096
1905	0.332	0.026	0.067	0.12
1906	0.156	0.082	0.063	0.104
1907	0.375	0.1	0.13	0.033

1908	0.208				0.01						0.051	0.042
1909	0.045				0.036						0.206	0.076
1910	0.219				0.038						0.028	0.059
1911	0.121	0.652	0.683		0.037						0.156	0.059
1912	0.235	0.343	0.712		0.059				0.177		0.065	0.034
1913	0.304	0.48	0.355		0.01				0.535		0.052	0.037
1914	0.119	0.196	0.39		0.047				0.221		0.069	0.096
1915	0.188	0.228	0.686		0.062				0.832		0.039	0.085
1916	0.2	0.266	0.532		0.034		0.156		0.331		0.059	0.058
1917	0.252	0.152	0.66		0.018		0.544		0.316		0.027	0.091
1918	0.182	0.205	0.265		0.049		0.168		0.303		0.027	0.05
1919	0.081	0.096	0.326		0.066		0.574		0.3		0.03	0.033
1920	0.023	0.046	0.29	1.006	0.034		0.231		0.137		0.02	0.086
1921	0.15	0.031	0.071	0.685	0.012		0.278	0.519	0.165		0.022	0.179
1922	0.026	0.048	0.117	0.454	0.024		0.543	0.287	0.143		0.068	0.188
1923	0.021	0.045	0.033	0.305	0.04		0.609	0.17	0.078		0.039	0.104
1924	0.081	0.047	0.179	0.414	0.027		0.752	0.292	0.087		0.037	0.176
1925	0.047	0.036	0.064	0.707	0.01		0.258	0.359	0.131		0.042	0.018
1926	0.087	0.026	0.133	0.255	0.025		0.334	0.069	0.108		0.024	0.008
1927	0.011	0.036	0.131	0.152	0.017		0.242	0.222	0.09		0.025	0.019
1928	0.069	0.051	0.083	0.095	0.014		0.126	0.044	0.114		0.024	0.021
1929	0.034	0.044	0.072	0.107	0.02		0.229	0.192	0.046		0.024	0.025
1930	0.075	0.037	0.182	0.098	0.01		0.124	0.317	0.122		0.102	0.025
1931	0.019	0.034	0.067	0.097	0.048	0.607	0.161	0.057	0.107		0.082	0.017
1932	0.129	0.05	0.151	0.03	0.015	0.824	0.151	0.152	0.112		0.064	0.017
1933	0.01	0.015	0.115	0.142	0.034	0.222	0.268	0.15	0.097		0.047	0.016
1934	0.032	0.053	0.186	0.038	0.037	0.319	0.205	0.186	0.149	0.246	0.064	0.013
1935	0.064	0.111	0.066	0.093	0.009	0.558	0.196	0.083	0.063	1.153	0.077	0.017
1936	0.018	0.058	0.063	0.073	0.051	0.781	0.231	0.174	0.031	0.628	0.038	0.01
1937	0.018	0.036	0.224	0.04	0.017	0.471	0.198	0.046	0.034	0.163	0.044	0.035
1938	0.022	0.054	0.123	0.124	0.025	0.544	0.27	0.041	0.035	0.368	0.135	0.026
1939	0.009	0.062	0.084	0.114	0.012	0.299	0.051	0.05	0.031	0.329	0.039	0.033

1940	0.013			0.032	0.084		0.059	0.04	0.194	0.092	0.051	0.037	0.164	0.022	0.029
1941	0.047			0.05	0.098		0.092	0.01	0.172	0.076	0.019	0.031	0.296	0.024	0.013
1942	0.011			0.055	0.048		0.054	0.026	0.139	0.11	0.037	0.018	0.199	0.042	0.013
1943	0.118			0.039	0.039		0.031	0.019	0.078	0.043	0.026	0.029	0.114	0.017	0.029
1944	0.045			0.024	0.036		0.043	0.011	0.086	0.044	0.009	0.017	0.109	0.019	0.014
1945	0.037			0.032	0.027		0.032	0.01	0.043	0.033	0.018	0.025	0.174	0.041	0.013
1946	0.017			0.025	0.067	0.104	0.046	0.012	0.117	0.042	0.025	0.038	0.036	0.027	0.02
1947	0.007			0.044	0.024	0.211	0.031	0.03	0.074	0.034	0.017	0.027	0.116	0.019	0.01
1948	0.013			0.035	0.025	0.45	0.024	0.012	0.093	0.03	0.041	0.027	0.104	0.042	0.024
1949	0.008			0.035	0.016	0.35	0.017	0.01	0.057	0.034	0.02	0.029	0.114	0.048	0.017
1950	0.029			0.07	0.048	0.453	0.048	0.014	0.024	0.033	0.031	0.035	0.142	0.016	0.01
1951	0.023			0.021	0.045	0.344	0.028	0.021	0.106	0.018	0.12	0.026	0.266	0.015	0.021
1952	0.012			0.03	0.039	0.315	0.042	0.011	0.02	0.124	0.037	0.073	0.058	0.034	0.036
1953	0.023			0.044	0.03	0.22	0.142	0.025	0.242	0.03	0.018	0.018	0.024	0.074	0.04
1954	0.069			0.068	0.081	0.026	0.021	0.015	0.097	0.026	0.014	0.037	0.022	0.065	0.014
1955	0.04			0.01	0.137	0.102	0.034	0.02	0.088	0.038	0.018	0.021	0.015	0.045	0.131
1956	0.018			0.034	0.036	0.083	0.012	0.014	0.066	0.031	0.021	0.02	0.06	0.037	0.072
1957	0.011			0.023	0.049	0.12	0.021	0.074	0.076	0.056	0.013	0.022	0.025	0.029	0.041
1958	0.011			0.029	0.064	0.057	0.014	0.015	0.079	0.039	0.07	0.031	0.019	0.022	0.03
1959	0.006			0.025	0.036	0.049	0.012	0.016	0.078	0.037	0.042	0.046	0.044	0.037	0.027
1960	0.025			0.041	0.052	0.113	0.022	0.015	0.123	0.036	0.029	0.033	0.027	0.028	0.023
1961	0.036			0.031	0.052	0.104	0.072	0.014	0.114	0.015	0.029	0.011	0.03	0.018	0.021
1962	0.009			0.043	0.056	0.136	0.035	0.027	0.084	0.036	0.05	0.049	0.039	0.018	0.046
1963	0.041			0.033	0.058	0.061	0.042	0.019	0.037	0.031	0.049	0.013	0.028	0.052	0.042
1964	0.011			0.059	0.059	0.135	0.039	0.022	0.029	0.026	0.02	0.032	0.037	0.028	0.059
1965	0.032			0.043	0.068	0.036	0.061	0.02	0.037	0.02	0.05	0.038	0.134	0.031	0.049
1966	0.022			0.013	0.03	0.104	0.038	0.015	0.02	0.019	0.017	0.022	0.029	0.038	0.009
1967	0.005			0.027	0.026	0.065	0.022	0.013	0.072	0.03	0.03	0.033	0.02	0.026	0.025
1968	0.013			0.013	0.023	0.035	0.039	0.027	0.079	0.027	0.014	0.022	0.024	0.024	0.028
1969	0.011	0.471		0.025	0.028	0.066	0.031	0.031	0.026	0.019	0.015	0.034	0.015	0.019	0.035
1970	0.016	0.923		0.023	0.045	0.076	0.012	0.032	0.056	0.024	0.009	0.015	0.015	0.05	0.012
1971	0.012	0.588		0.024	0.039	0.105	0.021	0.044	0.066	0.031	0.009	0.017	0.038	0.013	0.044

1972		0.016	0.823		0.015	0.029	0.023	0.03	0.023	0.046	0.015	0.014	0.017	0.046	0.02	0.009
1973		0.047	0.776		0.021	0.032	0.03	0.023	0.03	0.035	0.032	0.031	0.019	0.057	0.021	0.011
1974		0.02	0.702		0.018	0.033	0.075	0.009	0.014	0.031	0.026	0.024	0.019	0.034	0.013	0.044
1975		0.01	0.553		0.022	0.052	0.091	0.008	0.017	0.032	0.014	0.012	0.025	0.024	0.035	0.02
1976		0.024	0.532		0.017	0.026	0.141	0.016	0.036	0.017	0.025	0.03	0.014	0.038	0.028	0.008
1977		0.016	0.418		0.02	0.053	0.023	0.036	0.028	0.02	0.039	0.019	0.013	0.033	0.033	0.021
1978		0.014	0.399		0.02	0.028	0.025	0.018	0.033	0.014	0.035	0.013	0.02	0.019	0.018	0.026
1979		0.017	0.303		0.014	0.019	0.013	0.035	0.029	0.024	0.021	0.022	0.023	0.012	0.021	0.013
1980		0.01	0.378		0.011	0.029	0.023	0.012	0.008	0.063	0.018	0.013	0.018	0.012	0.033	0.017
1981		0.012	0.185		0.012	0.049	0.029	0.012	0.022	0.072	0.027	0.021	0.013	0.017	0.02	0.018
1982		0.009	0.258		0.013	0.037	0.077	0.019	0.012	0.09	0.016	0.008	0.009	0.017	0.011	0.032
1983		0.009	0.267		0.017	0.028	0.016	0.014	0.006	0.046	0.027	0.005	0.015	0.011	0.01	0.048
1984		0.008	0.2	0.317	0.021	0.046	0.086	0.024	0.01	0.034	0.034	0.004	0.013	0.011	0.018	0.04
1985		0.016	0.149	0.512	0.022	0.029	0.057	0.01	0.006	0.061	0.022	0.01	0.013	0.03	0.015	0.044
1986		0.019	0.134	0.444	0.031	0.034	0.03	0.027	0.008	0.046	0.036	0.025	0.027	0.023	0.032	0.047
1987	0.292	0.012	0.108	0.343	0.013	0.04	0.06	0.025	0.01	0.023	0.061	0.02	0.018	0.037	0.009	0.039
1988	0.226	0.026	0.092	0.309	0.027	0.029	0.059	0.049	0.014	0.092	0.028	0.02	0.011	0.024	0.043	0.029
1989	0.317	0.019	0.063	0.638	0.028	0.024	0.116	0.019	0.013	0.067	0.034	0.03	0.02	0.011	0.024	0.054
1990	0.32	0.016	0.016	0.442	0.049	0.027	0.026	0.033	0.031	0.022	0.034	0.021	0.019	0.015	0.022	0.068
1991	0.553	0.011	0.067	0.163	0.056	0.049	0.054	0.051	0.015	0.018	0.03	0.013	0.019	0.017	0.019	0.067
1992	0.338	0.04	0.044	0.243	0.026	0.032	0.019	0.038	0.011	0.024	0.017	0.028	0.016	0.015	0.014	0.086
1993	0.257	0.008	0.107	0.189	0.021	0.047	0.013	0.028	0.035	0.059	0.022	0.01	0.026	0.018	0.033	0.041
1994	0.312	0.025	0.071	0.614	0.026	0.039	0.018	0.014	0.02	0.041	0.019	0.045	0.031	0.032	0.015	0.018
1995	0.567	0.012	0.068	0.37	0.015	0.064	0.041	0.013	0.019	0.032	0.017	0.013	0.008	0.053	0.022	0.02
1996	0.211	0.026	0.045	1.007	0.029	0.038	0.02	0.005	0.01	0.041	0.027	0.01	0.021	0.011	0.025	0.017
1997	0.46	0.018	0.056	0.726	0.015	0.036	0.016	0.014	0.016	0.031	0.026	0.006	0.011	0.012	0.034	0.025
1998	0.318	0.018	0.067	0.39	0.022	0.039	0.025	0.009	0.01	0.054	0.014	0.007	0.022	0.055	0.026	0.025
1999	0.529	0.011	0.059	0.255	0.016	0.059	0.019	0.008	0.02	0.023	0.02	0.009	0.012	0.014	0.015	0.027
2000	0.121	0.012	0.072	0.571	0.01	0.031	0.024	0.022	0.014	0.034	0.01	0.013	0.009	0.018	0.006	0.026
2001	0.112	0.015	0.046	0.361	0.011	0.043	0.035	0.007	0.014	0.024	0.022	0.009	0.012	0.034	0.019	0.014
2002	0.032	0.011	0.093	0.241	0.014	0.113	0.036	0.012	0.007	0.035	0.014	0.023	0.02	0.039	0.013	0.026
2003	0.054	0.01	0.072	0.562	0.014	0.037	0.01	0.013	0.013	0.048	0.011	0.009	0.028	0.033	0.037	0.031

2004	0.031	0.021	0.054	0.185	0.006	0.049	0.027	0.01	0.007	0.023	0.014	0.013	0.026	0.031	0.006	0.019
2005	0.078	0.021	0.044	0.035	0.01	0.038	0.01	0.014	0.016	0.027	0.007	0.008	0.019	0.055	0.005	0.036
2006	0.032	0.039	0.031	0.038	0.011	0.015	0.033	0.009	0.02	0.054	0.014	0.029	0.01	0.008	0.006	0.011
2007	0.071	0.018	0.037	0.087	0.022	0.017	0.01	0.009	0.008	0.009	0.007	0.006	0.012	0.009	0.013	0.028
2008		0.009	0.022	0.03	0.015	0.018	0.014	0.021	0.014	0.026	0.014	0.013	0.012	0.038	0.018	0.021

Year	C7L3	C7L6	C7L14	C7L16	C7L47	C7L48	C7L56	C7L61	C7L62	C7L66	C7L67	C7L77	C7L83	C7L10	C7L12	C7L110	C7L119	C7L120
1825								0.15										
1826								0.087										
1827								0.11										
1828								0.06										
1829								0.026										
1830								0.005										
1831								0.03										
1832								0.051										
1833								0.043										
1834								0.026										
1835								0.011										
1836								0.053										
1837								0.047										
1838								0.051	0.058									
1839								0.012	0.3									
1840								0.127	0.048									
1841								0.065	0.1									
1842								0.08	0.38									
1843								0.014	0.177									
1844								0.047	0.279									
1845								0.042	0.098									
1846								0.005	0.125									

1847		0.017	0.178
1848		0.03	0.125
1849		0.038	0.027
1850		0.008	0.021
1851		0.018	0.029
1852		0.014	0.056
1853		0.025	0.192
1854		0.01	0.012
1855		0.036	0.045
1856		0.009	0.012
1857		0.084	0.04
1858		0.01	0.031
1859		0.063	0.007
1860		0.079	0.052
1861		0.068	0.07
1862		0.018	0.012
1863		0.03	0.025
1864		0.019	0.025
1865		0.008	0.073
1866		0.015	0.066
1867		0.048	0.054
1868		0.024	0.026
1869	0.335	0.02	0.009
1870	0.656	0.06	0.074
1871	0.491	0.012	0.103
1872	0.294	0.014	0.042
1873	0.436	0.022	0.088
1874	0.407	0.012	0.038

1875	0.435	0.03	0.034				
1876	0.162	0.012	0.012				
1877	0.049	0.075	0.046				
1878	0.136	0.034	0.016				
1879	0.186	0.03	0.011				
1880	0.083	0.051	0.014				
1881	0.065	0.021	0.007				
1882	0.059	0.032	0.057				
1883	0.137	0.055	0.01				
1884	0.057	0.011	0.029				
1885	0.099	0.02	0.013				
1886	0.117	0.03	0.055				
1887	0.099	0.039	0.006			0.309	
1888	0.172	0.063	0.089			0.162	
1889	0.044	0.027	0.011			0.13	
1890	0.181	0.013	0.061			0.163	
1891	0.177	0.033	0.014			0.232	
1892	0.17	0.033	0.013			0.087	
1893	0.155	0.009	0.071		0.855	0.211	
1894	0.192	0.008	0.047		0.958	0.151	0.257
1895	0.042	0.012	0.047		0.822	0.046	0.118
1896	0.023	0.018	0.062		0.384	0.039	0.392
1897	0.045	0.017	0.009		0.185	0.087	0.616
1898	0.072	0.008	0.012		0.514	0.041	0.41
1899	0.1	0.024	0.032		0.203	0.044	0.471
1900	0.097	0.009	0.055		0.398	0.097	0.288
1901	0.03	0.012	0.017	0.068	0.319	0.18	0.211
1902	0.076	0.008	0.021	0.038	0.315	0.052	0.19

1903		0.03		0.04	0.026	0.115	0.179	0.156	0.118
1904		0.068		0.026	0.05	0.073	0.288	0.166	0.264
1905		0.063		0.012	0.051	0.174	0.107	0.246	0.16
1906		0.043		0.025	0.026	0.133	0.089	0.116	0.124
1907		0.033		0.011	0.024	0.149	0.083	0.269	0.158
1908		0.062		0.023	0.011	0.055	0.183	0.025	0.14
1909		0.061		0.015	0.01	0.151	0.126	0.083	0.053
1910	0.077	0.029		0.017	0.021	0.01	0.107	0.02	0.045
1911	0.256	0.032		0.017	0.044	0.078	0.055	0.075	0.031
1912	0.051	0.012		0.045	0.004	0.02	0.083	0.012	0.088
1913	0.183	0.013		0.016	0.013	0.059	0.097	0.063	0.083
1914	0.111	0.095		0.014	0.013	0.045	0.153	0.038	0.091
1915	0.151	0.151		0.011	0.013	0.034	0.074	0.035	0.046
1916	0.093	0.039		0.028	0.015	0.027	0.109	0.036	0.078
1917	0.582	0.027		0.01	0.021	0.019	0.085	0.034	0.018
1918	0.139	0.013		0.011	0.008	0.016	0.103	0.007	0.051
1919	0.378	0.032		0.005	0.008	0.014	0.129	0.026	0.061
1920	0.39	0.058		0.01	0.017	0.038	0.058	0.035	0.055
1921	0.7	0.055		0.007	0.015	0.012	0.048	0.022	0.02
1922	0.269	0.055		0.014	0.011	0.105	0.09	0.008	0.023
1923	0.662	0.063	0.372	0.01	0.02	0.051	0.063	0.01	0.033
1924	0.068	0.077	0.469	0.007	0.03	0.026	0.119	0.028	0.034
1925	0.18	0.061	0.663	0.015	0.016	0.019	0.061	0.014	0.009
1926	0.154	0.058	0.163	0.02	0.012	0.037	0.112	0.051	0.007
1927	0.052	0.013	0.108	0.006	0.027	0.123	0.06	0.014	0.033
1928	0.136	0.023	0.616	0.077	0.032	0.099	0.048	0.038	0.04
1929	0.056	0.032	0.23	0.013	0.02	0.102	0.058	0.01	0.009
1930	0.087	0.021	0.515	0.005	0.016	0.068	0.041	0.049	0.03

1931		0.109	0.023		0.292	0.009	0.037		0.076	0.042	0.158	0.12
1932		0.093	0.033		0.149	0.008	0.015		0.06	0.081	0.041	0.023
1933		0.085	0.076		0.127	0.008	0.02		0.003	0.063	0.044	0.026
1934		0.059	0.06		0.22	0.015	0.006		0.008	0.054	0.021	0.029
1935		0.037	0.016		0.236	0.02	0.01		0.088	0.07	0.016	0.028
1936		0.048	0.011		0.167	0.016	0.011		0.016	0.056	0.024	0.029
1937		0.077	0.033	0.474	0.067	0.036	0.011		0.124	0.045	0.027	0.04
1938		0.04	0.05	0.345	0.072	0.012	0.009		0.061	0.06	0.008	0.038
1939		0.058	0.043	0.329	0.089	0.006	0.016		0.026	0.078	0.029	0.012
1940		0.051	0.017	0.062	0.048	0.022	0.01		0.06	0.018	0.013	0.059
1941		0.237	0.012	0.131	0.047	0.006	0.023		0.013	0.054	0.018	0.006
1942		0.047	0.028	0.158	0.14	0.018	0.004		0.029	0.036	0.031	0.034
1943		0.036	0.051	0.093	0.098	0.015	0.008		0.06	0.045	0.037	0.036
1944		0.076	0.006	0.142	0.072	0.019	0.015		0.066	0.037	0.042	0.032
1945	0.44	0.036	0.019	0.176	0.212	0.009	0.008		0.068	0.071	0.018	0.04
1946	0.264	0.025	0.018	0.062	0.079	0.009	0.082		0.045	0.045	0.012	0.02
1947	0.249	0.026	0.027	0.146	0.085	0.026	0.011		0.104	0.036	0.042	0.012
1948	0.171	0.089	0.053	0.202	0.109	0.021	0.009		0.05	0.043	0.026	0.025
1949	0.197	0.086	0.019	0.623	0.052	0.006	0.005		0.065	0.031	0.014	0.033
1950	0.078	0.1	0.005	0.063	0.086	0.012	0.01		0.039	0.045	0.009	0.02
1951	0.078	0.057	0.046	0.24	0.049	0.01	0.011		0.017	0.034	0.034	0.028
1952	0.277	0.074	0.025	0.096	0.074	0.004	0.009		0.007	0.049	0.014	0.029
1953	0.077	0.065	0.011	0.322	0.053	0.01	0.015		0.019	0.026	0.034	0.022
1954	0.045	0.043	0.04	0.265	0.029	0.015	0.04		0.045	0.069	0.048	0.026
1955	0.325	0.045	0.014	0.123	0.038	0.014	0.026	0.129	0.007	0.033	0.008	0.025
1956	0.112	0.017	0.041	0.141	0.033	0.014	0.018	0.06	0.006	0.014	0.022	0.01
1957	0.287	0.008	0.014	0.103	0.059	0.016	0.013	0.032	0.019	0.047	0.033	0.026
1958	0.293	0.007	0.019	0.319	0.105	0.037	0.008	0.102	0.018	0.035	0.023	0.014

1959	0.215	0.005		0.013		0.29	0.029	0.006	0.007	0.242	0.061	0.041		0.011	0.022		
1960	0.211	0.028		0.016		0.153	0.018	0.026	0.009	0.065	0.05	0.029		0.039	0.015		
1961	0.054	0.004		0.016		0.117	0.022	0.008	0.025	0.229	0.012	0.032		0.008	0.008		
1962	0.037	0.009		0.03		0.083	0.016	0.014	0.015	0.035	0.011	0.035		0.01	0.017		
1963	0.178	0.017		0.022		0.278	0.02	0.017	0.019	0.047	0.01	0.035		0.057	0.021		
1964	0.029	0.022		0.04		0.092	0.018	0.014	0.008	0.429	0.038	0.036		0.02	0.015		
1965	0.085	0.029		0.03		0.143	0.018	0.021	0.006	0.051	0.01	0.016		0.015	0.017		
1966	0.077	0.034		0.017		0.205	0.034	0.019	0.009	0.098	0.025	0.032		0.048	0.027		
1967	0.093	0.017		0.045		0.069	0.025	0.003	0.006	0.034	0.012	0.04		0.006	0.019		
1968	0.109	0.042		0.045		0.127	0.012	0.006	0.008	0.115	0.02	0.032		0.025	0.011		
1969	0.171	0.019		0.008		0.08	0.011	0.015	0.007	0.133	0.013	0.036		0.011	0.007		
1970	0.053	0.011		0.021		0.052	0.038	0.01	0.01	0.035	0.019	0.059		0.009	0.024		
1971	0.035	0.013		0.055		0.249	0.025	0.01	0.016	0.074	0.025	0.055		0.022	0.011		
1972	0.135	0.017		0.008		0.077	0.039	0.026	0.01	0.264	0.036	0.028		0.013	0.009		
1973	0.089	0.016		0.009		0.131	0.039	0.025	0.017	0.013	0.02	0.037		0.021	0.01		
1974	0.07	0.02		0.008		0.059	0.019	0.021	0.005	0.09	0.013	0.036		0.017	0.02		
1975	0.117	0.006		0.014		0.273	0.02	0.035	0.016	0.034	0.013	0.049		0.01	0.016		0.254
1976	0.055	0.016		0.008		0.031	0.018	0.01	0.011	0.186	0.027	0.025		0.012	0.012		0.364
1977	0.135	0.013		0.009		0.023	0.009	0.015	0.013	0.008	0.04	0.04		0.017	0.01		0.158
1978	0.08	0.025		0.047		0.062	0.032	0.008	0.007	0.014	0.043	0.025		0.041	0.01		0.424
1979	0.146	0.04		0.011		0.107	0.019	0.026	0.013	0.097	0.023	0.027		0.045	0.006	0.164	0.201
1980	0.089	0.02		0.018		0.159	0.006	0.023	0.024	0.158	0.046	0.031		0.006	0.023	0.138	0.216
1981	0.108	0.044		0.024		0.198	0.048	0.012	0.005	0.175	0.052	0.09		0.016	0.022	0.179	0.333
1982	0.036	0.016		0.008		0.122	0.023	0.023	0.006	0.165	0.044	0.045	1.098	0.027	0.016	0.236	0.155
1983	0.037	0.027		0.007		0.091	0.021	0.007	0.003	0.022	0.027	0.036	1.565	0.011	0.016	0.234	0.099
1984	0.048	0.012		0.007		0.122	0.018	0.006	0.015	0.126	0.047	0.058	0.858	0.031	0.02	0.239	0.13
1985	0.07	0.036		0.038	0.574	0.139	0.027	0.011	0.027	0.014	0.022	0.037	0.445	0.026	0.019	0.284	0.236
1986	0.134	0.04		0.031	0.437	0.212	0.021	0.006	0.018	0.021	0.013	0.052	0.242	0.016	0.008	0.417	0.213

1987	0.061	0.026	0.06	0.041	0.128	0.032	0.016	0.007	0.011	0.061	0.039	0.039	1.603	0.015	0.027	0.367	0.216	0.184
1988	0.093	0.023	0.06	0.014	0.156	0.09	0.028	0.024	0.014	0.013	0.013	0.031	0.445	0.03	0.025	0.602	0.358	0.267
1989	0.073	0.013	0.055	0.02	0.743	0.044	0.034	0.013	0.019	0.033	0.036	0.031	0.538	0.019	0.01	0.478	0.241	0.194
1990	0.028	0.035	0.058	0.015	0.34	0.036	0.006	0.006	0.016	0.037	0.018	0.034	0.364	0.043	0.013	0.45	0.115	0.146
1991	0.039	0.023	0.104	0.007	0.12	0.033	0.017	0.007	0.01	0.008	0.005	0.026	0.466	0.005	0.017	0.17	0.156	0.307
1992	0.052	0.037	0.012	0.01	0.363	0.064	0.04	0.007	0.018	0.038	0.006	0.023	0.621	0.005	0.028	0.143	0.096	0.042
1993	0.032	0.015	0.005	0.021	0.138	0.072	0.021	0.008	0.012	0.056	0.036	0.028	0.765	0.029	0.103	0.338	0.149	0.433
1994	0.095	0.016	0.021	0.023	0.506	0.054	0.018	0.008	0.012	0.046	0.007	0.037	0.395	0.013	0.037	0.246	0.176	0.381
1995	0.005	0.011	0.028	0.015	0.293	0.017	0.008	0.011	0.015	0.009	0.015	0.034	0.349	0.006	0.016	0.485	0.457	0.068
1996	0.016	0.011	0.008	0.01	0.465	0.022	0.024	0.023	0.012	0.01	0.019	0.05	0.339	0.006	0.025	0.259	0.131	0.102
1997	0.03	0.012	0.009	0.015	0.116	0.059	0.012	0.013	0.015	0.034	0.01	0.032	0.565	0.01	0.03	0.034	0.097	0.17
1998	0.017	0.007	0.021	0.015	0.289	0.019	0.027	0.014	0.014	0.053	0.014	0.032	0.599	0.022	0.03	0.107	0.202	0.057
1999	0.025	0.014	0.064	0.005	0.226	0.076	0.032	0.015	0.019	0.026	0.011	0.047	0.647	0.011	0.019	0.081	0.13	0.415
2000	0.021	0.018	0.038	0.005	0.177	0.06	0.011	0.005	0.016	0.022	0.036	0.038	0.206	0.019	0.016	0.019	0.026	0.606
2001	0.03	0.013	0.003	0.027	0.04	0.047	0.013	0.01	0.01	0.008	0.031	0.01	0.274	0.008	0.012	0.151	0.222	0.162
2002	0.033	0.009	0.005	0.018	0.042	0.024	0.021	0.012	0.011	0.033	0.014	0.021	0.378	0.036	0.01	0.214	0.327	0.452
2003	0.057	0.021	0.017	0.014	0.397	0.022	0.014	0.011	0.017	0.018	0.01	0.021	0.044	0.018	0.014	0.067	0.098	0.05
2004	0.033	0.015	0.114	0.008	0.1	0.015	0.014	0.019	0.016	0.032	0.011	0.022	0.184	0.011	0.009	0.13	0.192	0.086
2005	0.059	0.014	0.006	0.011	0.056	0.075	0.013	0.007	0.01	0.015	0.012	0.025	0.226	0.016	0.008	0.028	0.044	0.054
2006	0.072	0.017	0.009	0.006	0.051	0.027	0.014	0.006	0.008	0.034	0.049	0.011	0.252	0.014	0.008	0.009	0.018	0.017
2007	0.015	0.042	0.021	0.029	0.089	0.033	0.011	0.02	0.011	0.008	0.008	0.017	0.323	0.027	0.008	0.019	0.006	0.054
2008	0.036	0.009	0.115	0.027	0.089		0.032	0.008	0.013	0.008	0.01	0.011	0.163	0.02	0.008		0.009	

Appendix 11F: Raw GI data for site C8

Year	C8L3	C8L4	C8L5	C8L6	C8L7	C8L8	C8L14	C8L15	C8L16	C8L17	C8L19	C8L31	C8L32	C8L34	C8L59
1859								1.112							
1860								0.685							

1861	0.908	1.134	
1862	1.066	0.745	
1863	1.571	0.488	
1864	1.187	0.2	
1865	0.659	0.245	
1866	0.32	0.19	
1867	0.242	0.192	
1868	0.104	0.204	
1869	0.147	0.154	
1870	0.078	0.03	
1871	0.076	0.035	
1872	0.14	0.153	
1873	0.139	0.129	
1874	0.045	0.079	
1875	0.091	0.099	
1876	0.202	0.044	
1877	0.035	0.016	
1878	0.164	0.044	
1879	0.216	0.088	1.585
1880	0.109	0.115	0.631
1881	0.058	0.092	0.412
1882	0.16	0.132	0.416
1883	0.112	0.048	0.646
1884	0.176	0.066	0.236
1885	0.062	0.051	0.479
1886	0.196	0.057	0.491
1887	0.091	0.069	0.526
1888	0.086	0.077	0.248
1889	0.114	0.097	0.069
1890	0.085	0.064	0.219
1891	0.078	0.133	0.304
1892	0.156	0.078	0.199

1893		0.186	0.057	0.261
1894		0.127	0.038	0.13
1895		0.087	0.046	0.264
1896		0.052	0.09	0.212
1897		0.135	0.071	0.166
1898		0.084	0.055	0.206
1899		0.095	0.089	0.166
1900		0.12	0.082	0.068
1901		0.084	0.105	0.038
1902	0.99	0.038	0.065	0.083
1903	1.289	0.081	0.06	0.141
1904	0.989	0.021	0.08	0.147
1905	0.604	0.069	0.044	0.098
1906	0.542	0.113	0.077	0.042
1907	0.365	0.138	0.025	0.104
1908	0.283	0.067	0.082	0.038
1909	0.374	0.128	0.058	0.117
1910	0.432	0.068	0.052	0.064
1911	0.16	0.094	0.029	0.042
1912	0.19	0.116	0.048	0.029
1913	0.17	0.063	0.056	0.036
1914	0.163	0.052	0.032	0.032
1915	0.183	0.065	0.031	0.042
1916	0.127	0.111	0.061	0.018
1917	0.103	0.058	0.044	0.026
1918	0.105	0.056	0.038	0.035
1919	0.111	0.06	0.052	0.034
1920	0.127	0.09	0.063	0.007
1921	0.088	0.073	0.041	0.028
1922	0.092	0.071	0.075	0.069
1923	0.136	0.084	0.019	0.033
1924	0.059	0.062	0.024	0.043

1925				0.107				0.088						0.032	0.032
1926				0.125				0.043						0.07	0.051
1927				0.189				0.026						0.032	0.043
1928				0.037				0.032						0.035	0.037
1929				0.031				0.049						0.054	0.024
1930	0.499			0.086				0.03				1.434		0.052	0.033
1931	0.579			0.09				0.064				0.967		0.02	0.016
1932	0.263			0.037				0.071				0.651		0.016	0.026
1933	0.243	0.307		0.046				0.048				0.637		0.022	0.007
1934	0.388	0.41		0.076				0.021				0.392		0.027	0.006
1935	0.151	1.476		0.049				0.019				1.022		0.027	0.034
1936	0.18	0.813		0.074				0.02				0.506		0.033	0.012
1937	0.118	0.753		0.062				0.021				0.313		0.017	0.025
1938	0.191	0.549		0.065				0.023	1.075			0.555		0.042	0.02
1939	0.114	0.119		0.077				0.027	1.136			0.375		0.04	0.025
1940	0.183	0.583		0.062				0.043	0.995			0.422		0.038	0.018
1941	0.167	0.599		0.03				0.029	0.772			0.221		0.037	0.017
1942	0.149	0.54		0.037				0.049	0.596			0.225		0.023	0.013
1943	0.148	0.456		0.044				0.062	0.697			0.286		0.025	0.025
1944	0.117	0.282		0.037				0.04	0.929			0.094		0.024	0.026
1945	0.085	0.127		0.046				0.027	0.939			0.121		0.039	0.028
1946	0.041	0.118		0.057				0.021	0.758		0.422	0.146	0.64	0.027	0.007
1947	0.084	0.166		0.032				0.068	0.746	0.768	0.793	0.147	0.638	0.055	0.009
1948	0.162	0.135		0.029				0.039	0.543	0.887	0.892	0.164	0.547	0.012	0.012
1949	0.069	0.125		0.024	0.439			0.061	0.326	0.754	0.683	0.083	0.408	0.013	0.005
1950	0.233	0.115		0.044	0.489			0.042	0.358	1.374	0.495	0.101	0.485	0.034	0.038
1951	0.116	0.102		0.036	0.468			0.05	0.312	0.289	0.55	0.058	0.428	0.01	0.014
1952	0.187	0.057	0.698	0.03	0.574		0.52	0.034	0.161	0.708	0.361	0.049	0.289	0.021	0.021
1953	0.056	0.032	0.696	0.033	0.543		0.541	0.051	0.139	1.002	0.212	0.047	0.267	0.014	0.021
1954	0.063	0.031	0.226	0.053	0.379	1.068	1.007	0.04	0.17	1.32	0.318	0.065	0.144	0.031	0.013
1955	0.159	0.071	1.099	0.044	0.578	0.928	0.87	0.054	0.17	0.779	0.211	0.097	0.076	0.015	0.021
1956	0.076	0.05	0.902	0.048	0.288	0.893	0.563	0.053	0.172	0.587	0.252	0.038	0.222	0.039	0.017

1957	0.033	0.042	0.43	0.035	0.045	0.653	0.528	0.021	0.148	0.179	0.155	0.102	0.18	0.016	0.011
1958	0.081	0.051	0.187	0.048	0.4	0.558	0.454	0.057	0.132	0.269	0.253	0.061	0.119	0.024	0.017
1959	0.064	0.015	0.858	0.04	0.195	0.41	0.456	0.033	0.076	0.266	0.238	0.098	0.127	0.016	0.013
1960	0.068	0.035	1.106	0.036	0.226	0.256	0.31	0.039	0.157	0.393	0.187	0.065	0.144	0.017	0.012
1961	0.066	0.018	0.905	0.034	0.226	0.336	0.296	0.039	0.134	0.069	0.023	0.061	0.1	0.02	0.019
1962	0.078	0.073	0.726	0.052	0.066	0.377	0.281	0.033	0.085	0.282	0.082	0.058	0.068	0.008	0.014
1963	0.076	0.118	0.701	0.052	0.076	0.302	0.218	0.047	0.073	0.258	0.139	0.024	0.052	0.018	0.025
1964	0.053	0.026	0.487	0.039	0.098	0.312	0.188	0.043	0.02	0.156	0.06	0.075	0.041	0.009	0.018
1965	0.042	0.05	0.243	0.05	0.152	0.426	0.129	0.013	0.027	0.13	0.114	0.047	0.075	0.048	0.037
1966	0.071	0.023	0.094	0.052	0.06	0.16	0.032	0.05	0.02	0.201	0.146	0.08	0.111	0.048	0.032
1967	0.039	0.014	0.114	0.048	0.058	0.08	0.096	0.073	0.037	0.22	0.073	0.025	0.069	0.029	0.015
1968	0.045	0.034	0.07	0.034	0.066	0.231	0.177	0.06	0.04	0.174	0.07	0.052	0.087	0.013	0.011
1969	0.055	0.034	0.061	0.014	0.072	0.176	0.079	0.057	0.034	0.185	0.059	0.116	0.071	0.018	0.01
1970	0.081	0.021	0.098	0.016	0.049	0.23	0.135	0.061	0.038	0.132	0.114	0.05	0.112	0.021	0.015
1971	0.048	0.015	0.074	0.022	0.041	0.106	0.07	0.089	0.038	0.077	0.084	0.049	0.059	0.019	0.027
1972	0.058	0.097	0.204	0.044	0.039	0.18	0.128	0.054	0.041	0.121	0.135	0.037	0.04	0.029	0.014
1973	0.074	0.027	0.124	0.046	0.035	0.195	0.118	0.03	0.043	0.077	0.114	0.027	0.042	0.024	0.025
1974	0.067	0.014	0.088	0.044	0.057	0.189	0.126	0.071	0.031	0.09	0.117	0.045	0.037	0.025	0.007
1975	0.021	0.023	0.046	0.028	0.019	0.075	0.115	0.027	0.036	0.057	0.107	0.047	0.026	0.016	0.019
1976	0.075	0.027	0.154	0.031	0.041	0.122	0.056	0.027	0.022	0.109	0.082	0.039	0.057	0.022	0.011
1977	0.061	0.028	0.082	0.027	0.032	0.066	0.015	0.039	0.022	0.062	0.113	0.058	0.035	0.014	0.01
1978	0.046	0.051	0.057	0.029	0.034	0.1	0.048	0.037	0.104	0.072	0.149	0.02	0.042	0.038	0.027
1979	0.033	0.02	0.012	0.027	0.064	0.122	0.055	0.064	0.075	0.054	0.234	0.035	0.05	0.027	0.024
1980	0.04	0.038	0.069	0.036	0.022	0.111	0.05	0.032	0.064	0.066	0.102	0.024	0.035	0.025	0.028
1981	0.04	0.055	0.075	0.031	0.053	0.051	0.059	0.033	0.078	0.064	0.09	0.023	0.054	0.037	0.025
1982	0.035	0.023	0.047	0.018	0.018	0.092	0.03	0.033	0.052	0.033	0.114	0.041	0.044	0.023	0.017
1983	0.069	0.025	0.05	0.02	0.016	0.129	0.066	0.016	0.045	0.073	0.13	0.01	0.034	0.015	0.023
1984	0.05	0.021	0.058	0.034	0.017	0.063	0.076	0.017	0.092	0.026	0.082	0.027	0.041	0.038	0.039
1985	0.045	0.037	0.128	0.043	0.019	0.052	0.085	0.026	0.046	0.08	0.077	0.028	0.038	0.02	0.022
1986	0.07	0.023	0.075	0.026	0.018	0.049	0.025	0.024	0.073	0.047	0.1	0.037	0.034	0.012	0.015
1987	0.15	0.03	0.058	0.03	0.025	0.068	0.04	0.031	0.049	0.086	0.08	0.054	0.041	0.011	0.044
1988	0.086	0.062	0.078	0.031	0.015	0.068	0.085	0.046	0.045	0.063	0.025	0.013	0.042	0.011	0.011

1989	0.04	0.032	0.048	0.017	0.023	0.046	0.062	0.037	0.027	0.074	0.079	0.017	0.046	0.03	0.017
1990	0.043	0.031	0.076	0.024	0.041	0.064	0.089	0.013	0.1	0.05	0.043	0.033	0.044	0.015	0.013
1991	0.033	0.026	0.052	0.026	0.016	0.061	0.07	0.031	0.038	0.041	0.056	0.028	0.044	0.01	0.013
1992	0.042	0.035	0.012	0.029	0.058	0.069	0.055	0.02	0.051	0.047	0.018	0.01	0.018	0.042	0.009
1993	0.035	0.022	0.036	0.022	0.024	0.083	0.062	0.037	0.047	0.064	0.018	0.021	0.036	0.02	0.007
1994	0.039	0.011	0.016	0.028	0.051	0.088	0.083	0.028	0.044	0.076	0.049	0.017	0.033	0.021	0.008
1995	0.086	0.025	0.061	0.028	0.034	0.051	0.066	0.037	0.035	0.035	0.048	0.043	0.024	0.02	0.013
1996	0.045	0.026	0.049	0.05	0.034	0.099	0.044	0.038	0.045	0.034	0.063	0.055	0.039	0.012	0.021
1997	0.068	0.018	0.018	0.009	0.033	0.057	0.04	0.027	0.038	0.037	0.065	0.026	0.026	0.022	0.01
1998	0.022	0.025	0.032	0.013	0.053	0.037	0.076	0.03	0.026	0.025	0.054	0.087	0.027	0.02	0.012
1999	0.046	0.034	0.06	0.027	0.069	0.031	0.053	0.025	0.031	0.046	0.036	0.038	0.036	0.02	0.015
2000	0.041	0.022	0.042	0.038	0.036	0.027	0.056	0.05	0.041	0.042	0.055	0.051	0.025	0.05	0.012
2001	0.037	0.019	0.036	0.03	0.019	0.039	0.043	0.035	0.041	0.027	0.073	0.02	0.044	0.012	0.024
2002	0.045	0.02	0.035	0.041	0.026	0.012	0.07	0.024	0.066	0.058	0.062	0.034	0.021	0.022	0.014
2003	0.073	0.031	0.092	0.025	0.031	0.048	0.035	0.031	0.039	0.055	0.048	0.03	0.043	0.03	0.027
2004	0.104	0.042	0.088	0.024	0.051	0.042	0.057	0.043	0.042	0.026	0.016	0.022	0.035	0.018	0.016
2005	0.102	0.01	0.054	0.01	0.038	0.034	0.02	0.033	0.04	0.068	0.014	0.056	0.048	0.012	0.02
2006	0.036	0.019	0.03	0.058	0.062	0.068	0.019	0.027	0.058	0.058	0.022	0.016	0.015	0.01	0.023
2007	0.038	0.015	0.04	0.029	0.013	0.012	0.062	0.014	0.038	0.031	0.041	0.028	0.023	0.013	0.017
2008	0.027	0.029	0.023	0.021	0.069	0.031	0.032		0.049	0.039	0.019	0.026	0.02	0.014	0.019

Year	C8x1	C8x2	C8x4	C8x5	C8x7	C8x3	C8x8	C8L24	C8L27	C8L29	C8L30	C8L33	C8x10	C8x11	C8x19
1845														0.67	
1846														0.93	
1847														0.597	
1848														0.462	
1849														0.084	
1850														0.384	
1851														0.243	
1852														0.211	
1853					1.093									0.235	
1854					0.583									0.316	
1855					0.57									0.414	
1856					0.578									0.22	
1857					0.143									0.206	
1858					0.239									0.093	
1859					0.201									0.129	
1860					0.303									0.024	
1861					0.195					0.779				0.045	
1862					0.23					0.385				0.019	
1863					0.102					0.547				0.025	
1864					0.147					0.892				0.061	
1865					0.152					0.94				0.081	
1866					0.074					0.352				0.048	
1867					0.115					0.516				0.032	
1868					0.1					0.305				0.013	
1869					0.139					0.209				0.05	
1870					0.143					0.287				0.084	
1871					0.079					0.115				0.027	
1872					0.12					0.207				0.05	
1873					0.081					0.08				0.031	
1874					0.128					0.108				0.037	
1875					0.171					0.091				0.041	
1876					0.06					0.075				0.043	

1877		0.058			0.113	0.013
1878		0.059			0.137	0.025
1879		0.052			0.101	0.043
1880		0.09			0.104	0.029
1881		0.091			0.093	0.038
1882		0.048			0.127	0.035
1883		0.049			0.065	0.015
1884		0.048			0.075	0.02
1885		0.042			0.085	0.056
1886		0.051			0.094	0.069
1887		0.024			0.124	0.026
1888		0.08			0.107	0.035
1889		0.038			0.103	0.022
1890		0.034			0.052	0.017
1891		0.084		0.745	0.168	0.025
1892		0.05		0.708	0.13	0.027
1893		0.034		1.063	0.096	0.033
1894		0.028		0.726	0.131	0.021
1895		0.034		0.729	0.083	0.016
1896		0.032		0.343	0.094	0.014
1897		0.018	1.058	0.351	0.117	0.04
1898		0.036	0.455	0.178	0.042	0.034
1899		0.082	0.399	0.126	0.091	0.037
1900		0.1	0.876	0.058	0.073	0.072
1901		0.062	0.634	0.094	0.041	0.077
1902		0.062	0.538	0.155	0.027	0.075
1903	1.032	0.042	0.718	0.074	0.026	0.047
1904	1.331	0.032	0.796	0.141	0.017	0.035
1905	1.337	0.042	0.622	0.074	0.03	0.016
1906	0.964	0.06	0.646	0.12	0.027	0.015
1907	0.9	0.036	0.751	0.095	0.029	0.009
1908	0.735	0.022	0.501	0.073	0.045	0.05

1909	0.557	0.048		0.385	0.081	0.061	1.105	0.042	
1910	0.444	0.018		0.204	0.095	0.036	0.552	0.019	
1911	0.264	0.032		0.221	0.072	0.035	1.219	0.021	
1912	0.267	0.028		0.143	0.083	0.04	1.501	0.023	
1913	0.19	0.052		0.15	0.07	0.022	1.02	0.03	
1914	0.049	0.038	0.797	0.131	0.063	0.025	0.939	0.022	
1915	0.058	0.034	1.048	0.113	0.082	0.019	0.597	0.016	
1916	0.024	0.038	1.05	0.092	0.123	0.023	0.601	0.013	
1917	0.031	0.032	0.959	0.193	0.085	0.018	0.83	0.011	
1918	0.089	0.012	0.522	0.157	0.07	0.043	0.76	0.024	
1919	0.036	0.042	0.156	0.075	0.067	0.028	0.844	0.025	
1920	0.069	0.032	1.235	0.114	0.101	0.024	0.772	0.017	0.832
1921	0.115	0.028	1.043	0.097	0.045	0.008	0.364	0.02	0.886
1922	0.043	0.054	0.575	0.119	0.087	0.026	0.399	0.014	1.343
1923	0.026	0.016	0.522	0.082	0.04	0.015	0.339	0.019	0.676
1924	0.062	0.018	0.665	0.036	0.026	0.013	0.25	0.02	1.195
1925	0.161	0.026	0.411	0.02	0.069	0.006	0.313	0.019	0.819
1926	0.105	0.042	0.421	0.018	0.108	0.013	0.129	0.02	1.013
1927	0.087	0.046	0.13	0.019	0.035	0.021	0.096	0.013	0.67
1928	0.046	0.032	0.245	0.019	0.06	0.029	0.118	0.017	0.538
1929	0.059	0.034	0.186	0.022	0.039	0.018	0.093	0.027	0.194
1930	0.068	0.048	0.158	0.025	0.037	0.026	0.141	0.016	0.233
1931	0.079	0.028	0.102	0.031	0.075	0.029	0.082	0.014	0.212
1932	0.028	0.024	0.025	0.029	0.039	0.044	0.105	0.016	0.194
1933	0.025	0.02	0.116	0.039	0.045	0.035	0.113	0.013	0.178
1934	0.038	0.022	0.052	0.061	0.061	0.024	0.12	0.014	0.139
1935	0.027	0.024	0.053	0.027	0.042	0.016	0.115	0.013	0.055
1936	0.016	0.036	0.088	0.031	0.019	0.023	0.1	0.005	0.029
1937	0.033	0.028	0.103	0.039	0.052	0.027	0.114	0.014	0.024
1938	0.055	0.03	0.062	0.055	0.032	0.033	0.07	0.011	0.099
1939	0.045	0.018	0.072	0.051	0.049	0.019	0.088	0.027	0.053
1940	0.037	0.012	0.038	0.019	0.124	0.022	0.085	0.01	0.062

1941				0.019	0.016	0.114	0.021	0.018		0.01		0.091		0.014	0.022
1942				0.048	0.028	0.028	0.021	0.025		0.018		0.095		0.024	0.037
1943				0.048	0.018	0.053	0.031	0.016		0.026		0.088		0.012	0.058
1944				0.019	0.014	0.037	0.033	0.039	0.931	0.019		0.015		0.012	0.094
1945				0.067	0.028	0.121	0.028	0.034	1.354	0.018		0.05		0.029	0.07
1946				0.036	0.038	0.142	0.033	0.018	0.515	0.029	1.664	0.06		0.019	0.084
1947				0.026	0.022	0.053	0.033	0.031	0.395	0.012	1.423	0.058		0.012	0.048
1948				0.033	0.02	0.055	0.014	0.029	0.331	0.012	1.093	0.064		0.016	0.096
1949			0.809	0.046	0.02	0.055	0.016	0.031	0.423	0.007	0.669	0.066		0.028	0.068
1950			0.856	0.045	0.036	0.079	0.017	0.034	0.888	0.009	0.484	0.066		0.011	0.046
1951			0.753	0.04	0.018	0.084	0.017	0.023	0.947	0.011	0.4	0.047		0.011	0.008
1952			0.738	0.07	0.01	0.062	0.015	0.036	0.523	0.011	0.241	0.034		0.03	0.009
1953	0.911		0.56	0.057	0.013	0.064	0.018	0.042	0.772	0.018	0.284	0.054		0.028	0.017
1954	0.825		0.52	0.013	0.024	0.053	0.014	0.034	0.306	0.006	0.229	0.039		0.015	0.023
1955	0.777		0.32	0.019	0.028	0.05	0.016	0.067	0.139	0.012	0.223	0.052	1.249	0.009	0.062
1956	0.639		0.347	0.025	0.02	0.071	0.048	0.019	0.427	0.01	0.236	0.035	1.195	0.009	0.019
1957	0.495		0.225	0.017	0.016	0.085	0.035	0.025	0.27	0.029	0.234	0.033	0.699	0.011	0.017
1958	0.784		0.256	0.049	0.014	0.058	0.029	0.023	0.327	0.023	0.24	0.049	1.218	0.01	0.053
1959	0.761		0.12	0.05	0.016	0.05	0.036	0.027	0.186	0.028	0.143	0.038	1.023	0.012	0.029
1960	0.58	1.207	0.169	0.013	0.018	0.062	0.026	0.016	0.243	0.022	0.191	0.041	1.738	0.012	0.037
1961	0.458	0.696	0.137	0.051	0.016	0.096	0.019	0.013	0.159	0.02	0.175	0.057	0.407	0.012	0.065
1962	0.44	0.604	0.069	0.06	0.028	0.056	0.039	0.033	0.134	0.024	0.128	0.025	0.273	0.021	0.093
1963	0.185	0.398	0.122	0.012	0.02	0.049	0.011	0.02	0.168	0.016	0.138	0.045	0.191	0.013	0.049
1964	0.32	0.239	0.148	0.05	0.024	0.028	0.021	0.028	0.027	0.009	0.12	0.016	0.253	0.028	0.056
1965	0.347	0.185	0.066	0.033	0.024	0.031	0.013	0.018	0.029	0.02	0.096	0.033	0.092	0.011	0.014
1966	0.164	0.205	0.157	0.017	0.018	0.043	0.025	0.015	0.093	0.019	0.088	0.022	0.205	0.011	0.044
1967	0.255	0.166	0.179	0.031	0.018	0.036	0.014	0.015	0.084	0.02	0.091	0.072	0.153	0.009	0.05
1968	0.17	0.137	0.118	0.036	0.024	0.019	0.032	0.016	0.073	0.017	0.127	0.028	0.17	0.02	0.021
1969	0.138	0.144	0.068	0.05	0.024	0.053	0.026	0.012	0.097	0.005	0.099	0.045	0.067	0.017	0.027
1970	0.131	0.174	0.083	0.039	0.018	0.031	0.027	0.046	0.079	0.031	0.073	0.072	0.199	0.011	0.042
1971	0.115	0.153	0.012	0.026	0.028	0.028	0.027	0.03	0.111	0.033	0.084	0.047	0.132	0.016	0.05
1972	0.137	0.12	0.023	0.044	0.032	0.025	0.037	0.028	0.069	0.018	0.07	0.031	0.228	0.019	0.038

1973	0.101	0.099	0.048	0.019	0.022	0.021	0.021	0.044	0.072	0.021	0.04	0.059	0.105	0.025	0.062
1974	0.186	0.108	0.089	0.015	0.02	0.034	0.02	0.022	0.079	0.024	0.09	0.026	0.103	0.022	0.03
1975	0.262	0.074	0.022	0.042	0.018	0.059	0.025	0.02	0.043	0.014	0.048	0.034	0.041	0.022	0.044
1976	0.069	0.045	0.067	0.037	0.01	0.049	0.018	0.05	0.022	0.034	0.062	0.03	0.104	0.009	0.017
1977	0.076	0.104	0.044	0.017	0.016	0.049	0.022	0.022	0.021	0.023	0.037	0.051	0.099	0.032	0.031
1978	0.086	0.093	0.02	0.045	0.02	0.013	0.022	0.026	0.099	0.012	0.035	0.063	0.036	0.013	0.061
1979	0.072	0.024	0.009	0.029	0.02	0.041	0.021	0.04	0.048	0.015	0.053	0.028	0.066	0.024	0.019
1980	0.103	0.06	0.018	0.015	0.026	0.041	0.023	0.036	0.079	0.014	0.052	0.032	0.05	0.022	0.035
1981	0.055	0.059	0.035	0.044	0.022	0.087	0.021	0.027	0.048	0.014	0.059	0.045	0.035	0.008	0.048
1982	0.044	0.034	0.045	0.058	0.024	0.045	0.032	0.029	0.053	0.018	0.046	0.028	0.115	0.012	0.019
1983	0.018	0.091	0.04	0.034	0.028	0.022	0.031	0.032	0.042	0.018	0.043	0.031	0.03	0.019	0.024
1984	0.07	0.076	0.073	0.038	0.036	0.012	0.018	0.034	0.032	0.013	0.06	0.034	0.074	0.038	0.096
1985	0.045	0.099	0.052	0.031	0.024	0.046	0.027	0.022	0.053	0.026	0.02	0.039	0.058	0.011	0.038
1986	0.076	0.089	0.038	0.02	0.032	0.044	0.025	0.057	0.039	0.019	0.07	0.044	0.044	0.009	0.02
1987	0.035	0.092	0.056	0.025	0.016	0.028	0.037	0.03	0.084	0.037	0.061	0.027	0.024	0.009	0.021
1988	0.083	0.075	0.049	0.015	0.016	0.044	0.034	0.02	0.07	0.025	0.041	0.023	0.081	0.017	0.011
1989	0.038	0.069	0.034	0.024	0.032	0.053	0.025	0.03	0.045	0.032	0.062	0.031	0.051	0.032	0.046
1990	0.063	0.026	0.043	0.036	0.022	0.044	0.015	0.028	0.057	0.032	0.043	0.025	0.05	0.008	0.011
1991	0.069	0.033	0.027	0.031	0.042	0.043	0.01	0.026	0.036	0.02	0.02	0.014	0.078	0.015	0.051
1992	0.071	0.04	0.027	0.02	0.024	0.039	0.018	0.031	0.036	0.024	0.037	0.042	0.017	0.014	0.021
1993	0.045	0.08	0.053	0.01	0.024	0.028	0.012	0.08	0.05	0.02	0.046	0.034	0.057	0.024	0.027
1994	0.074	0.016	0.038	0.04	0.018	0.015	0.02	0.049	0.031	0.007	0.044	0.04	0.049	0.029	0.026
1995	0.097	0.078	0.033	0.013	0.034	0.012	0.02	0.018	0.045	0.024	0.054	0.02	0.07	0.009	0.052
1996	0.03	0.096	0.041	0.022	0.036	0.047	0.039	0.083	0.051	0.025	0.044	0.026	0.035	0.026	0.01
1997	0.083	0.066	0.059	0.022	0.016	0.025	0.023	0.026	0.046	0.023	0.035	0.036	0.063	0.021	0.013
1998	0.049	0.058	0.025	0.015	0.024	0.034	0.019	0.093	0.045	0.01	0.053	0.036	0.025	0.015	0.013
1999	0.057	0.042	0.028	0.015	0.016	0.02	0.021	0.033	0.047	0.02	0.031	0.015	0.042	0.027	0.014
2000	0.019	0.072	0.028	0.035	0.028	0.031	0.033	0.036	0.029	0.018	0.036	0.042	0.028	0.01	0.027
2001	0.108	0.041	0.053	0.032	0.032	0.019	0.013	0.081	0.019	0.012	0.025	0.047	0.036	0.012	0.019
2002	0.072	0.066	0.014	0.044	0.028	0.021	0.057	0.034	0.016	0.012	0.031	0.037	0.018	0.01	0.013
2003	0.075	0.066	0.046	0.03	0.026	0.056	0.039	0.05	0.04	0.01	0.031	0.026	0.036	0.009	0.023
2004	0.046	0.059	0.031	0.026	0.03	0.04	0.025	0.016	0.021	0.011	0.018	0.007	0.031	0.017	0.031

2005	0.036	0.055	0.018	0.047	0.03	0.025	0.019	0.026	0.005	0.011	0.036	0.009	0.054	0.012	0.018
2006	0.083	0.064	0.017	0.007	0.016	0.015	0.039	0.048	0.008	0.014	0.029	0.02	0.053	0.016	0.047
2007	0.055	0.082	0.024	0.024	0.016	0.012	0.014	0.068		0.018	0.016	0.012	0.029	0.026	0.006
2008	0.035	0.032	0.016	0.035	0.041	0.037	0.016	0.077		0.018	0.017	0.016	0.053	0.026	0.016

Appendix 11G: Inner vs. outer shell measurements (detrended)

	C6L85 Outer	C6L85 Umbo	C6L66 Outer	C6L66 Umbo
1999	1.235			
2000	0.9469		1.205	
2001	1.1763		0.771	0.9776
2002	0.6445		0.95	0.9186
2003	1.3306	1.2169	1.349	1.3993
2004	1.125	0.7676	0.508	0.6905
2005	0.2071	0.7549	0.879	0.7204
2006	0.2078	1.3624	1.337	1.3789
2007	0.5404	0.8746	1.059	0.9706
2008	2.7852	1.024	0.954	0.9437

	C7L14 Outer	C7L14 Umbo	C7L110 Outer	C7L110 Umbo	C7L136 Outer	C7L136 Umbo	C1L120 Outer	C1L120 Umbo
1957	1.3621							
1958	1.0514							
1959	0.933							
1960	0.4663							
1961	0.2595							
1962	0.7766							
1963	0.6941							
1964	2.0169							
1965	0.2367							
1966	1.3744							
1967	0.5059							
1968	0.8763							
1969	1.2462							
1970	0.2375							
1971	2.4923							
1972	0.2679							
1973	1.1522							
1974	2.2911							
1975	0.3487							
1976	1.0497							
1977	2.4857							
1978	2.3054							
1979	1.1506		2.4118	2.1755				
1980	1.5502		0.4634	1.0682				
1981	1.2876		0.3332	0.9624				
1982	2.0031		2.0012	0.9803				
1983	0.668		0.7223	0.8083				
1984	1.4419		1.0643	0.7252				
1985	0.1217		0.5921	0.7901	0.2776			
1986	0.7267		1.3468	1.1011	0.9195			
1987	1.3879	0.7874	1.5725	0.9464	0.0523	0.6872		0.711
1988	1.1156	0.9166	0.5538	1.553	3.1354	0.5548		1.055
1989	0.5054	0.9821	0.1155	1.2594	0.8611	0.8134	1.1003	0.784
1990	0.3932	1.2141	1.7007	1.2329	0.1374	0.8598	0.8054	0.604
1991	0.3774	2.5545	0.1656	0.4921	0.5957	1.5596	0.6965	1.3
1992	0.7196	0.3451	0.1108	0.4437	0.9438	1.003	0.5401	0.182
1993	0.1913	0.1672	0.7068	1.1386	1.2869	0.8046	1.2009	1.926
1994	0.2411	0.8054	0.5847	0.9105	0.6354	1.0337	0.1495	1.738
1995	0.3569	1.2054	2.4291	1.9944	2.2157	1.9947	1.3033	0.318
1996	0.2833	0.375	1.2538	1.1958	1.0773	0.7912	1.2586	0.491
1997	0.2645	0.4421	5.1276	0.178	2.4147	1.8467	0.9305	0.841
1998	0.4665	1.0365	1.8893	0.6419	1.5323	1.3736	0.8509	0.29
1999	0.4369	3.0455	0.2472	0.5624	0.089	2.4727	4.7711	2.173
2000	0.2098	1.6821	0.4633	0.1543	3.3874	0.6162	0.4983	3.27
2001	0.3455	0.1202	0.3834	1.45	0.3301	0.6265	0.3585	0.902

2002	0.3982	0.1779	0.3424	2.4604	0.3825	0.1985	2.5251	2.597
2003	1.184	0.5316	0.2314	0.9354	0.1238	0.376	0.3995	0.297
2004	0.9197	3.1162	0.7731	2.2414	0.1315	0.246	0.4934	0.528
2005	0.4929	0.1432	0.2495	0.6089	0.2781	0.7192	0.065	0.344
2006	2.2374	0.188	0.5667	0.2538	0.1515	0.3521	0.2631	0.112
2007	2.2093	0.3853	0.8525	0.7224	0.6341	0.9688	0.1474	0.37
2008	5.3374	1.8612	0.4647		1.4375		0.2207	

Year	C1L2 Outer	C1L2 Umbo	C1L4 Outer	C1L4 Umbo	C1L14 Outer	C1L14 Umbo
1843				1.0011		
1844				0.9952		
1845				1.0979		
1846				0.8103		
1847				1.0737		
1848				1.1557		
1849				0.9002		
1850				0.464		
1851				0.8607		
1852				0.5336		
1853				1.2579		
1854				1.5728		
1855				0.915		
1856				1.1584		
1857				3.0072		
1858				2.534		
1859				3.0785		
1860			1.06	1.8806		
1861			0.847	1.4238		
1862			0.824	1.2749		
1863			1.152	1.4415		
1864			1.192	1.6911		
1865			0.822	3.2821		
1866			1.117	3.1404		
1867			2.041	2.7566		
1868			0.842	4.1134		
1869			0.937	4.4814		
1870			0.577	3.4373		
1871			0.243	3.2978		
1872			0.837	2.1236		
1873			1.312	1.0631		
1874			0.882	1.9214		
1875			0.653	1.9227		
1876			0.802	2.8412		
1877			0.706	1.4212		
1878			0.582	2.2804		
1879			0.757	1.1553		
1880			0.972	1.2147		
1881			0.765	1.3038		
1882			0.974	1.5706		
1883			0.942	1.304		
1884			0.892	2.371		
1885			1.162	1.0373		
1886			1.29	0.8892		0.9878
1887			1.249	1.2449		1.2551

1888			1.326	1.0967		0.7538
1889			1.783	1.2449		0.7593
1890			2.48	1.0671		0.7973
1891			1.657	0.9189		0.8804
1892			1.971	0.8003	1.083	0.6824
1893			1.367	0.5039	1.026	1.1886
1894			0.76	0.8003	0.675	1.7557
1895			1.671	1.0375	1.647	2.1026
1896			0.82	0.5928	0.614	1.2973
1897			1.623	0.7114	0.679	1.6291
1898			1.021	0.6225	0.347	2.3437
1899			1.543	0.7707	1.006	1.2565
1900			0.674	0.741	1.214	1.9561
1901			1.089	1.0078	2.467	1.6989
1902			0.992	1.0967	0.865	1.4446
1903			1.061	1.245	1.248	1.303
1904			1.618	2.2528	0.985	2.1575
1905	0.454		0.795	0.8003	0.91	0.1189
1906	1.572		1.415	1.7489	0.892	0.9698
1907	1.277		0.927	1.0671	0.867	1.5993
1908	0.956		0.818	1.0078	0.643	1.5427
1909	0.515		1.018	1.1264	0.797	1.6814
1910	1.455		0.896	0.6225	1.045	0.8841
1911	1.35		1.217	2.2824	1.25	1.1422
1912	0.512		0.771	0.83	0.741	0.9172
1913	0.39	0.8627	1.034	0.5632	0.853	2.4528
1914	0.892	0.9238	0.965	0.5928	1.242	2.4836
1915	1.438	0.9972	0.709	0.741	0.646	2.6158
1916	1.692	1.5014	0.647	0.4743	1.04	1.9257
1917	1.473	1.1973	0.844	0.7707	0.998	1.5677
1918	1.541	1.2434	0.59	0.8003	0.819	1.2344
1919	0.947	0.9045	0.387	0.4743	0.448	1.1579
1920	0.825	0.7384	0.663	0.2668	0.418	1.39
1921	0.503	0.6554	0.729	0.4446	1.391	1.9311
1922	0.533	0.642	0.597	0.4743	0.627	0.9529
1923	0.555	0.8006	0.993	0.5632	0.849	0.8243
1924	0.483	0.6549	0.926	1.5414	0.897	1.623
1925	0.623	0.8362	0.985	0.5632	1.038	1.7004
1926	1.03	1.3004	1.511	0.741	0.632	1.8809
1927	0.602	0.7476	0.853	0.5039	0.851	0.773
1928	0.496	0.9473	1.585	0.83	0.724	1.3657
1929	0.529	0.906	0.864	0.3557	1.772	1.2885
1930	1.077	1.1838	1.05	1.0078	1.746	2.3966
1931	1.242	1.5888	0.663	1.2746	2.06	2.0359
1932	1.076	1.348	1.264	0.6521	1.438	0.3092
1933	1.02	1.2186	0.991	0.9782	1.101	0.4896
1934	1.082	1.4336	0.992	0.8596	0.984	0.6443
1935	0.521	0.7169	0.732	0.6521	1.012	0.3093
1936	0.588	0.7403	1.188	1.0375	1.164	0.335
1937	0.763	0.9554	1.584	0.7114	0.885	0.5927
1938	1.388	1.7466	1.382	0.5928	0.923	0.6701
1939	0.764	1.0552	1.517	0.5039	1.008	0.1289

1940	0.678	0.7916	1.389	0.3557	0.73	0.335
1941	0.872	1.2191	1.335	0.4446	1.34	0.6701
1942	1.28	1.7597	0.736	0.741	0.64	1.469
1943	1.755	1.9014	0.806	1.0078	0.58	1.1855
1944	1.056	0.9085	0.664	0.4446	1.36	0.902
1945	0.654	0.968	1.205	0.2964	0.775	0.2319
1946	0.598	0.6915	0.859	0.6521	1.089	0.1546
1947	0.62	0.8049	1.4	0.9189	1.397	0.3866
1948	1.039	1.0022	1.725	1.156	1.85	0.5412
1949	0.536	0.6226	0.859	0.741	1.662	0.5927
1950	0.613	0.715	0.723	0.3261	0.825	0.7216
1951	0.824	0.9574	0.929	0.3261	0.717	0.567
1952	1.046	1.5048	0.532	0.2075	1.442	1.2886
1953	1.126	1.2801	0.735	0.4446	0.556	0.3608
1954	1.546	1.3344	0.613	0.6521	0.566	0.4381
1955	1.293	0.9696	0.337	0.3557	0.611	0.1804
1956	0.908	0.7984	0.674	0.2668	1.18	0.5154
1957	1.19	1.2937	0.531	0.2668	0.906	0.7989
1958	0.735	0.7174	0.613	0.83	1.071	0.6185
1959	0.977	1.0585	0.806	0.4743	0.891	0.1546
1960	1.262	0.7235	0.592	0.8003	0.9	0.1031
1961	1.016	0.8395	1.013	0.5336	0.513	0.2577
1962	0.654	0.5007	0.939	0.6818	0.625	0.1289
1963	0.787	0.776	1.744	0.5928	1.05	0.2577
1964	1.061	1.0524	0.47	0.5632	0.479	0.1804
1965	0.725	0.5732	1.948	0.6521	0.579	1.1082
1966	0.646	0.5743	0.735	0.5039	0.339	0.2577
1967	0.701	0.6673	1.217	0.5039	0.565	0.1546
1968	0.398	0.3917	1.275	0.2075	0.642	0.2062
1969	0.932	0.6922	0.527	0.6521	0.516	0.1804
1970	1.313	1.2705	0.672	0.4743	0.405	0.2577
1971	0.568	0.4162	1.2	0.5039	0.423	0.3866
1972	0.797	0.5554	0.602	0.2075	0.29	0.3608
1973	0.662	0.5559	0.592	0.2668	0.65	0.3866
1974	1.579	1.2748	0.806	0.8893	0.795	0.1546
1975	0.711	0.7189	0.733	0.7114	0.641	0.2835
1976	1.375	1.2762	0.939	0.3557	0.465	0.2577
1977	1.691	1.3697	1.542	0.2075	0.424	0.2319
1978	1.305	0.8361	1.613	0.1779	0.594	0.3866
1979	2.059	1.4405	1.228	0.4446	0.342	0.4897
1980	1.883	1.4177	0.806	0.2075	0.499	0.4381
1981	2.475	1.7668	0.664	0.4446	0.481	1.9071
1982	1.356	0.9999	0.532	0.2668	0.788	0.8762
1983	1.643	1.3025	1.286	0.3557	0.761	0.3866
1984	1.548	1.2097	0.483	0.3557	2.897	0.3866
1985	1.597	1.2564	1.001	0.2964	1.395	0.1031
1986	1.738	1.2101	1.379	0.4743	0.858	1.469
1987	0.811	0.4655	1.095	0.3557	0.867	1.3659
1988	1.04	0.4423	0.647	0.2668	1.024	1.237
1989	1.308	0.8148	1.045	0.2668	0.947	0.335
1990	0.912	0.7683	1.045	0.83	1.095	1.4432
1991	1.277	1.0012	1.054	0.8893	1.461	1.8556

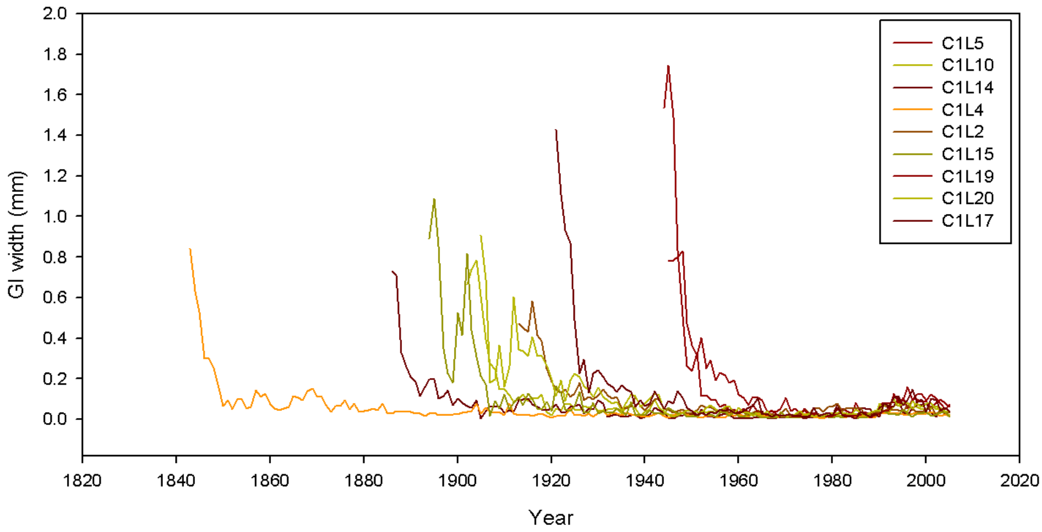
1992	1.426	1.2108	1.027	0.83	1.508	1.4432
1993	1.234	1.0944	1.183	0.8893	1.259	1.6494
1994	1.143	1.0712	0.919	0.9485	1.324	2.8091
1995	0.869	0.885	0.968	0.741	2.19	0.8247
1996	1.792	1.6303	1.726	0.6818	1.225	0.5927
1997	1.537	1.1878	0.986	0.8596	1.36	1.469
1998	1	0.9083	0.836	0.8596	1.26	1.7782
1999	1.117	0.9084	0.889	0.741	1.678	1.7782
2000	1.244	1.0947	1.347	0.83	1.602	1.9586
2001	2.067	1.5606	1.587	1.0671	1.448	0.8505
2002	0.791	0.5125	0.819	0.8003	1.621	0.2835
2003	1.643	1.1647	1.024	0.5336	1.234	1.2113
2004	0.825	0.6988	0.898	0.741	2.479	0.7732
2005	1.14	0.8386	0.898	0.5336		

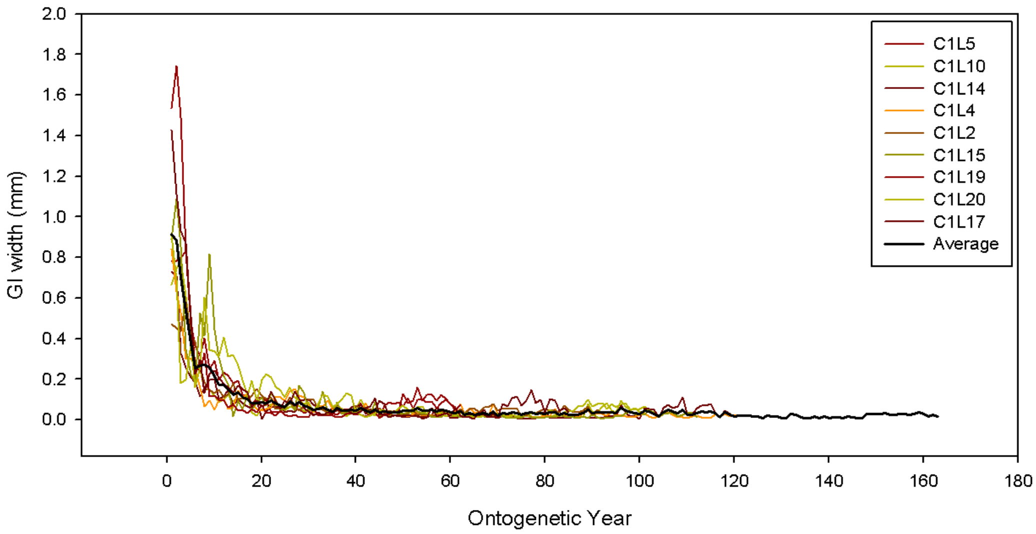
Year	L17 Outer	L17 Umbo	L19 Outer	L19 Umbo
1908	0.483			
1909	1.221			
1910	1.526			
1911	1.598			
1912	0.364			
1913	1.185			
1914	0.586			
1915	1.003			
1916	0.479			
1917	2.005			
1918	1.354			
1919	0.751			
1920	1.022			
1921	0.404	0.9842		
1922	1.055	0.9858		
1923	1.048	1.0626		
1924	0.775	1.2696		
1925	0.8	0.906		
1926	0.791	0.5319		
1927	0.658	0.8715	1.029	
1928	0.973	0.4885	0.972	
1929	0.784	1.025	0.586	
1930	0.867	1.3259	0.417	
1931	0.529	1.3625	0.342	
1932	0.698	1.3563	1.653	
1933	0.581	1.4438	1.267	
1934	0.814	1.3571	4.128	
1935	1.257	1.9	2.462	
1936	1.011	1.8632	2.346	
1937	0.721	1.8002	1.606	
1938	1.072	0.8885	1.071	
1939	1.082	1.4045	0.73	
1940	1.864	1.024	0.23	

1941	1.612	1.287	1.286	
1942	1.041	2.3255	0.753	
1943	0.836	1.6058	0.814	
1944	0.576	0.9376	0.902	0.8149
1945	0.759	1.6178	1.06	1.2258
1946	0.705	1.3674	0.579	1.3808
1947	0.692	2.523	0.451	1.0142
1948	0.584	1.9079	0.847	0.8147
1949	1.019	1.0668	0.735	0.5458
1950	1.149	0.762	0.703	0.6399
1951	1.082	0.382	0.344	1.1352
1952	1.212	0.638	0.522	0.504
1953	1.03	0.3834	0.366	0.6675
1954	1.742	0.6947	0.517	0.6833
1955	1.507	0.5672	0.401	0.8089
1956	1.155	0.8972	0.376	0.6364
1957	1.675	0.7512	0.429	0.8668
1958	0.91	0.8798	0.818	0.6018
1959	0.913	0.5867	0.338	0.7719
1960	1.28	0.4952	0.278	0.5469
1961	0.823	0.752	0.285	1.0035
1962	1.075	1.064	0.216	0.6961
1963	0.54	1.2293	0.346	1.5747
1964	0.666	1.945	0.637	0.7231
1965	0.431	0.4588	0.205	0.7703
1966	0.508	0.4955	0.265	0.465
1967	1.43	0.2386	0.45	1.1145
1968	0.498	0.4588	0.457	0.626
1969	0.314	0.312	0.359	0.414
1970	0.44	0.3487	0.334	0.5651
1971	0.325	0.4588	0.254	0.3215
1972	0.511	0.3304	0.426	0.2983
1973	0.638	0.3304	0.636	0.3244
1974	0.643	0.257	0.498	1.3762
1975	0.321	0.2386	0.563	0.5266
1976	0.251	1.0829	0.359	0.5777
1977	0.192	0.312	0.487	0.5532
1978	0.586	0.4405	0.701	0.4782
1979	0.445	0.5873	0.623	0.3274
1980	0.517	0.4038	0.783	0.378
1981	0.578	1.0278	0.536	0.7058
1982	0.714	0.3854	0.411	0.7817
1983	0.712	0.2386	0.319	0.5801
1984	1.681	0.2386	0.709	0.5802
1985	0.581	0.0551	0.294	0.4289
1986	0.724	0.6975	1.215	0.6055
1987	0.785	0.4405	1.122	0.9841
1988	1.06	0.257	1.308	0.1766
1989	1.28	0.5323	0.813	0.5804
1990	1.313	0.2386	1.544	0.7066
1991	2.795	1.45	0.812	1.0347
1992	3.246	1.193	2.884	1.1357

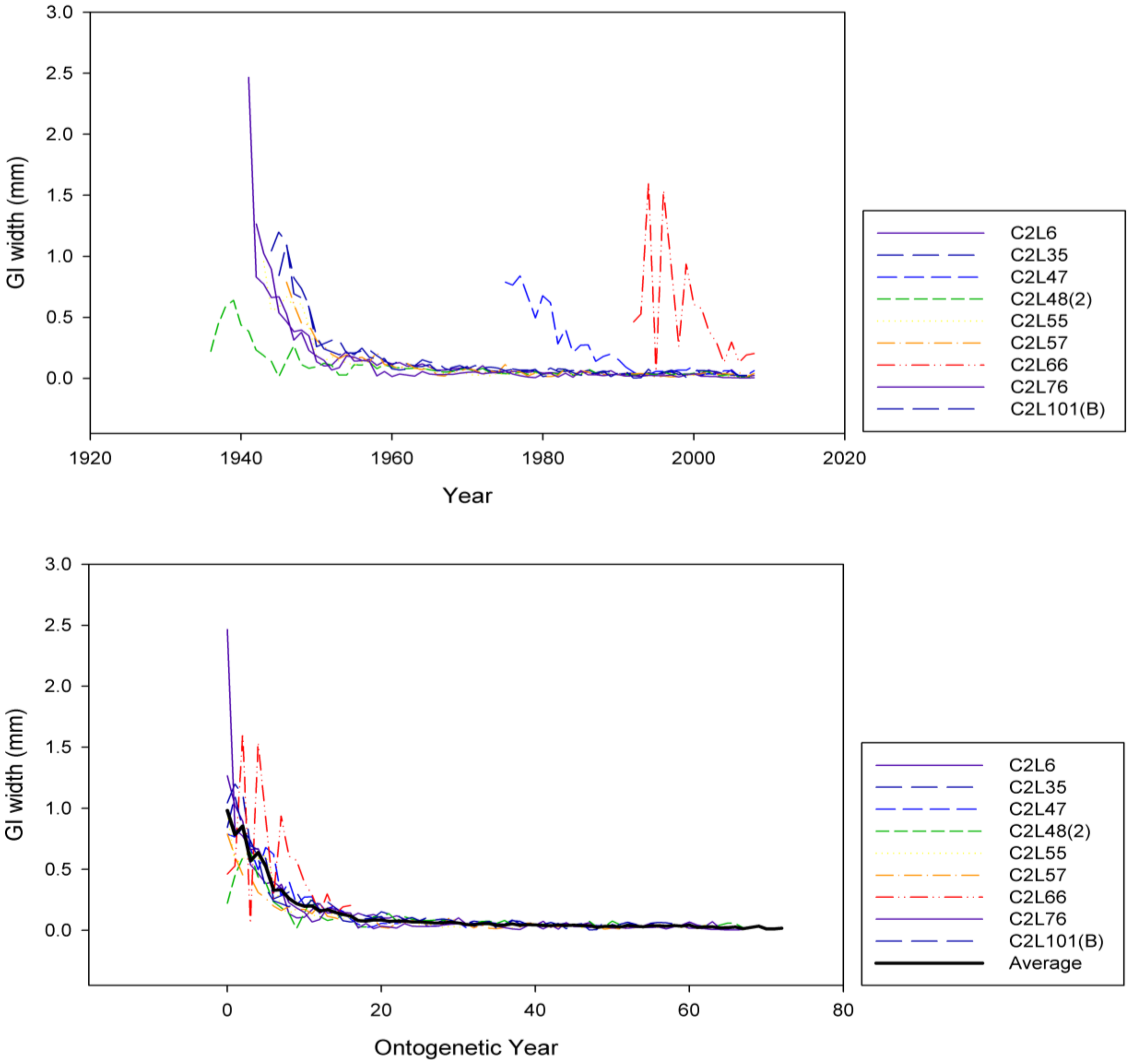
1993	2.021	1.9639	0.857	3.2051
1994	1.957	2.1107	1.545	2.0695
1995	3.842	1.2848	0.795	2.4228
1996	1.828	1.7436	1.318	4.0633
1997	1.329	2.698	1.736	2.3471
1998	1.248	1.5234	2.988	3.1547
1999	0.984	1.817	2.341	3.1547
2000	2.623	0.6791	2.38	2.3976
2001	2.645	1.8905	2.461	3.1295
2002	1.461	1.7253	1.659	2.5995
2003	1.663	0.8076	0.637	1.9686
2004	1.126	1.0645	0.988	1.2114

Appendix 12: Raw growth increment data for all six sites (crossdated shell data only). These graphs help to illustrate the common ontogenetic growth patterns between the shells at each of the sites.

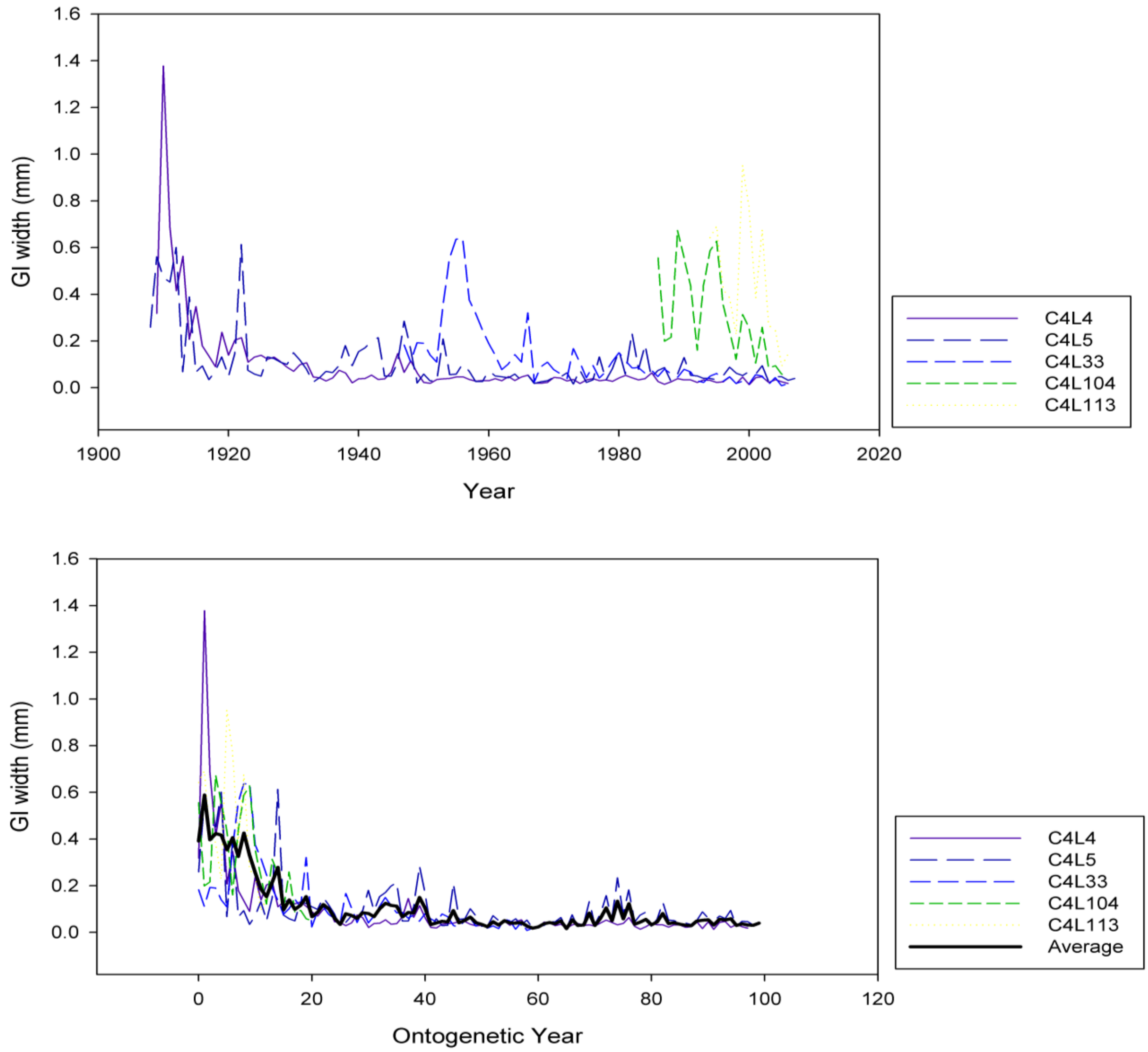




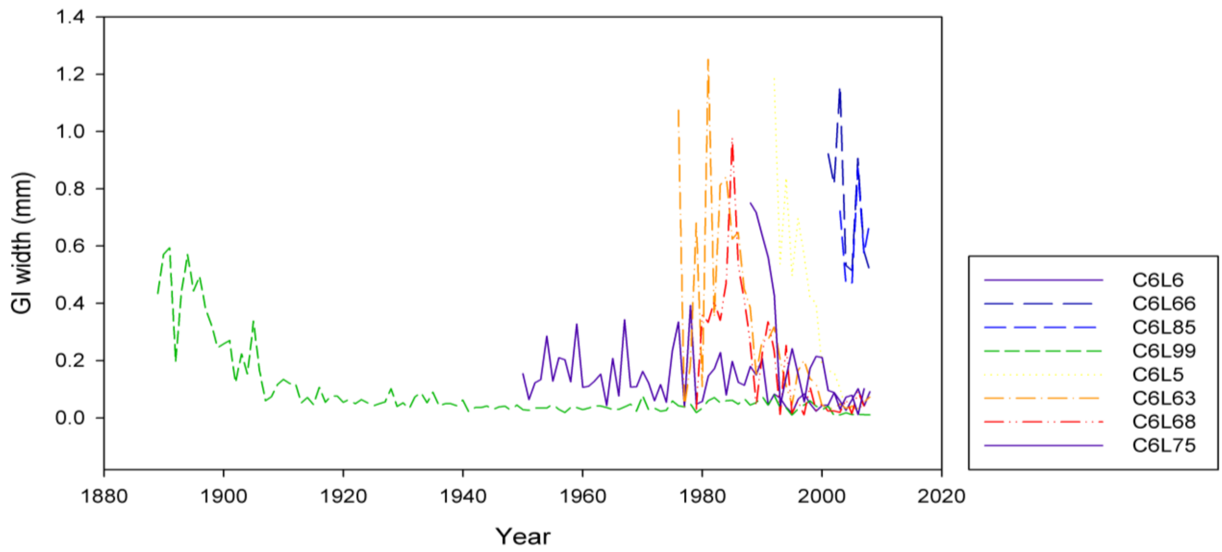
Appendix 12A: Site C1 raw growth increment data. The top panel illustrates the raw data by calendar year while in the bottom panel all the raw data is aligned starting from ontogenetic year one to investigate how similar the growth trend for all data are. Also illustrated in the bottom panel is the average raw growth series for all shells crossdated at the site.

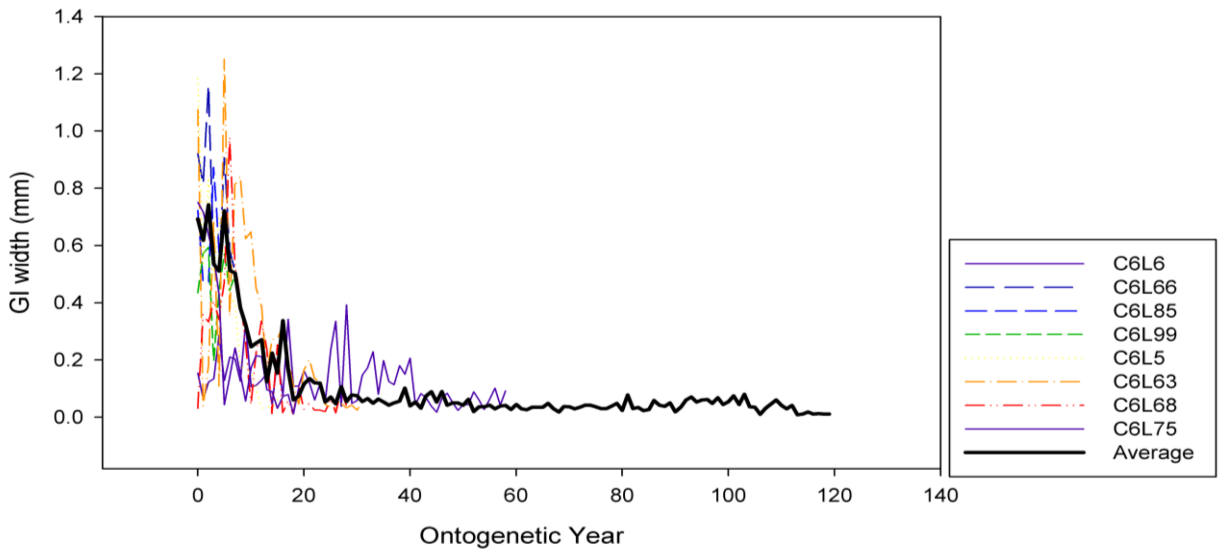


Appendix 12B: Site C2 raw growth increment data. The top panel illustrates the raw data by calendar year while in the bottom panel all the raw data is aligned starting from ontogenetic year one to investigate how similar the growth trend for all data are. Also illustrated in the bottom panel is the average raw growth series for all shells crossdated at the site.

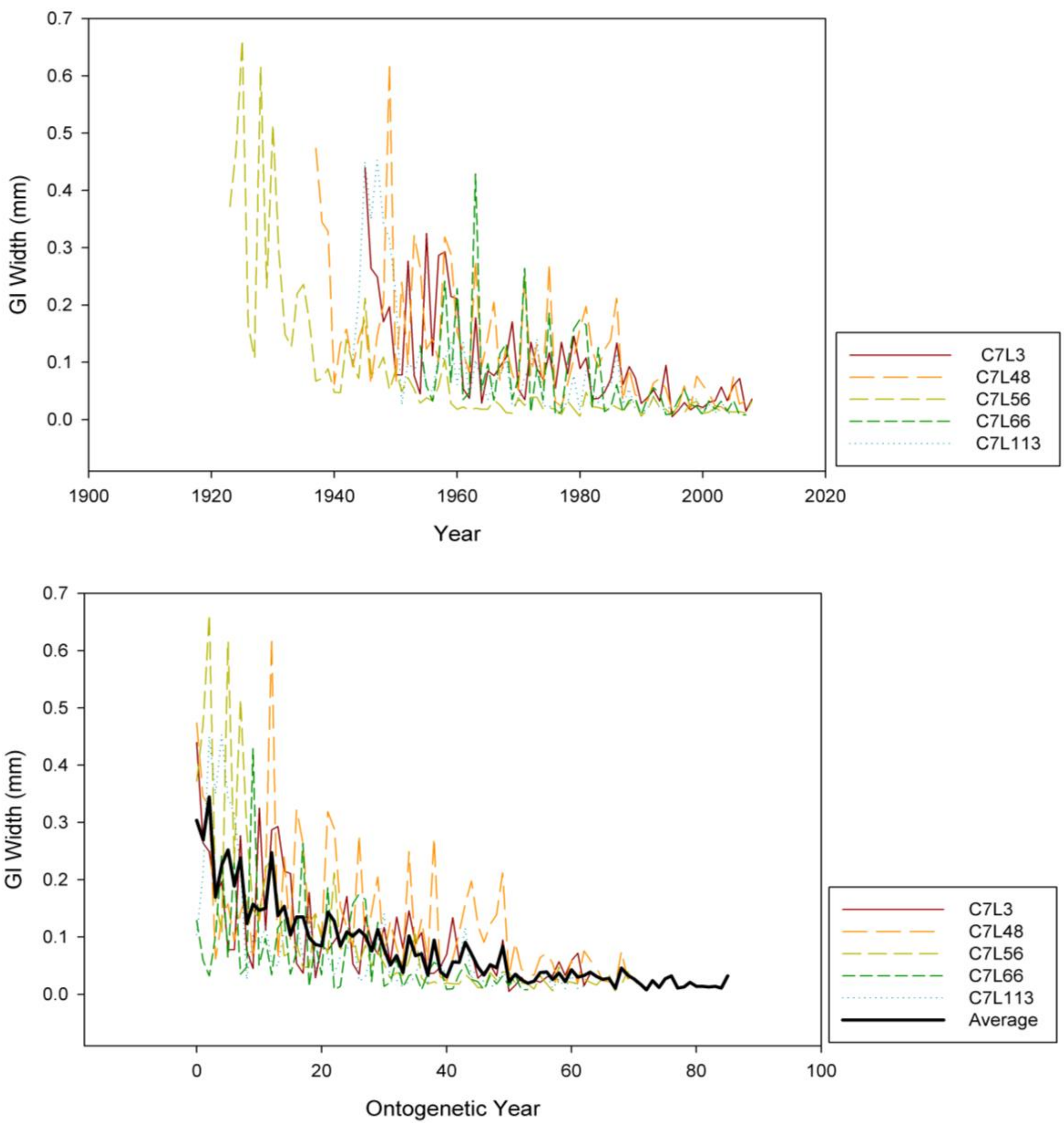


Appendix 12C: Site C4 raw growth increment data. The top panel illustrates the raw data by calendar year while in the bottom panel all the raw data is aligned starting from ontogenetic year one to investigate how similar the growth trend for all data are. Also illustrated in the bottom panel is the average raw growth series for all shells crossdated at the site.

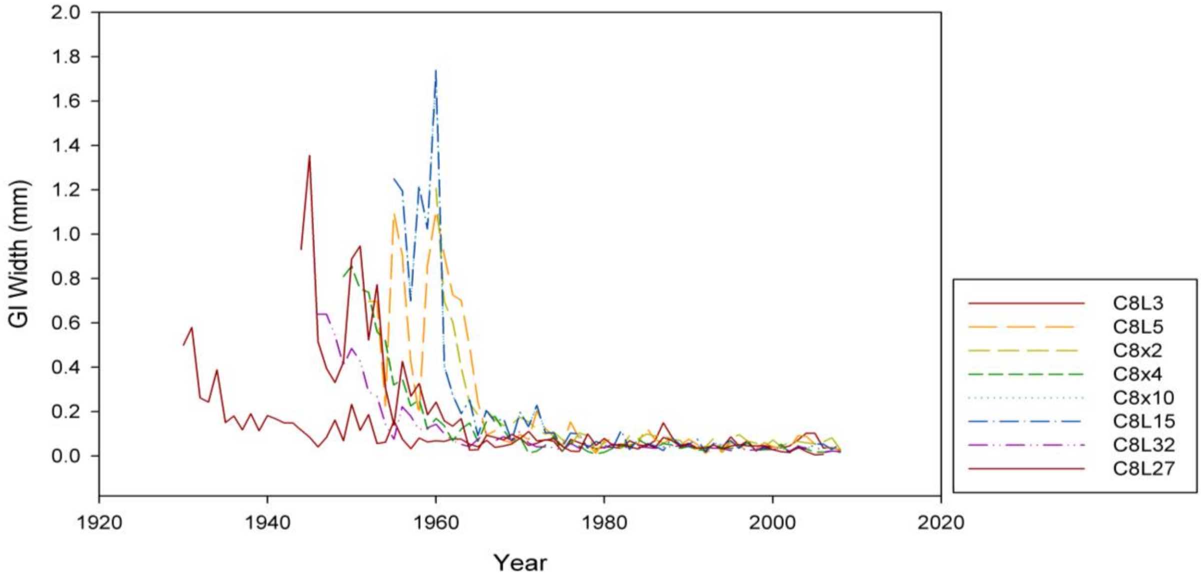


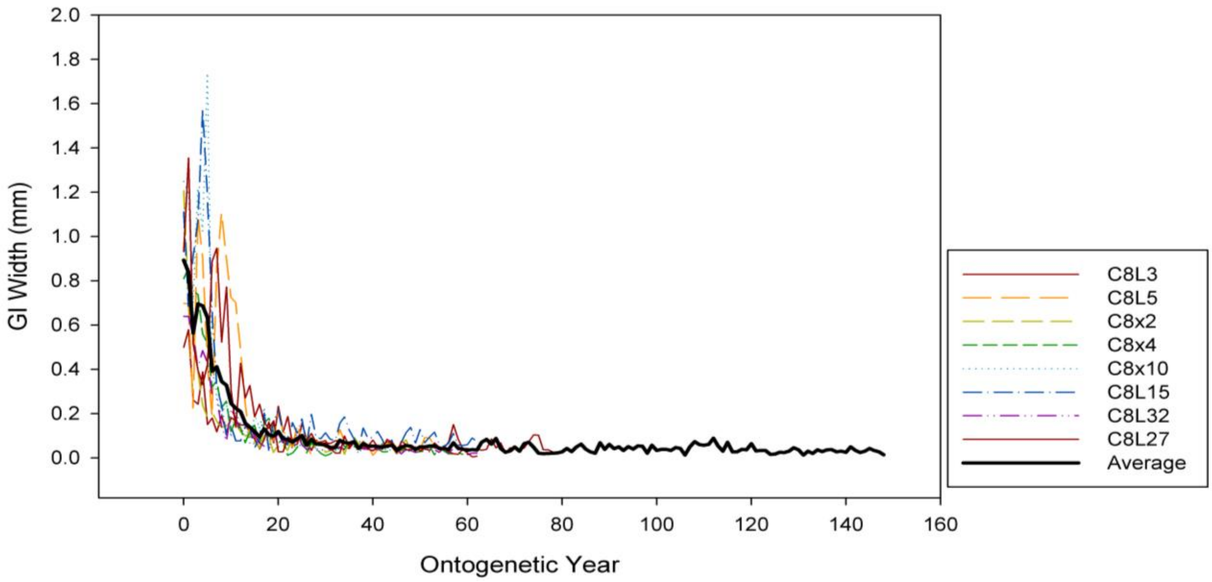


Appendix 12D: Site C6 raw growth increment data. The top panel illustrates the raw data by calendar year while in the bottom panel all the raw data is aligned starting from ontogenetic year one to investigate how similar the growth trend for all data are. Also illustrated in the bottom panel is the average raw growth series for all shells crossdated at the site.



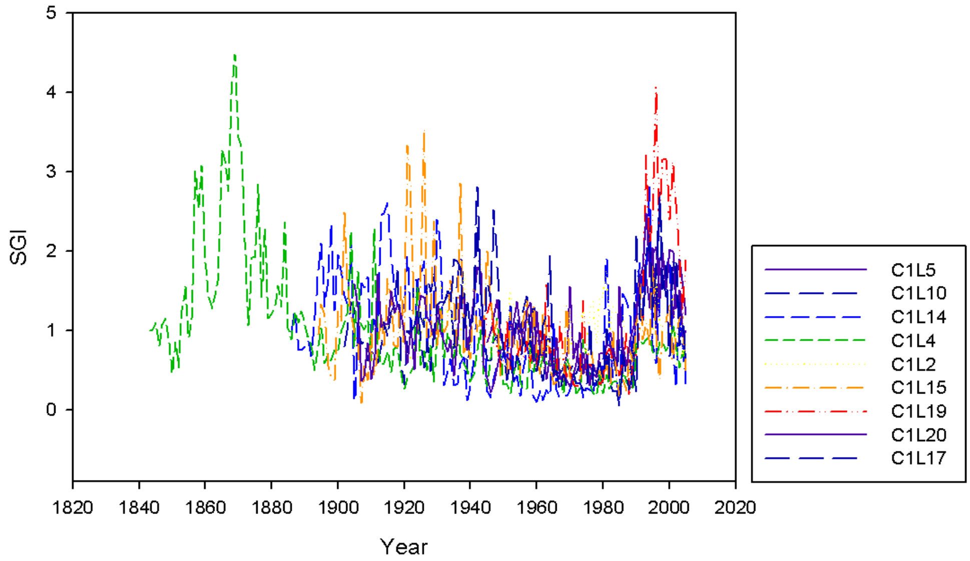
Appendix 12E: Site C7 raw growth increment data. The top panel illustrates the raw data by calendar year while in the bottom panel all the raw data is aligned starting from ontogenetic year one to investigate how similar the growth trend for all data are. Also illustrated in the bottom panel is the average raw growth series for all shells crossdated at the site.



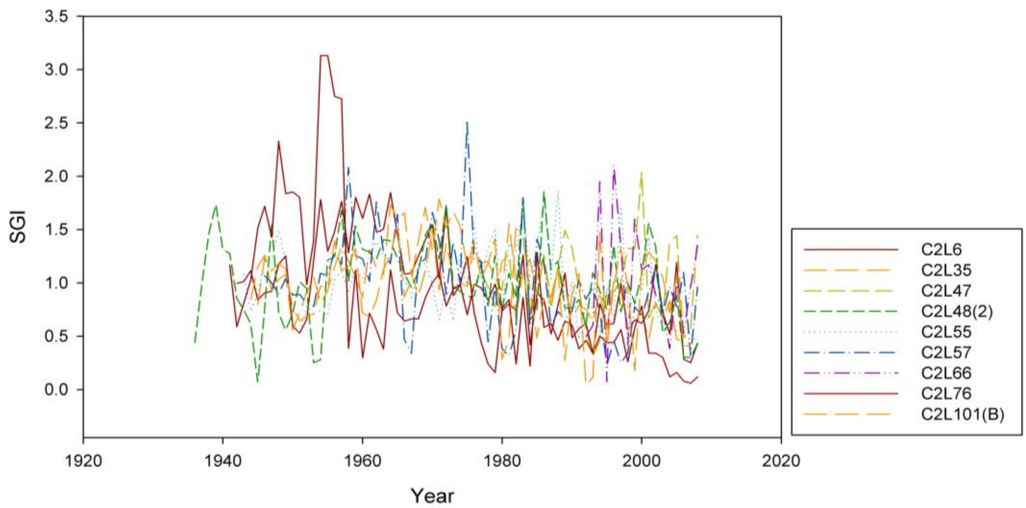


Appendix 12F: Site C8 raw growth increment data. The top panel illustrates the raw data by calendar year while in the bottom panel all the raw data is aligned starting from ontogenetic year one to investigate how similar the growth trend for all data are. Also illustrated in the bottom panel is the average raw growth series for all shells crossdated at the site.

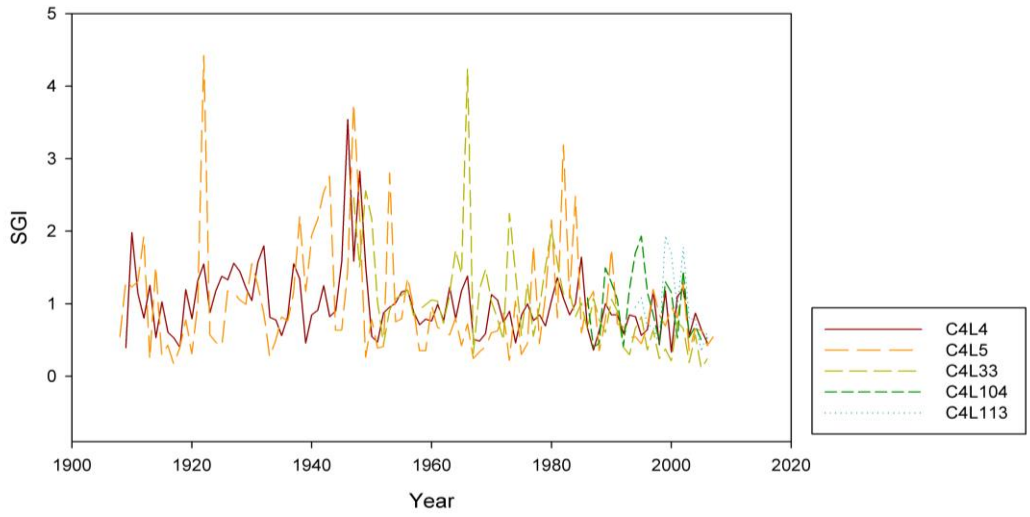
Appendix 13: Graphs for individual series used to create master chronologies for all sites. These graphs illurate the detrended GI data for each of the cross dated shells for all six sites. These results are averaged together to generate the master chronologies presented in Chapter 4.



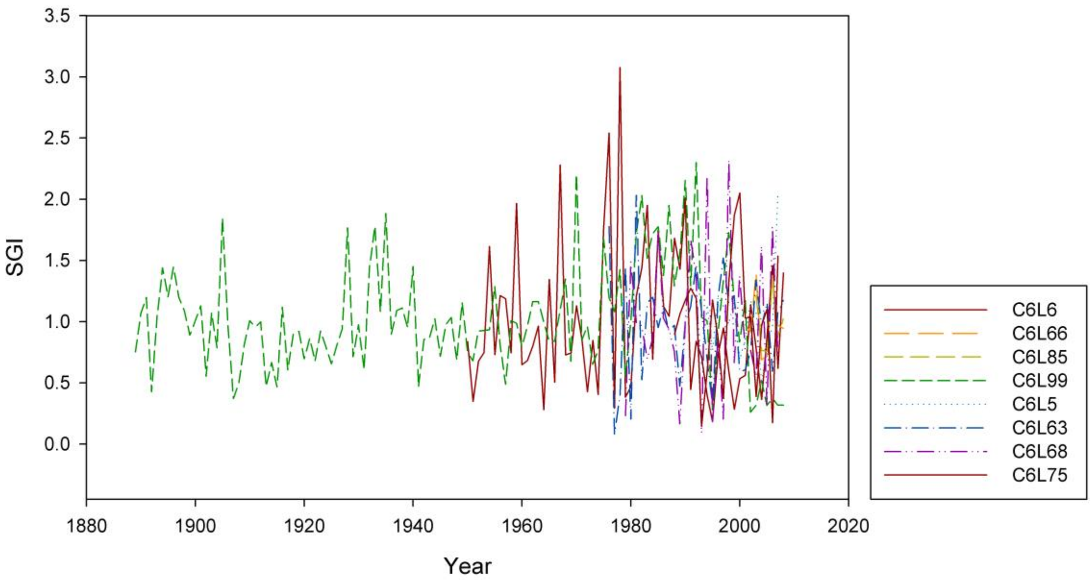
Appendix 13A: Site C1 graph showing all the detrended series for each of the individual shell chronologies used in the final master chronology in Figure 4.6



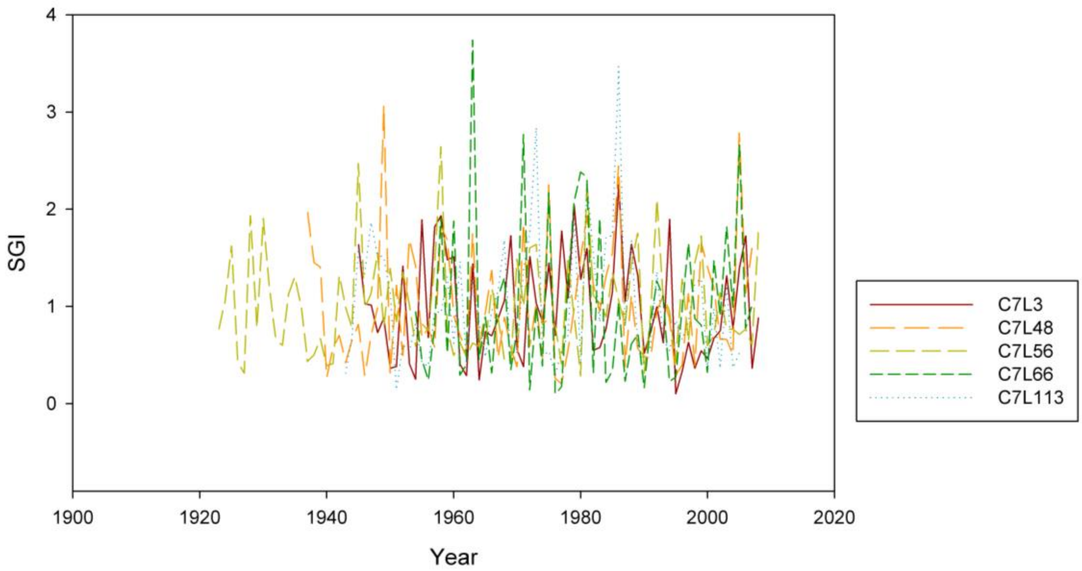
Appendix 13B: Site C2 graph showing all the detrended series for each of the individual shell chronologies used in the final master chronology in Figure 4.7



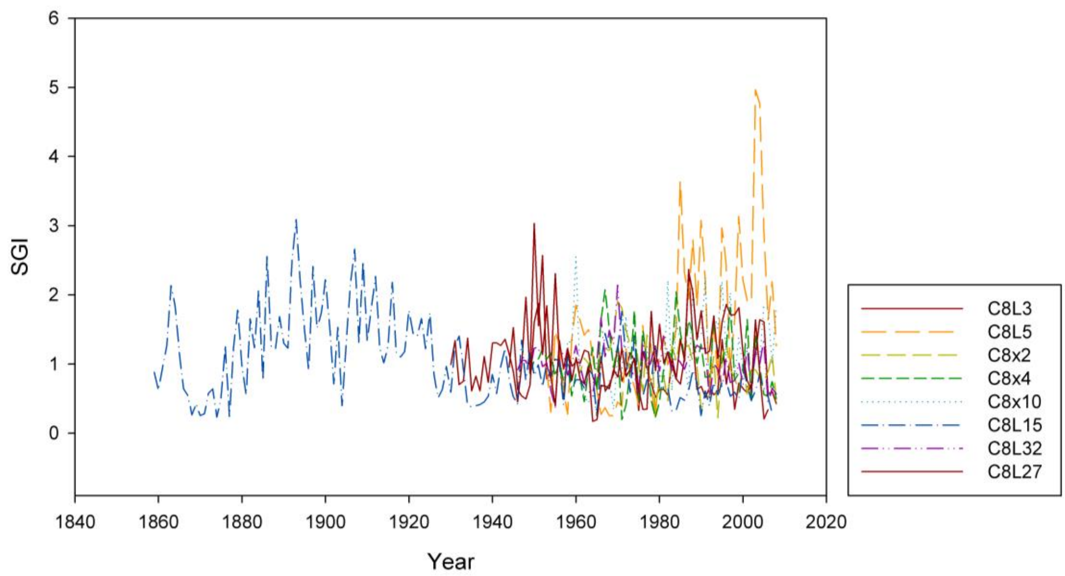
Appendix 13C: Site C4 graph showing all the detrended series for each of the individual shell chronologies used in the final master chronology in Figure 4.8



Appendix 13D: Site C6 graph showing all the detrended series for each of the individual shell chronologies used in the final master chronology in Figure 4.9



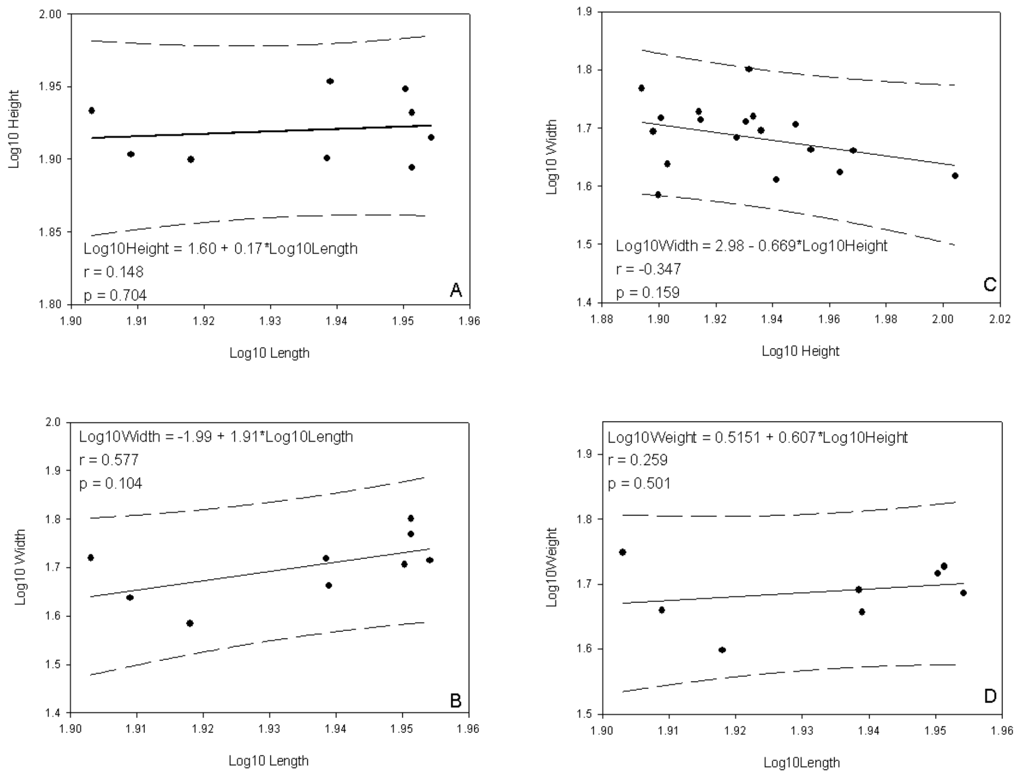
Appendix 13E: Site C7 graph showing all the detrended series for each of the individual shell chronologies used in the final master chronology in Figure 4.10



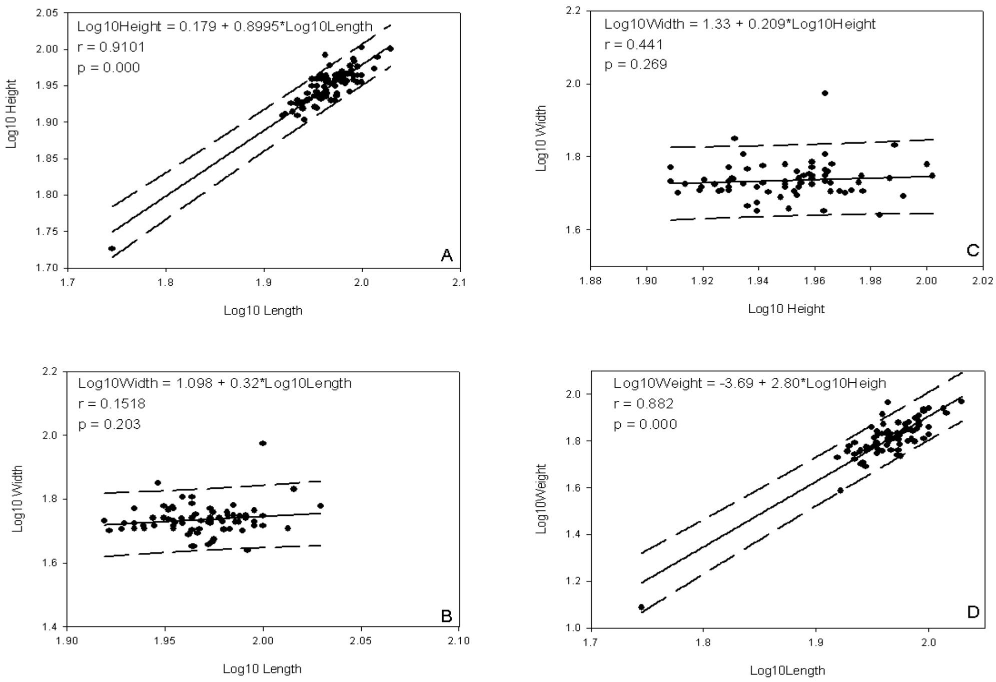
Appendix 13F: Site C8 graph showing all the detrended series for each of the individual shell chronologies used in the final master chronology in Figure 4.11

Appendix 14: Allometric information for each site.

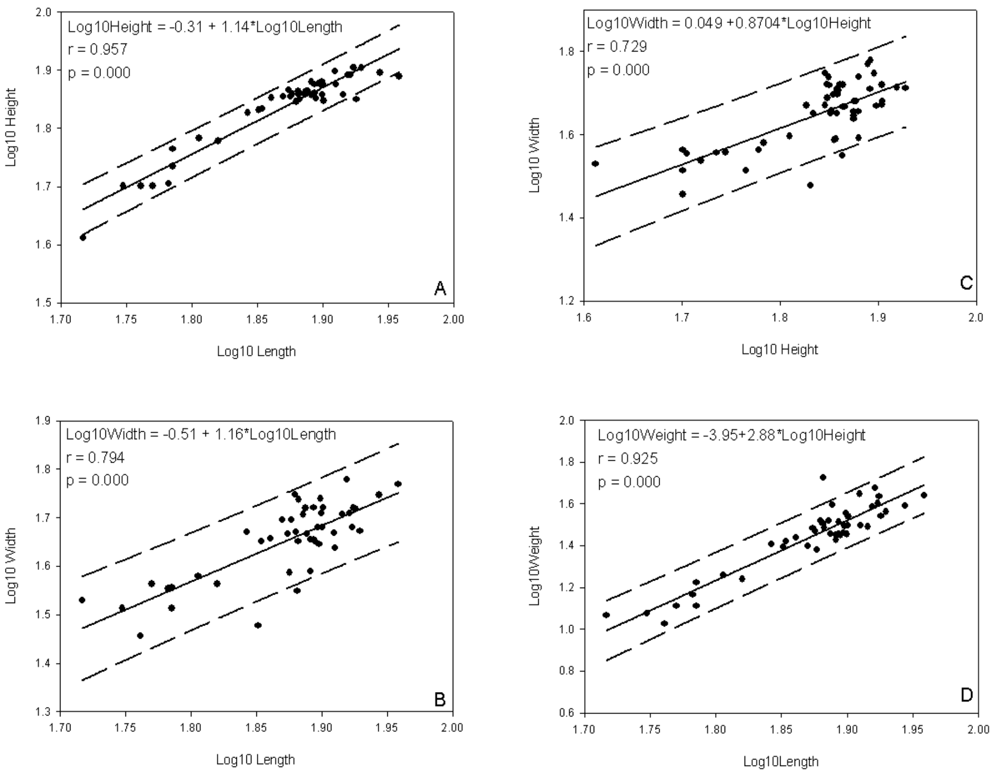
In Chapter 5 the allometrics for all six sites are presented together, in this appendix the results for the individual sites are presented for comparison purposes.



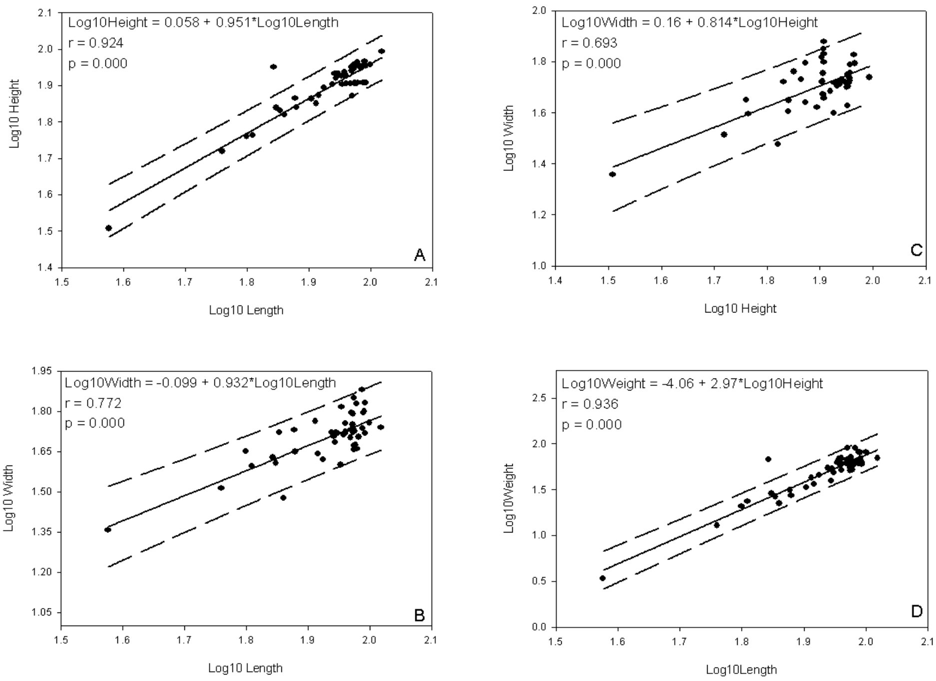
Appendix 14A: Site C1 allometric relationship investigations between A) length-height (Isometric), B) length-width (Isometric), C) height -width (Negatively Allometric) and D) length –weight (Negatively Allometric).



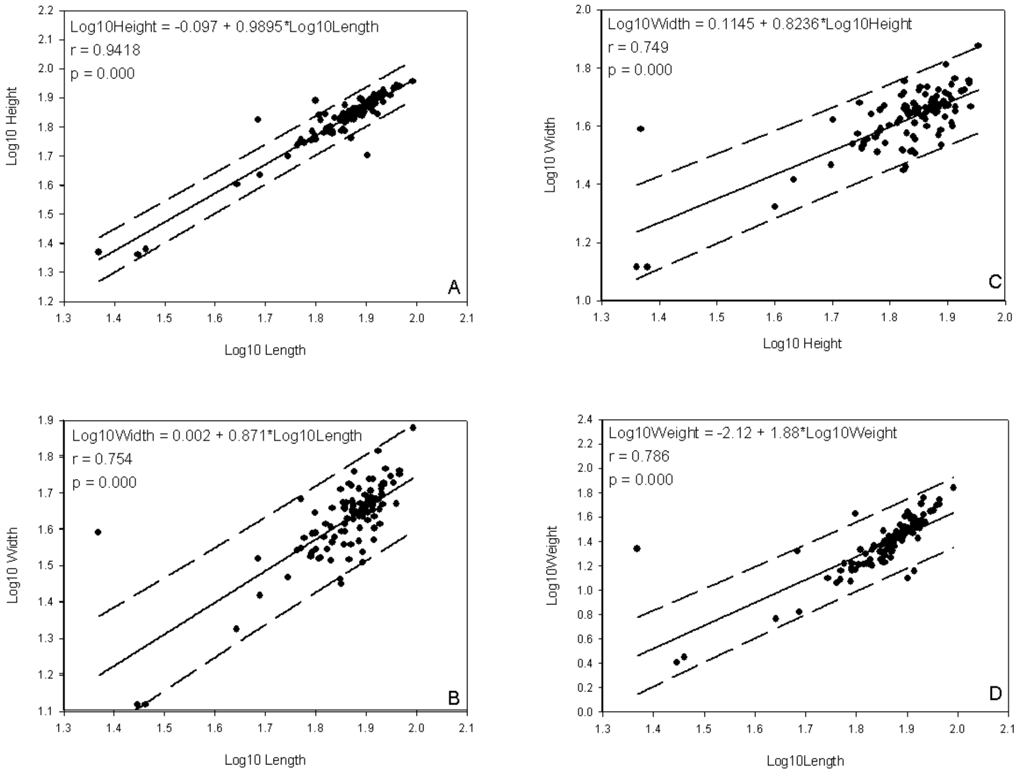
Appendix 14 B: Site C2 allometric relationship investigations between A) length-height (Isometric), B) length-width (Negatively Allometric), C) height –width(Negatively Allometric) and D) length –weight (Isometric).



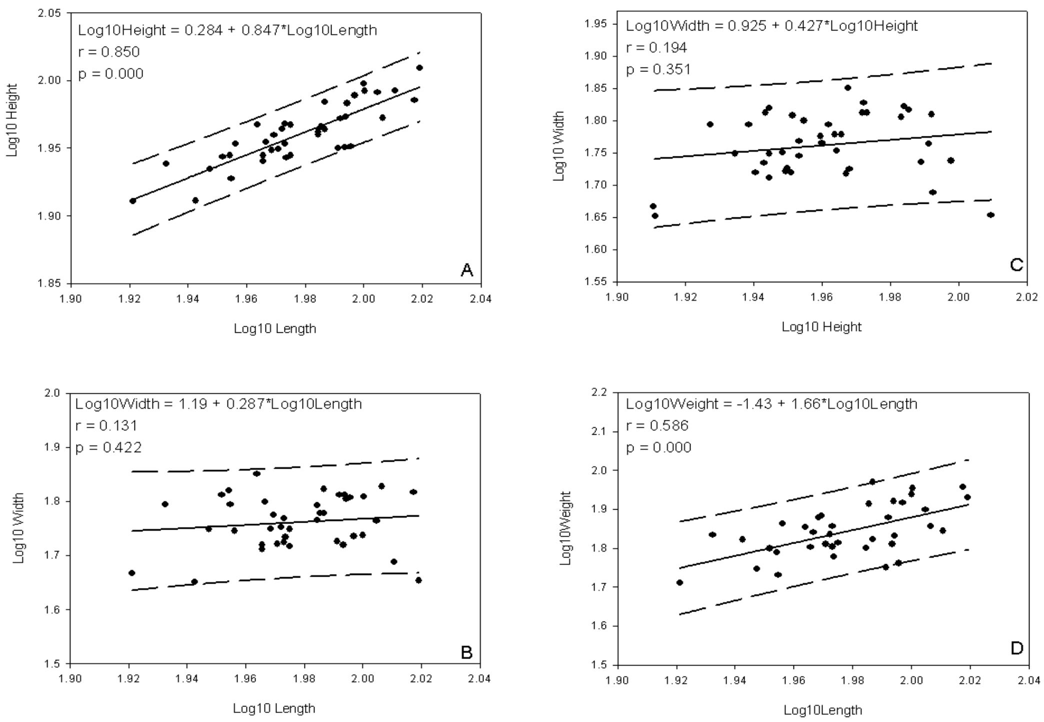
Appendix 14C: Site C4 allometric relationship investigations between A) length-height (Positively Allometric), B) length-width (Isometric), C) height -width (Isometric) and D) length – weight(Isometric).



Appendix 14 D: Site C6 allometric relationship investigations between A) length-height (Isometric), B) length-width (Isometric), C) height –width (Isometric) and D) length –weight (Isometric).



Appendix 14 E: Site C7 allometric relationship investigations between A) length-height (Negatively Allometric), B) length-width (Black – Isometric), C) height -width (Black – Isometric) and D) length –weight (Black – Negatively Allometric).



Appendix 14 F: Site C8 allometric relationship investigations between A) length-height (Isometric), B) length-width (Isometric), C) height –width (Isometric) and D) length –weight (Negatively Allometric).

Appendices 14G to 14L include the raw biometric and morphological data used in Chapter 5.

Appendix 14G: Biometric and morphological data for site C1

ID	Whole Shell Wet Wt.(g)	Soft Tissue Wt.(g)	Wet Empty Shell Wt.(g)	Dry Wt.(both shells) (g)	Dry Wt.(g)	Ht. (mm)	Length (mm)	Single shell Width (mm)	Actual Width (mm)	Log10 Whole Shell Wet Wt.(g)	Log10 Soft Tissue Wt.(g)	Log10 Wet Empty Shell Wt.(g)	Log10 Dry Wt. (both shells) (g)	Log10 Dry Wt.(g)	Log10 Ht. (mm)	Log10 Length (mm)	Log10 Width (mm)
C1L1a	182.17	45.85	89.37	87.21	43.60	79.07		24.70	49.40	2.26	1.66	1.95	1.94	1.64	1.90		1.69
C1L2a	221.71	53.35	120.33	119.71	59.86	86.29		24.80	49.60	2.35	1.73	2.08	2.08	1.78	1.94		1.70
C1L3a	133.08	43.48	64.57			79.00				2.12	1.64	1.81			1.90		
C1L4a	258.07	57.86	144.85	136.80	68.40	85.25		25.70	51.40	2.41	1.76	2.16	2.14	1.84	1.93		1.71
C1L5a	198.64	56.58	97.38	93.56	46.78	87.39		20.40	40.80	2.30	1.75	1.99	1.97	1.67	1.94		1.61
C1L6a	221.88	52.62	109.76	106.47	53.24	85.47	89.40	31.60	63.20	2.35	1.72	2.04	2.03	1.73	1.93	1.95	1.80
C1L7a	191.71	51.82	100.06	98.19	49.09	79.56	86.80	26.10	52.20	2.28	1.71	2.00	1.99	1.69	1.90	1.94	1.72
C1L8a	191.52	58.02	98.43	95.98	47.99	82.04	84.70	26.70	53.40	2.28	1.76	1.99	1.98	1.68	1.91		1.73
C1L9a	214.94	60.19	107.84	103.98	51.99	88.74	89.20	25.40	50.80	2.33	1.78	2.03	2.02	1.72	1.95	1.95	1.71
C1L10a	189.05	52.64	98.43	91.20	45.60	80.00	81.10	21.70	43.40	2.28	1.72	1.99	1.96	1.66	1.90	1.91	1.64
C1L11a	265.97	69.82	136.23	126.97	63.49	93.00				2.42	1.84	2.13	2.10	1.80	1.97		
C1L12a	223.79	60.47	121.93	115.83	57.92	93.00		22.90	45.80	2.35	1.78	2.09	2.06	1.76	1.97		1.66
C1L13a	232.05	60.30	110.85	105.04	52.52	92.00		21.00	42.00	2.37	1.78	2.04	2.02	1.72	1.96		1.62
C1L14a	219.60	63.35	112.76	111.99	56.00	85.76	80.00	26.20	52.40	2.34	1.80	2.05	2.05	1.75	1.93	1.90	1.72
C1L15a	138.42	39.25	80.54	79.31	39.65	79.39	82.80	19.20	38.40	2.14	1.59	1.91	1.90	1.60	1.90	1.92	1.58
C1L16a	188.23	47.38	108.60	106.91	53.46	78.35	89.40	29.30	58.60	2.27	1.68	2.04	2.03	1.73	1.89	1.95	1.77
C1L17a	198.12	53.48	102.13	100.32	50.16	84.62		24.10	48.20	2.30	1.73	2.01	2.00	1.70	1.93		1.68
C1L18a	215.31	60.03	91.25	90.69	45.34	89.86	86.90	23.00	46.00	2.33	1.78	1.96	1.96	1.66	1.95	1.94	1.66
C1L19a	172.59	45.64	99.06	97.08	48.54	82.16	90.00	25.90	51.80	2.24	1.66	2.00	1.99	1.69	1.91	1.95	1.71
C1L20a	280.48	73.49	152.76	147.64	73.82	101.00		20.70	41.40	2.45	1.87	2.18	2.17	1.87	2.00		1.62

Appendix 14H: Biometric and morphological data for site C2

ID	Whole Shell Wet Wt.(g)	Soft Tissue Wt.(g)	Wet Empty Shell Wt.(g)	Dry Wt.(both shells) (g)	Dry Wt.(g)	Ht. (mm)	Length (mm)	Single shell Width (mm)	Actual Width (mm)	Log10 Whole Shell Wet Wt.(g)	Log10 Soft Tissue Wt.(g)	Log10 Wet Empty Shell Wt.(g)	Log10 Dry Wt. (both shells) (g)	Log10 Dry Wt.(g)	Log10 Ht. (mm)	Log10 Length (mm)	Log10 Width (mm)
C2-L1a	215.34	59.47	155.87	147.49	73.75	96.20	98.20	21.80	43.60	2.33	1.77	2.19	2.17	1.87	1.98	1.99	1.64
C2-L2a	257.70	73.41	184.29	173.70	86.85	100.50	100.00	27.90	55.80	2.41	1.87	2.27	2.24	1.94	2.00	2.00	1.75
C2-L3a	184.31	54.62	129.69	125.97	62.99	89.90	95.90	28.70	57.40	2.27	1.74	2.11	2.10	1.80	1.95	1.98	1.76
C2-L5a	233.74	61.41	172.33	165.91	82.96	97.40	103.70	33.90	67.80	2.37	1.79	2.24	2.22	1.92	1.99	2.02	1.83
C2-L8a	186.29	44.12	142.17	136.80	68.40	87.80	92.00	25.20	50.40	2.27	1.64	2.15	2.14	1.84	1.94	1.96	1.70
C2-L9a	211.78	55.29	156.49	148.82	74.41	90.20	95.40	26.80	53.60	2.33	1.74	2.19	2.17	1.87	1.96	1.98	1.73
C2-L10a	186.11	52.00	134.11	128.19	64.10	91.90	92.00	22.40	44.80	2.27	1.72	2.13	2.11	1.81	1.96	1.96	1.65
C2-L11a	196.03	48.63	147.40	142.47	71.23	93.50	97.60	25.10	50.20	2.29	1.69	2.17	2.15	1.85	1.97	1.99	1.70
C2-L12a	172.99	41.24	131.75	124.05	62.02	87.40	89.90	29.80	59.60	2.24	1.62	2.12	2.09	1.79	1.94	1.95	1.78
C2-L14a	163.14	42.95	120.20	114.98	57.49	89.90	92.60	24.70	49.40	2.21	1.63	2.08	2.06	1.76	1.95	1.97	1.69
C2-L15a	172.20	44.97	127.23	121.07	60.53	98.10	91.80	24.60	49.20	2.24	1.65	2.10	2.08	1.78	1.99	1.96	1.69
C2-L16a	187.64	53.14	134.50	130.11	65.06	94.90	92.80	25.40	50.80	2.27	1.73	2.13	2.11	1.81	1.98	1.97	1.71
C2-L17a	188.14	44.62	143.51	135.96	67.98	89.30	93.80	22.70	45.40	2.27	1.65	2.16	2.13	1.83	1.95	1.97	1.66
C2-L18a	191.46	45.82	145.64	138.77	69.39	92.40	96.80	26.70	53.40	2.28	1.66	2.16	2.14	1.84	1.97	1.99	1.73
C2-L19a	193.08	54.85	138.23	133.51	66.75	92.20	94.30	28.70	57.40	2.29	1.74	2.14	2.13	1.82	1.96	1.97	1.76
C2-L20a	148.25	40.62	107.63	120.03	60.02	86.30	89.50	29.20	58.40	2.17	1.61	2.03	2.08	1.78	1.94	1.95	1.77
C2-L21a	195.34	48.47	146.86	141.16	70.58	89.70	96.20	25.40	50.80	2.29	1.69	2.17	2.15	1.85	1.95	1.98	1.71
C2-L22a	180.86	53.10	127.77	121.88	60.94	86.30	94.20	23.10	46.20	2.26	1.73	2.11	2.09	1.78	1.94	1.97	1.66
C2-L23a	197.71	54.16	143.56	135.75	67.88	90.80	92.40	28.30	56.60	2.30	1.73	2.16	2.13	1.83	1.96	1.97	1.75
C2-L24a	164.82	46.06	118.76	113.76	56.88	84.30	84.70	25.40	50.80	2.22	1.66	2.07	2.06	1.75	1.93	1.93	1.71
C2-L25a	172.29	40.46	131.83	129.86	64.93	83.30	89.50	27.30	54.60	2.24	1.61	2.12	2.11	1.81	1.92	1.95	1.74
C2-L26a	179.85	49.31	130.53	142.57	71.28	92.40	95.50	25.30	50.60	2.25	1.69	2.12	2.15	1.85	1.97	1.98	1.70
C2-L27a	189.64	49.31	140.32	135.54	67.77	85.30	90.90	27.40	54.80	2.28	1.69	2.15	2.13	1.83	1.93	1.96	1.74
C2-L28a	185.79	51.29	134.51	128.80	64.40	94.60	99.00	26.80	53.60	2.27	1.71	2.13	2.11	1.81	1.98	2.00	1.73
C2-L29a	150.88	38.07	112.81	108.57	54.28	87.00	94.40	23.60	47.20	2.18	1.58	2.05	2.04	1.73	1.94	1.97	1.67
C2-L30a	176.07	41.83	134.24	140.23	70.12	90.40	96.60	28.00	56.00	2.25	1.62	2.13	2.15	1.85	1.96	1.98	1.75
C2-L32a	143.19	41.82	101.37	97.96	48.98	85.20	87.90	27.50	55.00	2.16	1.62	2.01	1.99	1.69	1.93	1.94	1.74
C2-L33a	195.80	54.89	140.91	136.05	68.03	88.70	91.60	24.40	48.80	2.29	1.74	2.15	2.13	1.83	1.95	1.96	1.69
C2-L34a	121.59	41.02	80.56	77.08	38.54	81.50	83.50	25.10	50.20	2.08	1.61	1.91	1.89	1.59	1.91	1.92	1.70
C2-L35a	185.93	52.49	133.44	128.40	64.20	92.50	96.60	30.10	60.20	2.27	1.72	2.13	2.11	1.81	1.97	1.98	1.78
C2-L36a	200.99	57.09	143.90	140.67	70.33	93.10	95.50	25.40	50.80	2.30	1.76	2.16	2.15	1.85	1.97	1.98	1.71
C2-L37a	157.86	36.94	120.92	114.73	57.37	84.50	87.00	25.50	51.00	2.20	1.57	2.08	2.06	1.76	1.93	1.94	1.71
C2-L38a	161.87	38.54	123.33	117.52	58.76	85.40	88.40	35.40	70.80	2.21	1.59	2.09	2.07	1.77	1.93	1.95	1.85
C2-L39a	210.93	48.75	162.18	157.64	78.82	94.80	97.30	27.90	55.80	2.32	1.69	2.21	2.20	1.90	1.98	1.99	1.75
C2-L40a	155.13	41.62	113.52	109.98	54.99	90.20	93.80	26.70	53.40	2.19	1.62	2.06	2.04	1.74	1.96	1.97	1.73
C2-L41A	231.69	63.94	167.75	116.37	58.19	86.00	90.20	26.60	53.20	2.36	1.81	2.22	2.07	1.76	1.93	1.96	1.73
C2-L42A	2213.88	50.80	2163.08	113.30	56.65	83.10	86.90	26.00	52.00	3.35	1.71	3.34	2.05	1.75	1.92	1.94	1.72
C2-L47A	245.79	50.73		125.35	62.67	87.40	97.20	26.70	53.40	2.39	1.71		2.10	1.80	1.94	1.99	1.73
C2-L48A	248.99	76.65	172.34	125.28	62.64	87.00	92.20	22.40	44.80	2.40	1.88	2.24	2.10	1.80	1.94	1.96	1.65

Appendix 14I: Biometric and morphological data for site C4

ID	Whole Shell Wet Wt.(g)	Soft Tissue Wt.(g)	Wet Empty Shell Wt.(g)	Dry Wt.(both shells) (g)	Dry Wt.(g)	Ht. (mm)	Length (mm)	Single shell Width (mm)	Actual Width (mm)	Log10 Whole Shell Wet Wt.(g)	Log10 Soft Tissue Wt.(g)	Log10 Wet Empty Shell Wt.(g)	Log10 Dry Wt. (both shells) (g)	Log10 Dry Wt.(g)	Log10 Ht. (mm)	Log10 Length (mm)	Log10 Width (mm)
C4 L 5a	190.04	41.59	101.42	94.81	47.41	77.90	83.40	25.60	51.20	2.28	1.62	2.01	1.98	1.68	1.89	1.92	1.71
C4 L 6a	97.78	30.29	60.59	62.84	31.42	75.00	81.30	21.70	43.40	1.99	1.48	1.78	1.80	1.50	1.88	1.91	1.64
C4 L 7a	85.70	31.11	49.39	57.21	28.61	73.10	77.20	26.20	52.40	1.93	1.49	1.69	1.76	1.46	1.86	1.89	1.72
C4 L 8a	148.79	35.45	68.42	57.89	28.95	75.40	78.90	23.90	47.80	2.17	1.55	1.84	1.76	1.46	1.88	1.90	1.68
C4 L 9a	129.12	32.92	54.99	47.89	23.95	72.20	75.30	24.80	49.60	2.11	1.52	1.74	1.68	1.38	1.86	1.88	1.70
C4 L 10a	128.35	30.06	63.25	56.93	28.47	75.00	78.30	22.60	45.20	2.11	1.48	1.80	1.76	1.45	1.88	1.89	1.66
C4 L 11a	142.27	40.83	94.95	88.60	44.30	79.10	81.20	23.30	46.60	2.15	1.61	1.98	1.95	1.65	1.90	1.91	1.67
C4 L 12a	108.07	36.67	66.85	62.31	31.15	75.00	79.10	22.10	44.20	2.03	1.56	1.83	1.79	1.49	1.88	1.90	1.65
C4 L 13a	93.02	29.09	62.74	56.23	28.12	71.00	78.50	22.40	44.80	1.97	1.46	1.80	1.75	1.45	1.85	1.89	1.65
C4 L 14a	106.56	40.46	63.79	56.63	28.31	75.80	77.90	22.60	45.20	2.03	1.61	1.80	1.75	1.45	1.88	1.89	1.66
C4 L 15a	140.23	44.37	93.94	87.24	43.62	77.50	90.90	29.40	58.80	2.15	1.65	1.97	1.94	1.64	1.89	1.96	1.77
C4 L 16a	124.80	41.26	55.45	49.97	24.98	71.50	74.10	24.80	49.60	2.10	1.62	1.74	1.70	1.40	1.85	1.87	1.70
C4 L 17a	122.62	35.92	86.70	77.69	38.85	78.70	87.90	27.90	55.80	2.09	1.56	1.94	1.89	1.59	1.90	1.94	1.75
C4 L 18a	168.46	16.78	28.58	36.20	18.10	60.70	63.90	19.00	38.00	2.23	1.22	1.46	1.56	1.26	1.78	1.81	1.58
C4 L 19a	168.46	34.46	87.06	78.78	39.39	73.10	77.40	23.20	46.40	2.23	1.54	1.94	1.90	1.60	1.86	1.89	1.67
C4 L 20a	168.46	29.50	76.99	76.91	38.46	78.00	83.00	30.00	60.00	2.23	1.47	1.89	1.89	1.58	1.89	1.92	1.78
C4 L 21a	164.09	33.87	68.62	71.51	35.76	75.90	79.30	27.40	54.80	2.22	1.53	1.84	1.85	1.55	1.88	1.90	1.74
C4 L 22a	131.25	30.20	76.99	65.89	32.94	72.40	76.90	25.40	50.80	2.12	1.48	1.89	1.82	1.52	1.86	1.89	1.71
C4 L 23a	153.59	34.24	71.47	62.66	31.33	75.10	79.50	23.90	47.80	2.19	1.53	1.85	1.80	1.50	1.88	1.90	1.68
C4 L 25a	113.63	30.69	54.64	49.39	24.70	67.80	71.00	15.00	30.00	2.06	1.49	1.74	1.69	1.39	1.83	1.85	1.48
C4 L 26a	56.61	13.34	28.55	25.73	12.86	54.30	61.00	18.00	36.00	1.75	1.12	1.46	1.41	1.11	1.73	1.79	1.56
C4 L 27a	105.76	28.78	56.05	53.38	26.69	71.90	77.90	19.40	38.80	2.02	1.46	1.75	1.73	1.43	1.86	1.89	1.59
C4 L 30a	134.30	42.43	65.60	58.76	29.38	71.60	75.10	19.30	38.60	2.13	1.63	1.82	1.77	1.47	1.85	1.88	1.59
C4 L 32a	71.87	21.73	36.42	33.37	16.69	58.20	61.00	16.30	32.60	1.86	1.34	1.56	1.52	1.22	1.76	1.79	1.51
C4 L 33a	110.37	22.02	55.21	51.04	25.52	67.10	69.60	23.40	46.80	2.04	1.34	1.74	1.71	1.41	1.83	1.84	1.67
C4 L 34a	144.94	56.52	60.88	56.85	28.42	72.10	79.40	25.60	51.20	2.16	1.75	1.78	1.75	1.45	1.86	1.90	1.71
C4 L36a	133.67	40.10	68.90	60.86	30.43	73.40	74.80	23.20	46.40	2.13	1.60	1.84	1.78	1.48	1.87	1.87	1.67
C4 L 41a	176.91	44.36	89.76	80.04	40.02	80.20	83.80	23.90	47.80	2.25	1.65	1.95	1.90	1.60	1.90	1.92	1.68
C4 L 43a	133.93	36.35	69.09	61.71	30.86	72.10	82.40	25.50	51.00	2.13	1.56	1.84	1.79	1.49	1.86	1.92	1.71
C4 L 44a	135.17	45.38	69.47	63.99	32.00	73.00	76.10	17.70	35.40	2.13	1.66	1.84	1.81	1.51	1.86	1.88	1.55
C4 L 45a	118.11	33.23	58.86	52.49	26.25	68.20	71.40	22.40	44.80	2.07	1.52	1.77	1.72	1.42	1.83	1.85	1.65
C4 L107	138.06	37.98	100.08	86.37	43.19	80.10	84.00	26.20	52.40	2.14	1.58	2.00	1.94	1.64	1.90	1.92	1.72
C4 L113	45.54	15.95	29.59	23.73	11.87	50.20	55.90	16.30	32.60	1.66	1.20	1.47	1.38	1.07	1.70	1.75	1.51
C4 L68	107.14	33.24	73.89	66.07	33.03	70.10	75.80	28.00	56.00	2.03	1.52	1.87	1.82	1.52	1.85	1.88	1.75
C4 L111	126.28	41.54	84.74	69.59	34.80	70.80	84.30	26.10	52.20	2.10	1.62	1.93	1.84	1.54	1.85	1.93	1.72
C4 L114	100.99	24.55	76.44	65.52	32.76	70.10	75.90	23.40	46.80	2.00	1.39	1.88	1.82	1.52	1.85	1.88	1.67
C4 L83	50.85	17.14	33.71	29.22	14.61	50.70	60.60	17.90	35.80	1.71	1.23	1.53	1.47	1.16	1.71	1.78	1.55
C4 L106	40.01	14.24	25.77	21.25	10.63	50.20	57.70	14.30	28.60	1.60	1.15	1.41	1.33	1.03	1.70	1.76	1.46
C4 L81	144.74	35.01	109.73	61.15	30.57	70.70	76.30	27.30	54.60	2.16	1.54	2.04	1.79	1.49	1.85	1.88	1.74

C4 L110	47.77	15.82	31.95	25.77	12.89	50.20	58.90	18.30	36.60	1.68	1.20	1.50	1.41	1.11	1.70	1.77	1.56
C4 L108	114.73	33.63	81.10	69.21	34.60	70.40	79.60	26.30	52.60	2.06	1.53	1.91	1.84	1.54	1.85	1.90	1.72
C4 L78	130.85	39.48	91.36	72.86	36.43	80.10	85.00	23.50	47.00	2.12	1.60	1.96	1.86	1.56	1.90	1.93	1.67
C4 L102	58.51	17.50	41.02	34.59	17.30	60.00	66.10	18.30	36.60	1.77	1.24	1.61	1.54	1.24	1.78	1.82	1.56
C4 L77	42.58	15.54	27.04	23.20	11.60	40.90	52.10	16.90	33.80	1.63	1.19	1.43	1.37	1.06	1.61	1.72	1.53

Appendix 14J: Biometric and morphological data for site C6

ID	Whole Shell Wet Wt.(g)	Soft Tissue Wt.(g)	Wet Empty Shell Wt.(g)	Dry Wt.(both shells) (g)	Dry Wt.(g)	Ht. (mm)	Length (mm)	Single shell Width (mm)	Actual Width (mm)	Log10 Whole Shell Wet Wt.(g)	Log10 Soft Tissue Wt.(g)	Log10 Wet Empty Shell Wt.(g)	Log10 Dry Wt. (both shells) (g)	Log10 Dry Wt.(g)	Log10 Ht. (mm)	Log10 Length (mm)	Log10 Width (mm)
C6L10a	173.75	135.42	38.33	128.07	64.04	87.20	93.30	26.90	53.80	2.24	2.13	1.58	2.11	1.81	1.94	1.97	1.73
C6L113	191.10	61.69	129.42	116.28	58.14	80.90	95.40	22.80	45.60	2.28	1.79	2.11	2.07	1.76	1.91	1.98	1.66
C6L11a	218.30	171.04	47.25	159.97	79.99	92.40	97.80	31.10	62.20	2.34	2.23	1.67	2.20	1.90	1.97	1.99	1.79
C6L12a	115.91	82.91	33.00	78.20	39.10	83.10	87.90	24.20	48.40	2.06	1.92	1.52	1.89	1.59	1.92	1.94	1.68
C6L17a	130.34	100.19	30.14	97.01	48.51	85.40	88.70	26.10	52.20	2.12	2.00	1.48	1.99	1.69	1.93	1.95	1.72
C6L18a	180.98	50.50	130.48	116.29	58.14	90.50	94.00	30.80	61.60	2.26	1.70	2.12	2.07	1.76	1.96	1.97	1.79
C6L19a	194.20	63.36	130.84	179.40	89.70	89.70	96.00	25.30	50.60	2.29	1.80	2.12	2.25	1.95	1.95	1.98	1.70
C6L3a	233.36	46.75	147.15	134.07	67.04	89.40	69.70	21.20	42.40	2.37	1.67	2.17	2.13	1.83	1.95	1.84	1.63
C6L4a	174.10	57.02	117.08	105.33	52.67	85.60	87.50	25.40	50.80	2.24	1.76	2.07	2.02	1.72	1.93	1.94	1.71
C6L51A	253.98	97.30	156.67	138.76	69.38	98.50	104.30	27.40	54.80	2.40	1.99	2.19	2.14	1.84	1.99	2.02	1.74
C6L52A	181.92	46.44	135.47	123.77	61.89	89.50	93.90	28.10	56.20	2.26	1.67	2.13	2.09	1.79	1.95	1.97	1.75
C6L53A	216.08	80.63	135.45	120.95	60.48	86.60	90.70	25.70	51.40	2.33	1.91	2.13	2.08	1.78	1.94	1.96	1.71
C6L54A	202.62	58.04	144.59	134.44	67.22	89.10	93.20	25.10	50.20	2.31	1.76	2.16	2.13	1.83	1.95	1.97	1.70
C6L55A	140.72	41.35	99.37	91.31	45.66	78.40	84.10	20.90	41.80	2.15	1.62	2.00	1.96	1.66	1.89	1.92	1.62
C6L57A	172.84	59.73	113.11	102.68	51.34	84.50	91.40	26.10	52.20	2.24	1.78	2.05	2.01	1.71	1.93	1.96	1.72
C6L5a	109.90	49.35	60.55	57.16	28.58	69.10	70.40	20.20	40.40	2.04	1.69	1.78	1.76	1.46	1.84	1.85	1.61
C6L60A	211.14	66.85	144.29	124.99	62.50	84.40	89.80	19.90	39.80	2.32	1.83	2.16	2.10	1.80	1.93	1.95	1.60
C6L63A	113.67	35.64	78.03	72.13	36.07	74.60	82.40	21.90	43.80	2.06	1.55	1.89	1.86	1.56	1.87	1.92	1.64
C6L65A	77.24	28.12	49.12	44.78	22.39	66.10	72.50	15.00	30.00	1.89	1.45	1.69	1.65	1.35	1.82	1.86	1.48
C6L66A	51.11	22.78	28.33	25.65	12.83	52.40	57.50	16.30	32.60	1.71	1.36	1.45	1.41	1.11	1.72	1.76	1.51
C6L68A	95.76	37.64	58.12	52.77	26.39	67.80	71.40	26.30	52.60	1.98	1.58	1.76	1.72	1.42	1.83	1.85	1.72
C6L6a	218.95	65.32	153.63	41.61	20.81	57.60	63.00	22.40	44.80	2.34	1.82	2.19	1.62	1.32	1.76	1.80	1.65
C6L70A	169.00	50.03	118.97	107.62	53.81	85.50	88.20	26.30	52.60	2.23	1.70	2.08	2.03	1.73	1.93	1.95	1.72
C6L75A	120.15	52.82	67.33	62.28	31.14	73.20	75.50	26.90	53.80	2.08	1.72	1.83	1.79	1.49	1.86	1.88	1.73
C6L7a	184.22	136.41	47.81	126.21	63.11	92.10	95.20	33.70	67.40	2.27	2.13	1.68	2.10	1.80	1.96	1.98	1.83
C6L83A	102.82	44.88	57.94	54.09	27.05	69.30	75.80	22.30	44.60	2.01	1.65	1.76	1.73	1.43	1.84	1.88	1.65
C6L85A	16.01	8.62	7.38	6.74	3.37	32.20	37.70	11.40	22.80	1.20	0.94	0.87	0.83	0.53	1.51	1.58	1.36
C6L8a	63.79	49.24	14.55	47.20	23.60	58.10	64.40	19.70	39.40	1.80	1.69	1.16	1.67	1.37	1.76	1.81	1.60
C6 L102	204.82	62.77	142.05	163.24	81.62	90.50	100.00	28.50	57.00	2.31	1.80	2.15	2.21	1.91	1.96	2.00	1.76
C6 L103	174.44	56.79	117.65	103.82	51.91	80.40	95.00	23.60	47.20	2.24	1.75	2.07	2.02	1.72	1.91	1.98	1.67
C6 L105	235.48	69.71	165.77	180.40	90.20	74.50	93.40	31.20	62.40	2.37	1.84	2.22	2.26	1.96	1.87	1.97	1.80
C6 L106	260.58	85.34	175.24	161.49	80.74	90.30	97.40	27.20	54.40	2.42	1.93	2.24	2.21	1.91	1.96	1.99	1.74

C6 L107	169.38	52.95	116.43	108.00	54.00	80.10	86.80	26.30	52.60	2.23	1.72	2.07	2.03	1.73	1.90	1.94	1.72
C6 L110	203.94	53.46	150.47	133.74	66.87	80.80	94.40	22.70	45.40	2.31	1.73	2.18	2.13	1.83	1.91	1.97	1.66
C6 L111	211.66	62.59	149.07	125.49	62.75	80.80	98.40	33.90	67.80	2.33	1.80	2.17	2.10	1.80	1.91	1.99	1.83
C6 L112	217.67	52.87	164.80	138.93	69.47	80.40	91.30	26.40	52.80	2.34	1.72	2.22	2.14	1.84	1.91	1.96	1.72
C6 L114	190.75	57.35	133.40	123.69	61.84	80.00	90.00	32.80	65.60	2.28	1.76	2.13	2.09	1.79	1.90	1.95	1.82
C6 L115	186.01	61.06	124.95	102.15	51.07	80.50	94.30	23.50	47.00	2.27	1.79	2.10	2.01	1.71	1.91	1.97	1.67
C6 L116	200.65	64.66	135.99	122.19	61.09	80.80	97.20	37.90	75.80	2.30	1.81	2.13	2.09	1.79	1.91	1.99	1.88
C6 L118	213.66	62.19	151.47	136.89	68.45	80.80	98.00	31.50	63.00	2.33	1.79	2.18	2.14	1.84	1.91	1.99	1.80
C6 L120	227.59	64.40	163.19	143.74	71.87	90.40	94.60	26.60	53.20	2.36	1.81	2.21	2.16	1.86	1.96	1.98	1.73
C6 L80	177.11	57.48	119.63	108.57	54.29	80.70	94.30	35.40	70.80	2.25	1.76	2.08	2.04	1.73	1.91	1.97	1.85
C6 L92	121.15	30.45	90.71	84.90	42.45	70.90	81.60	28.90	57.80	2.08	1.48	1.96	1.93	1.63	1.85	1.91	1.76
C6 L98	206.14	61.24	144.90	118.55	59.27	90.00	98.40	26.10	52.20	2.31	1.79	2.16	2.07	1.77	1.95	1.99	1.72
C6 L99	184.03	53.01	131.02	121.06	60.53	80.50	91.30	28.40	56.80	2.26	1.72	2.12	2.08	1.78	1.91	1.96	1.75

Appendix 14K: Biometric and morphological data for site C7

ID	Whole Shell Wet Wt.(g)	Soft Tissue Wt.(g)	Wet Empty Shell Wt.(g)	Dry Wt.(both shells) (g)	Dry Wt.(g)	Ht. (mm)	Length (mm)	Single shell Width (mm)	Actual Width (mm)	Log10 Whole Shell Wet Wt.(g)	Log10 Soft Tissue Wt.(g)	Log10 Wet Empty Shell Wt.(g)	Log10 Dry Wt. (both shells) (g)	Log10 Dry Wt.(g)	Log10 Ht. (mm)	Log10 Length (mm)	Log10 Width (mm)
C7L10	84.29	19.26	65.03	46.01	23.01	66.90	70.90	14.00	28.00	1.93	1.28	1.81	1.66	1.36	1.83	1.85	1.45
C7L17	79.60	32.66	46.93	43.03	21.52	23.40	23.40	19.40	38.80	1.90	1.51	1.67	1.63	1.33	1.37	1.37	1.59
C7L136	67.33	23.93	43.41	41.40	20.70	66.80	48.50	16.40	32.80	1.83	1.38	1.64	1.62	1.32	1.82	1.69	1.52
C7L120	18.52	4.88	13.64	13.06	6.53	43.10	48.90	13.00	26.00	1.27	0.69	1.13	1.12	0.81	1.63	1.69	1.41
C7L119	37.55	12.23	25.33	24.66	12.33	50.00	55.60	14.60	29.20	1.57	1.09	1.40	1.39	1.09	1.70	1.75	1.47
C7L98	33.11	8.90	24.21	22.67	11.34	54.50	57.90	17.30	34.60	1.52	0.95	1.38	1.36	1.05	1.74	1.76	1.54
C7L110	36.88	11.59	25.30	24.09	12.04	56.10	58.90	23.90	47.80	1.57	1.06	1.40	1.38	1.08	1.75	1.77	1.68
C7L66	68.37	28.80	39.57	32.38	16.19	55.70	59.90	18.70	37.40	1.83	1.46	1.60	1.51	1.21	1.75	1.78	1.57
C7L83	40.29	15.53	24.76	23.18	11.59	56.60	61.70	16.60	33.20	1.61	1.19	1.39	1.37	1.06	1.75	1.79	1.52
C7L134	48.80	17.23	31.57	29.83	14.92	56.60	61.90	16.90	33.80	1.69	1.24	1.50	1.47	1.17	1.75	1.79	1.53
C7L3	60.65	17.64	43.01	32.72	16.36	57.00	62.10	17.10	34.20	1.78	1.25	1.63	1.51	1.21	1.76	1.79	1.53
C7L100	51.63	20.22	31.42	28.62	14.31	60.90	62.10	19.20	38.40	1.71	1.31	1.50	1.46	1.16	1.78	1.79	1.58
C7L14	69.70	3.79	65.91	28.86	14.43	58.80	62.90	21.90	43.80	1.84	0.58	1.82	1.46	1.16	1.77	1.80	1.64
C7L47	138.29	45.50	92.79	83.30	41.65	77.70	63.00	19.30	38.60	2.14	1.66	1.97	1.92	1.62	1.89	1.80	1.59
C7L113	52.19	20.84	31.35	29.04	14.52	57.10	63.10	17.40	34.80	1.72	1.32	1.50	1.46	1.16	1.76	1.80	1.54
C7L87	47.89	14.75	33.14	31.83	15.91	69.20	64.00	16.40	32.80	1.68	1.17	1.52	1.50	1.20	1.84	1.81	1.52
C7L81	56.17	26.66	29.51	42.37	21.18	66.50	64.50	16.50	33.00	1.75	1.43	1.47	1.63	1.33	1.82	1.81	1.52
C7L2	63.85	10.59	53.26	32.18	16.09	60.20	65.50	18.80	37.60	1.81	1.02	1.73	1.51	1.21	1.78	1.82	1.58
C7L106	69.07	27.31	41.76	38.92	19.46	69.90	66.00	20.40	40.80	1.84	1.44	1.62	1.59	1.29	1.84	1.82	1.61
C7L76	53.98	19.00	34.98	32.48	16.24	62.20	66.40	17.40	34.80	1.73	1.28	1.54	1.51	1.21	1.79	1.82	1.54
C7L73	71.75	28.20	43.55	35.18	17.59	63.25	67.50	20.00	40.00	1.86	1.45	1.64	1.55	1.25	1.80	1.83	1.60
C7L137	63.29	29.86	33.43	31.87	15.93	60.20	67.50	16.20	32.40	1.80	1.48	1.52	1.50	1.20	1.78	1.83	1.51
C7L70	62.10	17.56	44.54	42.23	21.12	60.90	68.00	22.60	45.20	1.79	1.24	1.65	1.63	1.32	1.78	1.83	1.66
C7L42	83.29	17.99	65.31	31.40	15.70	59.80	68.10	18.20	36.40	1.92	1.25	1.81	1.50	1.20	1.78	1.83	1.56

C7L95	92.93	44.05	48.87	45.81	22.91	67.80	68.70	18.80	37.60	1.97	1.64	1.69	1.66	1.36	1.83	1.84	1.58
C7L72	88.25	38.10	50.15	40.78	20.39	67.50	70.50	14.40	28.80	1.95	1.58	1.70	1.61	1.31	1.83	1.85	1.46
C7L94	72.97	26.09	46.89	35.31	17.66	66.40	70.70	25.40	50.80	1.86	1.42	1.67	1.55	1.25	1.82	1.85	1.71
C7L74	92.92	12.52	80.40	33.21	16.60	61.90	71.40	23.40	46.80	1.97	1.10	1.91	1.52	1.22	1.79	1.85	1.67
C7L61	92.32	29.12	63.19	60.23	30.12	70.00	71.70	17.90	35.80	1.97	1.46	1.80	1.78	1.48	1.85	1.86	1.55
C7L31	77.12	25.07	52.05	47.97	23.98	67.90	71.80	22.60	45.20	1.89	1.40	1.72	1.68	1.38	1.83	1.86	1.66
C7L102	73.47	31.84	41.63	37.53	18.77	65.30	72.00	20.40	40.80	1.87	1.50	1.62	1.57	1.27	1.81	1.86	1.61
C7L135	72.19	28.16	44.03	41.32	20.66	67.00	72.00	22.90	45.80	1.86	1.45	1.64	1.62	1.32	1.83	1.86	1.66
C7L121	73.21	19.77	53.44	49.95	24.97	67.30	72.50	23.40	46.80	1.86	1.30	1.73	1.70	1.40	1.83	1.86	1.67
C7L97	83.86	37.81	46.06	42.59	21.29	66.00	72.80	21.10	42.20	1.92	1.58	1.66	1.63	1.33	1.82	1.86	1.63
C7L45	116.17	22.65	93.53	47.00	23.50	68.80	73.40	16.30	32.60	2.07	1.36	1.97	1.67	1.37	1.84	1.87	1.51
C7L112	105.51	45.72	59.78	54.50	27.25	71.20	73.40	26.40	52.80	2.02	1.66	1.78	1.74	1.44	1.85	1.87	1.72
C7L96	53.34	14.44	38.91	36.46	18.23	57.80	74.10	17.90	35.80	1.73	1.16	1.59	1.56	1.26	1.76	1.87	1.55
C7L130	61.05	18.80	42.25	40.93	20.47	67.00	74.20	26.00	52.00	1.79	1.27	1.63	1.61	1.31	1.83	1.87	1.72
C7L52	69.54	21.74	47.80	43.88	21.94	70.00	74.50	23.60	47.20	1.84	1.34	1.68	1.64	1.34	1.85	1.87	1.67
C7L107	76.73	31.39	45.34	41.54	20.77	67.70	74.60	22.30	44.60	1.88	1.50	1.66	1.62	1.32	1.83	1.87	1.65
C7L93	83.44	34.72	48.72	51.07	25.53	70.10	74.70	22.10	44.20	1.92	1.54	1.69	1.71	1.41	1.85	1.87	1.65
C7L431a	73.23	21.19	52.04	49.57	24.79	67.70	74.80	23.20	46.40	1.86	1.33	1.72	1.70	1.39	1.83	1.87	1.67
C7L64	124.44	24.02	100.42	51.70	25.85	70.00	74.90	22.90	45.80	2.09	1.38	2.00	1.71	1.41	1.85	1.87	1.66
C7L89	91.16	37.67	53.48	48.52	24.26	67.10	75.10	28.40	56.80	1.96	1.58	1.73	1.69	1.38	1.83	1.88	1.75
C7L88	83.26	31.86	51.40	45.10	22.55	68.20	75.20	21.70	43.40	1.92	1.50	1.71	1.65	1.35	1.83	1.88	1.64
C7L90	93.54	33.24	60.30	54.73	27.37	73.10	76.80	25.50	51.00	1.97	1.52	1.78	1.74	1.44	1.86	1.89	1.71
C7L105	97.54	39.26	58.28	52.52	26.26	69.60	76.80	18.30	36.60	1.99	1.59	1.77	1.72	1.42	1.84	1.89	1.56
C7L56	86.34	26.93	59.41	54.14	27.07	73.40	77.10	19.90	39.80	1.94	1.43	1.77	1.73	1.43	1.87	1.89	1.60
C7L57	113.47	40.87	72.60	67.44	33.72	78.90	77.30	23.30	46.60	2.05	1.61	1.86	1.83	1.53	1.90	1.89	1.67
C7L13	101.81	19.88	81.93	55.19	27.60	70.80	77.70	22.20	44.40	2.01	1.30	1.91	1.74	1.44	1.85	1.89	1.65
C7L15	95.43	35.18	60.25	54.06	27.03	72.40	78.10	21.40	42.80	1.98	1.55	1.78	1.73	1.43	1.86	1.89	1.63
C7L4	119.19	24.41	94.77	58.53	29.27	70.05	78.20	16.00	32.00	2.08	1.39	1.98	1.77	1.47	1.85	1.89	1.51
C7L50	98.01	33.50	64.51	60.40	30.20	77.80	78.20	17.10	34.20	1.99	1.53	1.81	1.78	1.48	1.89	1.89	1.53
C7L54	96.43	33.81	62.62	56.48	28.24	71.20	79.00	22.90	45.80	1.98	1.53	1.80	1.75	1.45	1.85	1.90	1.66
C7L91	100.27	42.04	58.22	24.66	12.33	50.40	80.00	20.90	41.80	2.00	1.62	1.77	1.39	1.09	1.70	1.90	1.62
C7L11	126.72	30.97	95.75	63.92	31.96	74.80	80.10	24.00	48.00	2.10	1.49	1.98	1.81	1.50	1.87	1.90	1.68
C7L109	89.26	22.61	66.65	62.51	31.25	73.50	80.60	27.10	54.20	1.95	1.35	1.82	1.80	1.49	1.87	1.91	1.73
C7L26	85.07	29.39	55.68	80.72	40.36	78.50	81.00	24.20	48.40	1.93	1.47	1.75	1.91	1.61	1.89	1.91	1.68
C7L62	111.21	26.19	85.02	76.02	38.01	76.40	81.00	25.20	50.40	2.05	1.42	1.93	1.88	1.58	1.88	1.91	1.70
C7L65	98.38	34.07	64.31	57.74	28.87	76.70	81.80	22.30	44.60	1.99	1.53	1.81	1.76	1.46	1.88	1.91	1.65
C7L111	133.75	69.16	64.59	57.62	28.81	71.50	81.90	27.10	54.20	2.13	1.84	1.81	1.76	1.46	1.85	1.91	1.73
C7L5	124.66	28.76	95.90	63.90	31.95	76.90	82.30	18.50	37.00	2.10	1.46	1.98	1.81	1.50	1.89	1.92	1.57
C7L63	117.62	33.79	83.83	77.69	38.85	78.90	82.40	21.40	42.80	2.07	1.53	1.92	1.89	1.59	1.90	1.92	1.63
C7L108	118.90	33.06	85.84	28.14	14.07	81.30	82.40	19.90	39.80	2.08	1.52	1.93	1.45	1.15	1.91	1.92	1.60
C7L114	118.28	39.37	78.91	72.74	36.37	79.30	83.80	32.40	64.80	2.07	1.60	1.90	1.86	1.56	1.90	1.92	1.81
C7L122	77.99	22.61	55.38	52.50	26.25	69.70	83.80	23.80	47.60	1.89	1.35	1.74	1.72	1.42	1.84	1.92	1.68
C7L22	119.48	42.97	76.52	69.63	34.82	82.30	84.40	22.40	44.80	2.08	1.63	1.88	1.84	1.54	1.92	1.93	1.65
C7L103	108.30	38.12	70.18	63.40	31.70	81.00	84.60	20.40	40.80	2.03	1.58	1.85	1.80	1.50	1.91	1.93	1.61

Appendix 14L: Biometric and morphological data for site C8

ID	Whole Shell Wet Wt.(g)	Soft Tissue Wt.(g)	Wet Empty Shell Wt.(g)	Dry Wt.(both shells) (g)	Dry Wt.(g)	Ht. (mm)	Length (mm)	Single shell Width (mm)	Actual Width (mm)	Log10 Whole Shell Wet Wt.(g)	Log10 Soft Tissue Wt.(g)	Log10 Wet Empty Shell Wt.(g)	Log10 Dry Wt. (both shells) (g)	Log10 Dry Wt.(g)	Log10 Ht. (mm)	Log10 Length (mm)	Log10 Width (mm)
C8-L1a	252.72	62.56	190.15	186.25	93.13	96.40	97.00	33.20	66.40	2.40	1.80	2.28	2.27	1.97	1.98	1.99	1.82
C8-L2a	212.90	63.27	149.63	151.40	75.70	93.70	98.20	32.40	64.80	2.33	1.80	2.18	2.18	1.88	1.97	1.99	1.81
C8-L3a	198.49	48.16	150.34	145.68	72.84	89.80	90.40	27.80	55.60	2.30	1.68	2.18	2.16	1.86	1.95	1.96	1.75
C8-L4a	203.50	49.07	154.43	152.61	76.31	91.10	93.20	29.80	59.60	2.31	1.69	2.19	2.18	1.88	1.96	1.97	1.78
C8-L5a	198.20	49.29	148.91	143.67	71.84	89.80	94.00	29.30	58.60	2.30	1.69	2.17	2.16	1.86	1.95	1.97	1.77
C8-L6a	245.55	64.83	180.73	170.34	85.17	102.20	104.50	22.50	45.00	2.39	1.81	2.26	2.23	1.93	2.01	2.02	1.65
C8-L7a	183.81	43.38	140.43	136.52	68.26	86.80	85.60	31.10	62.20	2.26	1.64	2.15	2.14	1.83	1.94	1.93	1.79
C8-L8a	178.17	44.57	133.60	125.93	62.97	87.80	89.50	32.40	64.80	2.25	1.65	2.13	2.10	1.80	1.94	1.95	1.81
C8-L9a	256.68	70.04	186.64	181.16	90.58	96.70	104.10	32.80	65.60	2.41	1.85	2.27	2.26	1.96	1.99	2.02	1.82
C8-L10a	206.95	66.87	140.08	132.49	66.24	81.50	87.60	22.40	44.80	2.32	1.83	2.15	2.12	1.82	1.91	1.94	1.65
C8-L11a	197.57	61.03	136.54	136.83	68.42	92.10	93.80	28.30	56.60	2.30	1.79	2.14	2.14	1.84	1.96	1.97	1.75
C8-L13a	196.50	60.36	136.15	129.12	64.56	89.30	98.50	26.20	52.40	2.29	1.78	2.13	2.11	1.81	1.95	1.99	1.72
C8-L14a	190.48	59.14	131.34	122.94	61.47	88.00	90.00	33.00	66.00	2.28	1.77	2.12	2.09	1.79	1.94	1.95	1.82
C8-L15a	265.14	79.47	185.67	179.69	89.85	98.20	100.10	32.20	64.40	2.42	1.90	2.27	2.25	1.95	1.99	2.00	1.81
C8-L16a	254.43	70.44	183.99	173.30	86.65	99.50	100.00	27.30	54.60	2.41	1.85	2.26	2.24	1.94	2.00	2.00	1.74
C8-L17a	199.52	49.70	149.82	142.85	71.43	92.80	92.00	35.40	70.80	2.30	1.70	2.18	2.15	1.85	1.97	1.96	1.85
C8-L18a	222.74	56.58	166.17	107.76	53.88	84.60	90.10	31.10	62.20	2.35	1.75	2.22	2.03	1.73	1.93	1.95	1.79
C8-L19a	189.01	54.74	134.28	129.33	64.66	89.00	93.50	26.30	52.60	2.28	1.74	2.13	2.11	1.81	1.95	1.97	1.72
C8-L20a	207.26	66.33	140.93	135.66	67.83	96.20	98.70	31.90	63.80	2.32	1.82	2.15	2.13	1.83	1.98	1.99	1.80
C8L25A	287.81	115.71	172.10	143.44	71.72	93.80	101.50	33.60	67.20	2.46	2.06	2.24	2.16	1.86	1.97	2.01	1.83
C8x1A	211.15	66.85	144.30	115.42	57.71	89.40	99.00	32.10	64.20	2.32	1.83	2.16	2.06	1.76	1.95	2.00	1.81
C8x2A	197.79	50.03	147.76	102.77	51.38	81.40	83.40	23.20	46.40	2.30	1.70	2.17	2.01	1.71	1.91	1.92	1.67
C8x3A	262.33	65.37	196.96	119.72	59.86	87.70	94.10	27.10	54.20	2.42	1.82	2.29	2.08	1.78	1.94	1.97	1.73
C8x4A	305.05	71.18	233.87	151.16	75.58	88.80	93.00	28.10	56.20	2.48	1.85	2.37	2.18	1.88	1.95	1.97	1.75
C8x5A	326.54	82.56	243.97	166.54	83.27	94.00	98.60	32.40	64.80	2.51	1.92	2.39	2.22	1.92	1.97	1.99	1.81
C8x7A	341.60	79.58	262.02	165.37	82.69	97.50	99.30	27.20	54.40	2.53	1.90	2.42	2.22	1.92	1.99	2.00	1.74

Appendix 15: Age, height and weight data and normality tests for Chapters 4 and 5. These tests were run on the age, height and weight data analysed to determine what tests were appropriate for their statstical analysis.

Appendix 15A: Normality test results for data used for age cluster analysis

Site	Anderson-Darling value	p-value	Normally or non-normally distributed?	n-value
C1	0.250	0.227	Normally distributed	2
C2	1.318	<0.005	Non-normally distributed	7
C6	0.286	0.404	Normally distributed	4
C8	0.555	0.118	Normally distributed	12

Appendix 15B: Normality test results for age data

Site	Anderson-Darling value	p-value	Normally or non-normally distributed?
C1	0.482	0.196	Normally distributed
C2	1.540	<0.005	Non-normally distributed
C4	1.076	0.007	Non-normally distributed
C6	0.564	0.134	Normally distributed
C7	0.579	0.122	Normally distributed
C8	1.492	<0.005	Non-normally distributed

Appendix 15C: Normality test results for height data

Site	Anderson-Darling value	p-value	Normally or non-normally distributed?
C1	0.273	0.614	Normally distributed
C2	0.603	0.107	Normally distributed
C4	1.052	0.008	Non-normally distributed
C6	1.409	<0.005	Non-normally distributed
C7	0.364	0.420	Normally distributed
C8	0.417	0.310	Normally distributed

Appendix 15D: Normality test results for weight data

Site	Anderson-Darling value	p-value	Normally or non-normally distributed?
C1	0.616	0.088	Normally distributed
C2	0.293	0.575	Normally distributed
C4	0.340	0.480	Normally distributed
C6	1.019	0.010	Non-normally distributed
C7	0.585	0.117	Normally distributed
C8	0.212	0.838	Normally distributed

Appendix 15E: Specimen Age Data.

C1	Age	C2	Age	C4	Age	C6	Age	C7	Age	C8	Age
L1	90	L6	68	L1	106	L5	16	L3	65	L3	80
L2	94	L7	59	L4	99	L6	59	L6	100	L4	77
L4	164	L8	95	L5	101	L9	130	L14	23	L5	58
L5	62	L10	108	L7	133	L11	159	L16	141	L6	108
L6	108	L11	68	L8	132	L12	57	L47	25	L7	61
L9	101	L14	57	L9	142	L15	126	L48	73	L8	56
L10	105	L41	40	L10	99	L18	167	L56	87	L14	58
L12	124	L42	70	L11	158	L51	105	L61	185	L15	150
L13	110	L45	74	L13	116	L52	163	L62	172	L16	72
L14	121	L47	35	L17	131	L53	135	L66	56	L17	63
L15	113	L48	67	L18	30	L55	125	L67	109	L19	64
L16	107	L48 (2)	74	L19	109	L57	132	L58	122	L31	80
L17	86	L51	64	L20	119	L60	108	L77	117	L32	64
L19	63	L54	66	L22	124	L63	34	L83	28	L33	101
L20	102	L57	64	L32	23	L65	30	L10	123	x1	57
		L66	18	L33	62	L66	9	L110	31	x2	50
		L68	60	L36	99	L68	30	L119	35	x4	61
		L35	66	L41	118	L75	21	L120	23	x5	107
		L55	67	L43	100	L83	20	L12	116	x7	157

	L101(B)	65	L45	133	L85	7	L136	23	L34	149
	L76	69	L104	23	L99	121	L69	109	L59	131
	L43	125	L113	15	L104	183	L113	67	x10	55
	L3	40	L72	56	L118	98	L49	41	L27	66
	L22	59	L91	50	L98	59	L30	26	x3	96
	L34	77	L103	88	L103	88	L7	99	x11	165
	L53	61	L165	42	L111	147	L108	99	x8	113
	L33	59	L75	61	L80	87	L38	90	x19	90
	L46(2)	38	L80	25	L92	52	L103	140	L24	119
	L101(A)	40	L87	21	L97	202	L8	79	L29	149
	L102	63	L107	68	L107	121	L12	94	L30	64
	L104	135	L73	146	L112	186	L74	89		
	L69	56	L77	15	L113	164	L92	98		
			L2	94	L116	59	L95	76		
			L48	110	L71	29	L158	121		
			L81	72	L115	98				
			L102	19						
			L112	21						
			L114	116						

Appendix 15F: Normality tests for shell age, weight and height data for shells analysed in Chapter 5 for age-weight and age-height relationships

Site	**Age**			**Height**			**Weight**		
	p-value	Normally distributed?	n-value	p-value	Normally distributed?	n-value	p-value	Normally distributed?	n-value
C1	0.196	Yes	15	0.614	Yes	15	0.088	Yes	15
C2	<0.005	No	32	0.107	Yes	30	0.575	Yes	24
C4	<0.005	No	38	0.005	No	38	0.373	Yes	37
C6	0.083	Yes	35	<0.005	No	35	0.017	No	35
C7	0.122	Yes	34	0.420	Yes	34	0.117	Yes	33
C8	<0.005	No	30	0.310	Yes	30	0.838	Yes	25

Appendix 15G: Median and Quartile Deviation (QD) data for shells analysed in Chapter 5 for age-weight and age-height relationships

Site	**Age**		**Height**		**Weight**	
	Median	QD	Median	QD	Median	QD
C1	106.0	11.5	85.52	4.37	52.52	5.495
C2	64.5	6.125	87.8	3.31	62.66	5.725
C4	99.0	44	71.2	8.6	30.13	9.835
C6	98	50.75	80.5	5,72	54.08	13.845
C7	88	35.625	67.15	9.735	20.95	8.31
C8	78.5	26.75	89.6	6.3	71.34	9.255

Appendix 16: Raw isotope data for all shell samples run whether presented in the thesis or not

Appendix 16A: Data for shell C1-L2 (Daniels, 2010)

Sample ID	Calendar year assigned	True $\delta^{13}C$ value	Standard deviation	True $\delta^{18}O$ value	Standard deviation
2-1A	1905	1.20	0.08979	1.38	0.10323
2-1B	1906	1.38	0.06777	2.26	0.06119
2-2	1906	1.40	0.07251	1.85	0.04441
2-3	1907	1.70	0.07591	1.98	0.06029
2-4a	1907	2.09	0.18316	2.62	0.05363
2-4b	1907	2.08	0.26719	1.69	0.08192
2-5	1908	2.00	0.11885	1.33	0.08509
2-6	1908	1.75	0.05294	2.30	0.04187
2-7	1908	2.40	0.05705	1.91	0.07201
2-9	1909	2.19	0.05231	1.87	0.08603
2-10	1910	2.29	0.04669	1.90	0.07803
2-11	1911	2.37	0.06371	2.39	0.06258
2-12	1911	2.21	0.48211	1.91	0.11224
2-13	1912	2.06	0.09475	1.48	0.10976
2-14	1913	1.83	0.21244	1.66	0.1004
2-15	1914	1.99	0.04252	2.04	0.05913
2-16	1915	1.63	0.31064	1.36	0.18576
2-17	1916	2.19	0.07222	2.06	0.06531
2-18	1917	2.30	0.2996	2.36	0.08341
2-19	1918	2.17	0.06997	2.09	0.04809
2-20	1919	1.60	0.07495	1.72	0.03871
2-21	1920	1.53	0.05371	1.82	0.06142
2-22	1922	2.37	0.73676	1.71	0.12018
2-23	1926	1.69	0.06491	1.86	0.06573
2-24	1929	1.85	0.37488	1.81	0.07305
2-25	1931	1.60	0.08703	1.92	0.05284
2-26	1939	2.37	0.45992	1.93	0.10542
2-27	1945	2.05	0.07961	2.44	0.05261
2-28	1967	2.32	0.29096	2.08	0.09174
2-29	1980	1.73	0.08514	2.10	0.08164
2-31	1998	1.47	0.09174	1.81	0.08423

Appendix 16B: Data for shell C1-L4 (Daniels, 2010)

Sample ID	Calendar year assigned	True $\delta^{13}C$ value	Standard deviation	True $\delta^{18}O$ value	Standard deviation
4-2	1860	2.10	0.1807	1.41	0.06501
4-4	1861	2.08	0.22247	1.89	0.0871
4-6	1862	2.41	0.11619	2.10	0.0626
4-8	1863	2.34	0.19534	2.04	0.07075
4-10	1964	2.81	0.1245	2.47	0.04556
4-12	1865	2.05	0.14569	2.04	0.07241
4-14	1866	2.58	0.18432	2.10	0.0581
4-16	1867	2.38	0.15592	1.98	0.06707
4-20	1869	1.78	0.12302	1.40	0.05902
4-22	1873	1.31	0.11899	1.55	0.06474
4-24	1876	1.21	0.09812	2.33	0.04431
4-26	1883	1.55	0.13989	1.58	0.05636
4-28	1890	1.41	0.12318	1.47	0.06135
4-30	1910	1.86	0.15473	1.80	0.06803
4-32	1946	2.20	0.15542	1.83	0.05466
4-34	1990	1.55	0.1539	1.58	0.07528

Appendix 16C: Data for shell C1-L14 (Daniels, 2010)

Sample ID	Calendar year assigned	True $\delta^{13}C$ value	Standard deviation	True $\delta^{18}O$ value	Standard deviation
14-1	1892	1.28	0.19655	1.24	0.03871
14-3	1893	2.12	0.10225	2.34	0.05899
14-5	1894	1.23	0.12918	1.46	0.04765
14-7	1895	2.24	0.14488	1.09	0.05329
14-9	1895	2.14	0.147	1.76	0.03665
14-11	1896	2.09	0.10941	1.41	0.05431
14-13	1897	1.70	0.12915	1.81	0.06006
14-15	1899	2.19	0.14778	1.63	0.05622
14-17	1901	2.33	0.08237	1.96	0.04576
14-19	1902	2.23	0.09633	1.59	0.04276
14-21	1904	2.23	0.09633	1.59	0.04276
14-23	1907	1.83	0.14104	1.31	0.03974
14-25	1912	1.46	0.11631	1.74	0.03694
14-27	1920	1.59	0.15211	1.19	0.04114
14-29	1931	1.59	0.15211	1.19	0.04114
14-31	1940	1.89	0.1027	1.77	0.07032
14-33	1955	2.29	0.11617	1.88	0.06531
14-35	1965	2.42	0.13981	2.21	0.054
14-37	1994	1.66	0.15027	1.70	0.10997

Appendix 16D: Data for shell C1-L17 (Daniels, 2010)

Sample ID	Calendar year assigned	True $\delta^{13}C$ value	Standard deviation	True $\delta^{18}O$ value	Standard deviation
17-1	1908	1.38	0.07417	1.44	0.22668
17-2	1908	1.14	0.06936	1.32	0.04032
17-3	1908	1.15	0.08467	0.76	0.06013
17-4	1909	1.10	0.11564	1.38	0.0697
17-5	1909	1.40	0.05376	1.80	0.03419
17-6	1909	1.80	0.06671	1.07	0.04
17-8	1910	2.16	0.07074	1.84	0.04015
17-9	1910	2.50	0.48729	1.66	0.13803
17-10	1910	2.05	0.07149	0.92	0.19789
17-11	1911	1.95	0.45284	1.94	0.15071
17-12	1911	2.10	0.0743	1.91	0.05557
17-13	1911	1.79	0.31095	1.63	0.11675
17-14	1911	2.24	0.10069	1.08	0.03467
17-16	1913	2.12	0.05555	1.93	0.05706
17-17	1913	1.82	0.06844	1.28	0.05475
17-18	1914	2.33	0.03479	2.53	0.0346
17-19	1915	2.21	0.15501	1.93	0.06731
17-20	1915	1.97	0.04982	1.54	0.07425
17-21	1917	3.06	0.63684	2.18	0.09946
17-22	1917	2.19	0.09895	1.91	0.07317
17-23	1917	2.12	0.39213	1.48	0.06556
17-24	1918	1.91	0.04593	1.95	0.02086
17-25	1918	0.57	0.47402	1.13	0.16984
17-26	1919	1.37	0.0498	1.88	0.03849
17-27	1920	1.18	0.07481	1.25	0.11673
17-28	1921	1.24	0.05147	1.30	0.05006
17-29	1922	1.26	0.52198	1.22	0.19195
17-30	1924	1.68	0.10831	1.20	0.05803
17-31	1925	1.60	0.3598	1.46	0.10054
17-32	1927	1.22	0.06128	1.34	0.05956
17-34	1935	1.42	0.08104	1.82	0.04158
17-35	1940	1.37	0.233	1.98	0.13437
17-36	1949	2.09	0.08842	1.74	0.06807
17-37	1959	2.33	0.53893	2.04	0.13576
17-38	1974	1.76	0.07113	1.99	0.05233
17-39	1992	1.18	0.29872	1.78	0.06762
17-40	1996	1.56	0.12161	1.88	0.08717
17-41	2001	1.53	0.44874	1.94	0.16298

Appendix 16E: Data for shell C1-L19 (Daniels, 2010). Note that there are no standard deviations presented here as these were not provided by the lab in Cambridge that ran the samples

Sample ID	Calendar year assigned	True $\delta^{13}C$ value	Standard deviation	True $\delta^{18}O$ value	Standard deviation	Cambridge lab code
19-1	1927	1.19	N/A	1.90	N/A	S09/1401
19-2	1927	1.55	N/A	1.44	N/A	S09/1402
19-3	1928	1.58	N/A	1.47	N/A	S09/1403
19-4	1928	1.99	N/A	1.32	N/A	S09/1404
19-5	1928	2.03	N/A	1.10	N/A	S09/1405
19-6	1929	1.88	N/A	1.55	N/A	S09/1406
19-7	1929	2.30	N/A	1.52	N/A	S09/1407
19-8	1930	2.44	N/A	1.20	N/A	S09/1408
19-9	1931	2.13	N/A	1.55	N/A	S09/1409
19-10	1932	2.54	N/A	1.71	N/A	S09/1410
19-11	1932	2.67	N/A	1.39	N/A	S09/1411
19-12	1933	2.53	N/A	1.31	N/A	S09/1412
19-13	1934	2.22	N/A	1.83	N/A	S09/1413
19-14	1934	2.70	N/A	2.14	N/A	S09/1414
19-15	1934	2.77	N/A	1.89	N/A	S09/1415
19-16	1934	2.81	N/A	1.50	N/A	S09/1416
19-17	1934	2.49	N/A	1.13	N/A	S09/1417
19-18	1935	2.57	N/A	1.98	N/A	S09/1418
19-19	1935	2.69	N/A	1.55	N/A	S09/1419
19-20	1936	2.60	N/A	1.27	N/A	S09/1420
19-21	1937	2.43	N/A	1.69	N/A	S09/1421
19-22	1939	1.93	N/A	1.08	N/A	S09/1422
19-23	1940	1.64	N/A	1.31	N/A	S09/1423
19-24	1942	1.43	N/A	1.60	N/A	S09/1424
19-25	1944	1.46	N/A	1.48	N/A	S09/1425
19-26	1947	1.27	N/A	1.30	N/A	S09/1426
19-27	1951	1.56	N/A	1.61	N/A	S09/1427
19-28	1966	1.00	N/A	1.64	N/A	S09/1428
19-29	1979	1.93	N/A	1.78	N/A	S09/1429
19-30	1982	1.36	N/A	1.64	N/A	S09/1430
19-31	1993	1.58	N/A	1.43	N/A	S09/1431
19-32	1998	1.61	N/A	1.46	N/A	S09/1432
19-33	2000	1.65	N/A	1.61	N/A	S09/1433

Appendix 16F: Data for shell C7-L48(2)

Sample ID	Calendar year assigned	True $\delta^{13}C$ value	Standard deviation	True $\delta^{18}O$ value	Standard deviation
48(2)-1	1914	0.790308	0.011391	2.21805	0.023952
48(2)-2	1914	1.813917	0.128125	2.229659	0.036198
48(2)-2		0.901446	0.099156	2.25602	0.204764
48(2)-3	1914	1.086631	0.023484	2.425359	0.034619
48(2)-4	1914	1.016334	0.017285	2.45345	0.015211
48(2)-5	1914	1.345046	0.042797	2.15394	0.042432
48(2)-6	1914	1.339452	0.043702	2.210126	0.053368
48(2)-8	1917	1.604527	0.028147	2.232758	0.033998
48(2)-9	1918	1.387883	0.030146	2.195573	0.035848
48(2)-10	1920	1.458012	0.014618	2.080437	0.018552
48(2)-11	1925	1.201119	0.016674	2.2252	0.034704
48(2)-12	1930	0.887372	0.013486	2.21187	0.035711
48(2)-13	1934	0.936292	0.028719	2.131497	0.049118
48(2)-14	1951	1.288854	0.039479	2.255898	0.027541
48(2)-16	1959	0.638959	0.041147	2.262176	0.041091
48(2)-18	1966	1.06244	0.100002	2.240718	0.076849

Appendix 16G: Data for shell C7-L104

Sample ID	Calendar year assigned	True $\delta^{13}C$ value	Standard deviation	True $\delta^{18}O$ value	Standard deviation
104-1	1912	1.560926	0.025432	2.031024	0.034073
104-3	1912	1.120288	0.050858	2.075371	0.043456
104-4	1912	1.106708	0.017096	2.096593	0.012953
104-5	1915	1.208067	0.02516	2.058039	0.027641
104-6	1916	1.446508	0.022108	2.087479	0.028294
104-7	1919	1.395899	0.013624	2.147062	0.014967
104-9	1923	1.114994	0.01872	2.105422	0.025938
104-11	1942	1.352281	0.009435	2.071291	0.020352
104-12	1952	0.729608	0.010559	2.186925	0.029306

Appendix 16H: Data for shell C7-L127

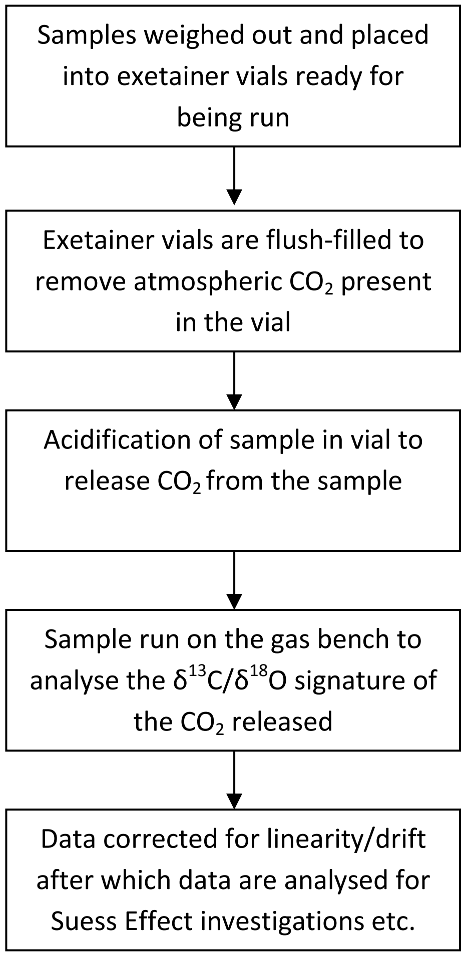
Sample ID	Calendar year assigned	True $\delta^{13}C$ value	Standard deviation	True $\delta^{18}O$ value	Standard deviation
127-1	1925	1.321824	0.018796	1.996691	0.027668
127-2	1925	1.442625	0.022569	2.012029	0.018715
127-3	1928	1.339221	0.025814	1.99429	0.026448
127-4	1929	1.461931	0.029013	1.897722	0.038056
127-5	1933	1.540676	0.042462	1.928464	0.047229
127-6	1934	1.429774	0.012481	1.954875	0.036953
127-7	1938	0.970802	0.025193	1.945291	0.028815
127-8	1940	1.538697	0.032573	1.913472	0.06545

Appendix 16 I: Radiocarbon data for shells C7-L48(2), C7-L104 and C7-L127

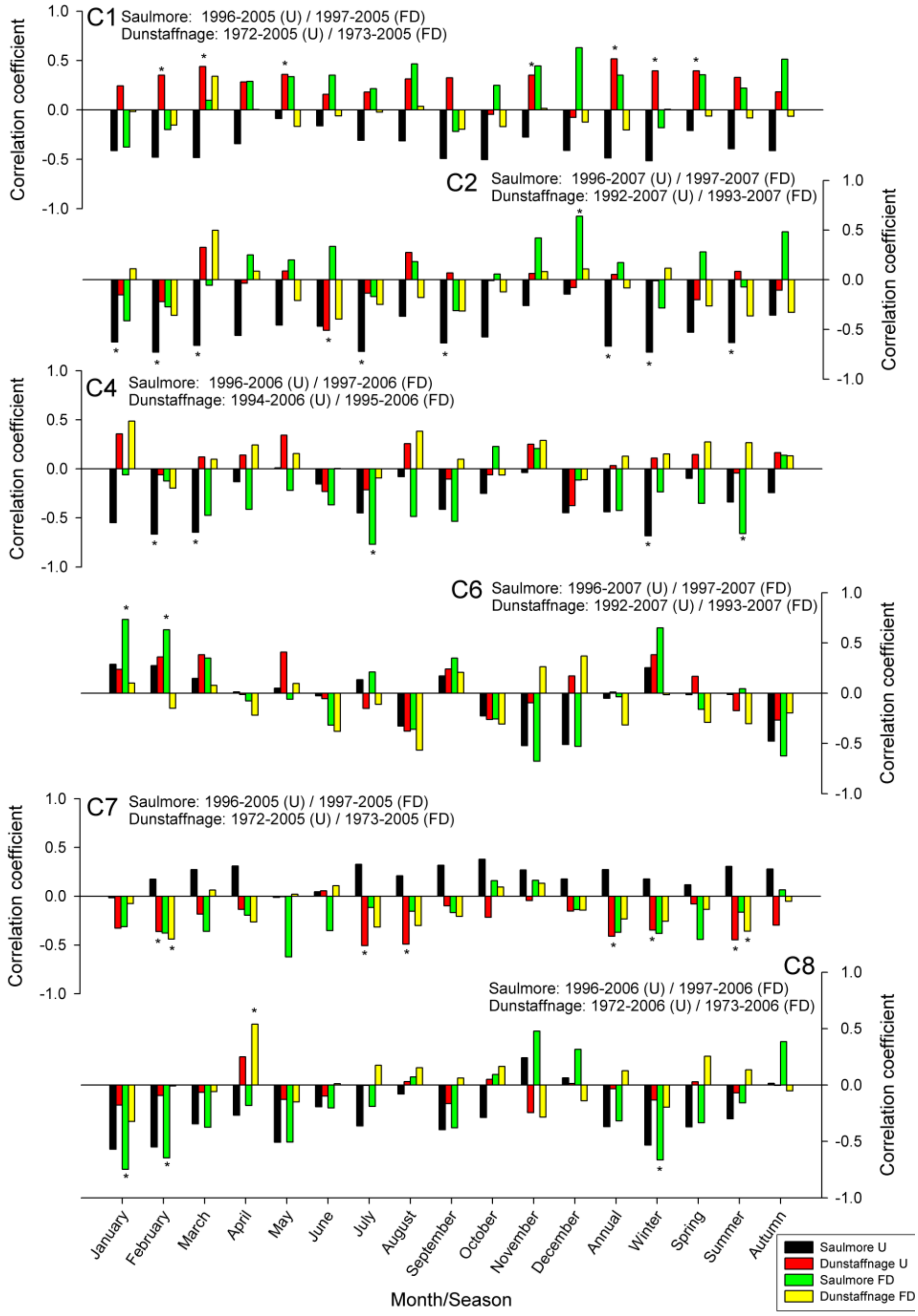
Publication code	Sample ID	^{14}C enrichment % modern ± 1σ	Conventional radiocarbon age (years BP ± 1σ)	Carbon content %	$\delta^{13}C$ ± 0.1%
SUERC-35191	C7L48(2)#2	96.52±0.44	284±37	11.2	1.4
SUERC-35192	C7L48(2)#F	125.04±0.57	modern	10.1	1.0*
SUERC-30484	C7L104(#2-2)	96.82±0.48	259±40	N/A	0.8*
SUERC-30485	C7L104(#2-8)	95.39±0.44	379±37	N/A	0.8*
SUERC-30486	C7L104(#2-10)	94.52±0.41	452±35	N/A	0.8*
SUERC-30487	C7L127(#1-9)	94.94±0.44	417±37	N/A	0.8*
SUERC-30488	C7L104(#2-13)	94.75±0.43	433±37	N/A	0.8*
SUERC-30489	C7L127(#1-10)	96.89±0.45	254±37	N/A	1.0
SUERC-30490	C7L127(#1-11)	95.19±0.42	396±35	N/A	0.9*
SUERC-30491	C7L127(#1-12)	99.19±0.46	65±37	N/A	0.9*
SUERC-30494	C7L48(2)(#5-19)	116.91±0.54	modern	N/A	1.0

*Estimated value, insufficient material for an independent $\delta^{13}C$ measurement

Appendix 17: $\delta^{13}C$ run protocol used for analysing $\delta^{13}C$ samples processed as part of this thesis.



Appendix 18: Comparison of master chronologies to the two 'local' instrumental datasets Saulmore and Dunstaffnage to determine if the shell master chronologies show a stronger relationship with these datasets compared to those results presented in Chapter 3.



To see if exploring the relationship between the two datasets located within the fjords would be more appropriate these have been compared to the master chronologies and the results are presented here. These results indicate that using the Saulmore and Dunstaffnage data are not appropriate.

Glossary

Acetate peels	Peels created from sectioned shells to look at growth rates
AMO	Atlantic Multidecadal Oscillation
AMOC	Atlantic Meridional Overturning Circulation
AMS	Accelerator Mass Spectrometry
CDendro	Software for analysing common patterns in GIs between shells
COFECHA	DOS-based programme for crossdating
CooRecorder	Software for measuring GIs
CRFA	Correlation response function analysis
CPR	Continuous Plankton Record
CTD	Conductivity, Temperature, Depth
Detrending	Method for removing the ontogenetic growth trend in the shell GIs
df	Degrees of freedom
EPS	Expressed Population Signal
GI	Growth Increment in the shell of *A. islandica*
Growth periods: Juvenile	First 10 years of growth
Young shell	First 30 years of growth
List method	Dendrochronological-based method for carrying out initial cross-dating
NAO	North Atlantic Oscillation
NERC	Natural Environment Research Council
NFSD	National Facility for Scientific Diving
Ontogenetic growth rate	As shell grows older there is an apparent decrease in shell growth rates
SAGES	Scottish Alliance of Geoscience, Environment and Society
SAMS	Scottish Association for Marine Science
SD	Standard deviation of the data
SE	Standard error of the data: $SE = SD/\sqrt{n}$

Seasons:	
Spring	April, May and June averaged data
Summer	July, August and September averaged data
Autumn	October, November and December averaged data
Winter	January, February and March averaged data
Sediment grain size definitions (after Wentworth, 1922):	
Clay	<4 µm
Silt	4 to 63 µm
Sand	>63 µm
SGI	Standardised Growth Index
Skeleton plotting	Dendrochronological-based technique for initial cross-dating
SST	Sea surface temperature