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Pliocene Global Warming
an ostracodal and sedimentological analysis of the Coralline Crag Formation, Suffolk

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Pliocene Global Warming: An ostracodal and sedimentological analysis of the Coralline Crag Formation, Suffolk

By

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List of Abbreviations

AGCM – Atmosphere Global Climatic Model
AOGCM – Atmosphere-Ocean Global Climatic Model
BP – Broom Pit
BWT – Bottom Water Temperature
CCS4 – Community Climate System 4 model
d.p. – Decimal place
ENSO – El Niño Southern Oscillation
ePWP – early-Pliocene Warm Period
GF – Gedgrave Farm
GSSP – Global boundary Stratotype Section and Point
IPCC – Intergovernmental Panel on Climate Change
MAT – Modern Analogue Technique
MCR – Mutual Climatic Range
mPWP – mid-Pliocene Warm Period
MSBT – Mean Summer Bottom Temperature
MWBT – Mean Winter Bottom Temperature
OC – Orford 'The Cliff'
PlioMIP – Pliocene Model Intercomparison Project
PRISM – Pliocene Research Interpretation and Synoptic Mapping
Ppm – Parts per million
RF – Richmond Farm
RM – Ramsholt Member
SK – Sutton Knoll
SM – Sudbourne Member
SST – Sea Surface Temperature
THC – Thermohaline Circulation

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Abstract

Climate change in the 21st Century is becoming a growing concern with a greater necessity for understanding the impacts of anthropogenic induced global warming in the latter part of this century being paramount. An understanding of former periods of global warming in our past may hold the key to explaining the effects in our future.

The Pliocene Epoch is the most recent geological period where warmer climates than modern were experienced. In particular, the mid-Pliocene warm period *c.* 3.3-3.0ma experienced between 2.7-4.0˚C warming which is similar to those predicted by the B1 IPCC projections for the late 21st Century of 1.1-2.9˚C. PRISM currently uses this time slice as part of its PRISM4 reconstruction to create a global-scale model of the Pliocene, which can be used to compare differences in Earth systems. Smaller scale climatic reconstructions, however, offer the basis for comparison with models for the Pliocene.

Sampling of sediments from the Coralline Crag Formation, United Kingdom allowed for the retrieval of benthic ostracod specimens which provided seasonal bottom water temperatures of the Pliocene. Developing upon the prior work of Wilkinson (1980) and Wood *et al.* (1993), it has been possible to develop temperature reconstructions for the Coralline Crag Formation utilising the mutual climatic range method for the first time. Statistical analyses using binary similarity coefficients and hierarchical clustering, further supplemented the findings to identify temperature changes between the Ramsholt and Sudbourne members of the Coralline Crag Formation. These were then compared against the temperatures produced from the PRISM3D reconstructions to determine the validity of the ranges produced from this work.

The findings determine an average bottom water temperature of 16.5˚C ± 1°C for the Coralline Crag Formation with a winter range of 12-13˚C ± 1°C and summer range of 19-21˚C ± 1°C. When compared to the temperature produced by PRISM3D of 13.21˚C ± 1°C it is suggested the environment of deposition for the Coralline Crag Formation was much warmer than the mPWP. The results produced by this work provide an

indication as to the temperatures experienced prior to the mPWP, which may aid in improving future PRISM models, providing a regional reconstruction.

1. Introduction

Anthropogenic induced climate change has become a growing concern in the 21st Century, with the potential for global implications of approximately 1.1-2.9°C warming based upon B1 projections from the IPCC (IPCC, 2013). An understanding of periods of warming from our geological past may be able to provide an indication as to the extent of the warming that might occur in the late 21st Century.

The Pliocene Epoch offers the most recent period of global warming experienced in our geological past (Haywood *et al.* 2016). The mid-Pliocene (3.26-3.02ma) experienced a period of warmth *c.* 2.7-4.0°C greater than present, similar to the expected temperature rise in the late 21st Century (Haywood *et al.* 2016). Suffolk, England, is home to arguably some of the best preserved sediments for climatic reconstructions from this period, with the Coralline Crag Formation, containing a wealthy supply of microfossils, particularly ostracods (Balson *et al.* 1993).

Aim:

Utilise an ostracodal and sedimentological analysis of the Coralline Crag Formation to deduce temperatures for the Pliocene and test their validity as an analogue of late 21st Century climate change.

Objectives:

- Undertake a review of relevant literature associated with the Pliocene and Coralline Crag Formation and the current application of geological time periods as indicators of future climate change
- Sample ostracods from locations in Suffolk where the Coralline Crag Formation can be identified while undertaking observations of the stratigraphy to identify the members and significant features
- Using ostracod specimens, determine temperature regimes by calculating the similarity between recent and fossil assemblages from a large binary database, utilising a multivariate analysis

- Construct a series of statistical and graphical plots of the temperature regimes, which will then allow for a comparison with modern values from the Suffolk area and PRISM3D regional temperatures

The Coralline Crag Formation was initially revived for ostracodal studies by Wilkinson (1980), nearly 100 years since the last work by Jones and Sherborn (1889). Subsequent studies by Wood *et al.* (1993) developed an initial temperature regime for the Coralline Crag Formation from benthic ostracods of between 10-24°C. Their work relied upon binary dissimilarity coefficients to determine mutuality between ostracods, however, there have been no other bottom water temperature reconstructions of the Coralline Crag Formation using other taxonomic groups.

Proposed methods for this research are the Mutual Climatic Range (MCR) method and Hierarchical clustering which determines species-level assemblage similarity. The MCR method applies genera temperature values which are plotted graphically and then overlain to determine an area of greatest overlap (mutuality) (Elias, 1997). The Dice binary similarity coefficient will also be applied to compare species, following the numeric methodology of Wood *et al.* (1993).

Finally, a comparison of the statistical and graphical temperature reconstructions will ultimately result in a temperature range for the Coralline Crag Formation, this can then be compared to other published temperature ranges and those produced by the PRISM project (Dowsett, 2013). This will then allow for a test of the validity of the Coralline Crag Formation as a potential climate analogue for late 21st Century climate change.

2. Literature Review

The following chapter will provide a review of the literature on the geological setting and approaches used in the analysis of mid-Pliocene conditions and the potential for this period as an analogue for late 21st Century warming.

2.1 The Cenozoic Era

The Cenozoic Era comprises the Palaeogene, Neogene and Quaternary periods (Berggren *et al.* 1995), with some of the best geological successions for the analysis of climate and sea level change (Hansen *et al.* 2013). The Palaeogene and Neogene periods extend from 65.5ma (million years ago) to 2.58ma and are succeeded by the Quaternary Period (Lowe and Walker, 1997; Hansen *et al.* 2013). The Neogene Period comprises two epochs, the Miocene and the Pliocene. The latter provides the focus for this thesis (see figure 2.1) (Gradstein *et al.* 2012).

Figure 2.1. The subdivisions of the Cenozoic Era (Gradstein *et al.* 2012).

2.2 The Neogene Period

The Neogene Period (23.03 – 2.58ma) constitutes the uppermost part of the Cenozoic Era, its chronology has been much debated, with numerous boundary changes in the past 50 years (see figure 2.2) (Gradstein *et al.* 2012).

Figure 2.2. Neogene timescale variation and adjustments since 1937 (Gradstein *et al.* 2012).

2.3 The Pliocene Epoch

The Global Boundary Stratotype Section and Point (GSSP) for the Pliocene is at Eraclea Minosa, Sicily, Italy (Hilgen and Langereis, 1993). Where the Zanclean base is located, underlain by the Messinian age Trubi Formation (Hilgen and Langereis, 1993; Di Grande and Giandinoto 2001; Gennari et al. 2008).

The term Pliocene was first used by Charles Lyell (1833) to define the base of the Neogene in the Mediterranean Basin. The base of the Pliocene is 5.33ma and represents the uppermost part of the Neogene (Haywood *et al.* 2009). This Epoch is sub-divided into the Zanclean and the Piacenzian stages (see figure 2.2) (Van Couvering *et al.* 2004; Gibbard *et al.* 2010; De Schepper *et al.* 2014).

The Pliocene has also been divided based on distinct climatic periods: an Early Pliocene Warm Period (ePWP); Mid-Pliocene Warm Period (mPWP) and a late Pliocene period of deterioration in climate conditions (Lisiecki and Raymo, 2005).

Global Pliocene climatic conditions during the mPWP were warmer and wetter than modern conditions, this is in part, due to the geographical positioning of the continents during the Piacenzian stage (Dodson and Macphall, 2004).

The main geological events that lead to these conditions were: the closing of the Isthmus of Panama *c.* 4.4 – 3.2ma (Barat *et al.* 2014); restriction of oceanic flow through the Indonesian Archipelago (Brierley and Fedorov, 2016) and sea level 25-30 m above modern levels (Dwyer and Chandler, 2009). Of these, the most important factor was the closing of the Isthmus, which resulted in the intensification of the Gulf Stream and enhanced strength of the Thermohaline Circulation (THC) (Barat *et al.* 2014: Brierley and Fedorov, 2016).

It has been suggested that warming during the mPWP can be accounted for, in part, by higher CO_2 levels, at *c.* 330-425ppm (Pagani *et al.* 2010). These concentrations are supported by Seki *et al.* (2010) who suggested that CO_2 levels were 50-120ppm higher than pre-industrial levels and similar to those of today.

Figure 2.3. Global surface temperatures, based upon O^{18} ratios for the a) Cenozoic, and b) Late Neogene to Present Day, green lines identifying mPWP (Hansen *et al.* 2013).

Pliocene of the United Kingdom

Pliocene strata outcrop extensively in East Anglia (Funnell, 1996). These sediments were first described by Charlesworth (1835) who identified the Coralline Crag. The Coralline Crag can be dated using foraminifera and calcareous micro-fossils placing it in the early Zanclean *c.* 4.1ma (Jenkins *et al.* 1987). The Coralline Crag is composed of calcarenites and shelly sands and underlain by London Clay Formation (Mathers and Smith, 2002).

The Pliocene stratigraphy of the U.K was most recently reviewed in detail by Wood *et al.* (2009), providing a stratigraphic evaluation of the East Anglian 'crags' (see figure 2.4).

Figure 2.4. Geographic location and distribution of the East Anglian Crags of Pliocene age (Wood *et al.* 2009).

2.4 Uniformitarianism and palaeoenvironmental reconstruction

Uniformitarianism states that “the present is the key to the past”; where modern organisms and sediments can aid our understanding of the past (Lyell, 1830; Gould, 1965). First proposed by Hutton (1795) and further developed upon by Lyell (1850), uniformitarianism can be utilised to develop our understanding of the environmental and climatic processes occurring during the mPWP.

Reconstruction of past environments involves several processes (Lowe and Walker, 1997). The analysis of stratigraphy in the field allows for the collection of fossils which can be used to correlate the succession (Jones and Keen, 1993; Lowe and Walker, 1997). These fossils can also be used in recent-fossil analogue research to reconstruct past environments (Romano, 2015).

2.5. Plio-Pleistocene Sediments

Plio-Pleistocene sediments have been identified across East Anglia, including the Coralline, Red, Norwich and Wroxham Crag formations (Funnell, 1996).

The Coralline Crag Formation

Samuel Dale (1704) first recorded the Crag deposits, with descriptions of fossiliferous sand and gravel overlying clay. The term ‘Crag’ was not applied, John Kirby (1764) described shelly deposits near Woodbridge, Suffolk. Coralline Crag was formally identified by Charles Lyell (1835), identifying two formations - the Red Crag and the Coralline Crag.

The Coralline Crag was first observed at Ramsholt Cliff, Suffolk by Charlesworth (1835). Prestwich (1871) identified the Coralline Crag at Rockhall Wood, now known as Sutton Knoll. Balson *et al.* (1993) were first to recognise the Coralline Crag as a formation (see figure 2.5).

Figure 2.5. Location of the Coralline Crag outcrop in Suffolk (Balson *et al.* 1993; Long and Zalasiewicz, 2011).

The Coralline Crag Formation is a composite of moderately to poorly sorted carbonate-rich skeletal sands, deposited during the early Zanclean to mid-Piacenzian stage, and is found throughout the Aldeburgh and Orford region of Suffolk (BGS, 2015; Balson, Mathers and Zalasiewicz, 1993). It is composed of three distinct members: the Ramsholt, Sudbourne and Aldeburgh (see figure 2.6) (Balson *et al.* 1993).

The Ramsholt Member (*c.* 7.5 m thick) is the basal stratum of the Coralline Crag, composed of carbonate sands and well-preserved molluscan and bryozoan fossils and unconformably overlays the London Clay and Harwich formations. The sediments of the Ramsholt Member were deposited under warm temperate conditions, inferred by the presence of a dinoflagellate *Impagidinium aculeatum* (Edwards, Mudie and De vernal, 1991). Brackish ostracods can be found in rare occurrence, suggesting a nearby estuarine environment, further supported by evidence of foraminifera (Wilkinson, 1980).

The Ramsholt Member is overlain unconformably by the Sudbourne Member, the latter is composed of cross-bedded, well-sorted carbonate sands, deposited by the migration of large submarine sand waves in a high energy marine environment (Balson, 1983). Dinoflagellates from this member indicate a warm temperate climate (Head, 1997). The Sudbourne and Aldeburgh members can be seen to overlap towards the north of the region, although this is only inferred from borehole data (Balson *et al.* 1993).

Due to post-depositional leaching, parts of the Sudbourne and Aldeburgh members are devoid of aragonitic skeletal material, consequently, there are only molluscan moulds preserved. Based on borehole data, the Aldeburgh Member is considered to be younger than the Ramsholt and of a similar age to the Sudbourne. Little evidence of micro fauna or flora is present within the Aldeburgh Member (Balson *et al.* 1993).

These sediments can be used for the recognition of isostatic and eustatic sea level change, sediment can then be compared to reconstruct ostracoda ecologies (Pillans, Chappell and Naish, 1998).

Figure 2.6. The Coralline Crag Formation, with red line distinguishing boundaries for Ramsholt and Sudbourne members at Sutton Knoll (52.04N 1.36E), spade and trowel for scale.

Localities of the Coralline Crag

Dixon (2011) produced an extensive guide to the Crags of East Anglia, with a focus on the Coralline Crag Formation at the Sutton Knoll site.

This site has the best-reported sequence of the Coralline Crag sediments with good exposures in the disused quarry pit at the north of the site and the ‘bullock yard pit’ (Daley, 1999).

‘The Cliff’ at Gedgrave, Suffolk, provides the southernmost exposure of the Coralline Crag Formation. This site, along with Broom Hill Pit and Sutton Knoll are the only three where the relationship between the Ramsholt and Sudbourne Members can be observed (Charlesworth, 1835; Daley and Balson, 1999).

Richmond Farm has a 6m section of the Sudbourne Member, with fossils being sparse within the well preserved, cross bedded sands (Daley and Balson, 1999).

Broom Hill Pit is the deepest of the excavations, again providing the contact between the Ramsholt and Sudbourne Members. First described by Prestwich (1871) this site has been affected by aragonitic dissolution (Balson *et al.* 1993; Daley and Balson, 1999).

The Crag Farm at Gedgrave section exposes cross-bedded calcarenites of the Sudbourne Member which were extensively analysed by Balson *et al.* (1993). The main composition of the strata is a limestone aggregate of carbonate grains containing bryozoan colonies in abundance compared to the other sites (Daley and Balson, 1999).

2.6 Fossil proxies

Fossil proxies have been widely used in the environmental reconstruction of Pliocene successions, notably ostracods, foraminifera, dinoflagellates and molluscs.

Ostracods

Ostracods are microscopic crustaceans (0.4-2mm) in length composed of a low magnesium-calcite (Mg-Ca), with the soft parts enclosed in a bivalve carapace (see figure 2.7) (Rodriguez-Lazaro and Ruiz-Muñoz 2012). The calcitic composition of an ostracod can be a mixture of varying elements in particular magnesium (Mg) or strontium (Sr) (Börner *et al.* 2013). Magnesium-calcite based ostracoda are common proxies for bottom water temperature, while Strontium-calcite ratios have been used for sea surface temperatures and salinity (Rosenthal and Linsley 2006). Mid-Pliocene bottom water temperatures have been determined for the North and South Atlantic using magnesium: calcium ratios (Mg: Ca) of *Krithe* genus shells (Cronin *et al.* 2005).

Figure 2.7. Internal organs of an ostracod with right valve removed (Smith, 2017).

Ostracods are abundant throughout the Phanerozoic Eon making them useful proxies for the analysis of the geological record. They have adapted to all aquatic environments (marine, brackish and freshwater); providing much palaeoenvironmental insight as they are particularly sensitive to temperature, salinity, depth and pollution (Ito *et al.* 2003).

Influences on ostracod temperature ranges

Marine ostracods have been used to reconstruct surface and bottom water temperatures. However, their distribution can be influenced by factors such as the chemistry of the water, water depth and dissolved oxygen concentration (Horne, 2007). Other influences include substrate and taphonomy (Horne, 2007; Athersuch, Whittaker and Horne, 1989).

Research into the Pliocene ostracods of East Anglia

The initial collection of ostracods was carried out by Wood (1848), subsequent to this; Jones (1857) researched these collections, later revised, Jones (1870) described the species from the Coralline and Red crags.

Wilkinson (1980) reinitiated sampling of ostracods from the Coralline Crag Formation, this was the first new work for nearly 100 years, since the prior work by Jones and Sherborn, 1889. The original list of species was expanded from 19 to 61 and a mid-Pliocene age was postulated.

Wood *et al.* (1993) used southern North Sea ostracods to reconstruct Pliocene temperatures, using 41 genera for this analysis. Three palaeotemperature curves were developed indicating temperatures for the Coralline Crag, Red Crag and Norwich Crag Formations. Summer temperatures for the Coralline Crag Formation were defined to have been between 12 and 19°C and winter temperatures of 9 to 14°C (Wood *et al.* 1993). Wood *et al.* (1993) also correlated the Coralline Crag Formation to the mPWP due to the dominance of warm water dwelling ostracods. It has been identified that there is a *c.* 50% reduction in species between the Ramsholt and Sudbourne Members, which suggests a cooling period *c.* 4.04ma (Hardenbol *et al.* 1998; Head, 1997).

There is a notable hiatus (*c.* 3.3-2.9 ma) between the Coralline Crag Formation and Red Crag, with no data for this ‘intra-Pliocene’ warming event *c.* 3 ma (see figure 2.8) (Dowsett and Poore, 1991).

Figure 2.8. Geological timescale for the deposition of the Coralline Crag, Red Crag and Norwich Crag Formations, red lines highlighting hiatus between Coralline and Red Crag formations (Lisiecki and Raymo, 2005; Wood *et al.* 2009).

Substrate

Ostracoda can be classified into two categories for substrate, phytal or epifaunal (Athersuch, Whittaker and Horne, 1989). Benthic ostracods may be found on either of these substrates, however, grain size will influence the abundance. Similarly, the availability of vegetation for phytal species will affect the quantity (Swain, Kornicker and Lundin, 1972).

Phytal dwelling ostracods often contain a mixture of genuine phytal species and epifaunal species due to algae entrained in sediment, along with ostracods roaming from their preferential habitats (Horne, 1982; Whatley, 1976).

Ontogeny

The ontogeny of ostracods reveals characteristics that aid in determining depositional environments, transport regimes and energy levels (Whatley, 1988). Instars are the layers produced by ostracods as they grow, the lower the energy levels the greater the likelihood of early instars to remain.

Boomer, Horne and Slipper (2003), highlight how the adult to juvenile ratio can indicate the palaeoenvironment, with a greater number of adults indicative of a high energy environment (see figure 2.9).

Figure 2.9. Taphonomy of ostracods from a high energy depositional environment (Boomer, Horne and Slipper, 2003).

Biodiversity of ostracods

The palaeobiology of generic and species level assemblages can indicate the characteristics and depositional conditions of an environment (Boomer *et al.* 2003). While the diversity of an assemblage may vary significantly due to post-depositional processes such as dissolution and reworking of the sediments (De Deckker *et al.* 1988).

Biodiversity of ostracods can be determined by applying various indices which require two main criteria; number of species and occurrence. The indices aim to interlink these two values by determining the higher or lower distribution of species based upon occurrence (Bandeira, 2013). Species occurrence provides a figure that can then be compared numerically through indices to others to provide abundance at a site which suggests an indication as to the distribution of species (Ehrlén and Morris, 2015).

The two most common biological indices are Simpson and Margalef (full name, Gleason-Margalef) (Washington, 1984). The Simpson index has a reciprocal calculation to evaluate if the index value increases with increasing diversity. While the Margalef index compares relationships between the number of species and the number of specimens within a sample (see section 3.10).

Climate reconstruction using proxies

Three major approaches can be used to undertake palaeoclimatic reconstructions using proxies, these are: indicator species, assemblage comparisons and multivariate calibration function approach (Birks *et al.* 2010). For each of these approaches, modern climatic tolerances of the taxa are required to determine fossil temperature ranges (Jackson and Williams, 2004).

Proxies can be either high or low resolution for climate reconstruction (Moberg, 2005). High-resolution proxies show temperature variation on an annual, decadal or centennial scale, while low resolution cover a multi-millennial time period. Tree rings, laminated lake/ ocean sediments, ice cores and corals all constitute high-resolution proxies, which are supplemented by low-resolution proxies such as boreholes and fossil assemblages (IPCC, 2013).

For the Pliocene, only low-resolution proxies provide a climatic comparison due to the timescale. Once a proxy has been chosen it is normal to use multivariate and multi-method comparisons to develop temperature ranges for the time period in question (Moberg, 2005).

Assumptions in climate reconstructions using proxies

At least six major assumptions can be applied to climate reconstructions using proxies (Birks *et al.* 1990; Maddy and Brew, 1995). These assumptions apply to each of the three approaches outlined above, see Birks *et al.* (2010):

1) The modern taxa are related to the climate they inhabit
2) Climate variable/s that are to be reconstructed are either linearly or monotonically linked to an ecologically significant component of the system being examined.
3) The modern and fossil taxa have the same ecological responses and can, therefore, be used to reconstruct changes through time.
4) Mathematical methods used are appropriate to the species environmental responses and allow for accurate and unbiased reconstructions of temperatures.
5) Environmental variables that are not studied do not influence the temperature range or parameter being examined; these variables are the same in the past as today or change the assemblage in the past similar to changes experienced today.
6) The statistical analysis and modelling of the variables are independent of any other factors that have been used to define the parameters for reconstruction.

The indicator species and assemblage approaches are used herein to reconstruct temperatures during the mid-Pliocene of Suffolk.

2.7 Mutual Climatic Range (MCR)

The MCR method is a quantitative, calibrated technique for understanding palaeoenvironmental reconstruction first developed by Coope *et al.* in 1982 (Elias, 1997). Assuming evolutionary tolerances are similar in modern living taxa (see above assumptions), it can be inferred that the fossil species inhabited comparable temperature ranges (Jones and Keen, 1993; Horne, 2007). Initially developed for coleoptera, the method has been adapted for pollen (Pross *et al.* 2000), molluscs (Moine *et al.* 2002), fresh water ostracods (Horne, 2007) and benthonic marine ostracods (Wood *et al*. 1993); utilising mean temperatures of summer and winter (Horne, Curry and Mesquita-Joanes, 2012).

The first use of ostracods in climatic comparisons was undertaken by Valentine (1971), who successfully calibrated 66 ostracod species of Quaternary age, inhabiting depths of 10 to 50 m in the southeast of Virginia, USA.

Tested by Atkinson *et al.* (1986), this method was initially used for European beetle assemblages. The modern geographical distribution of assemblages is used as a base for the methodology, while temperature ranges are provided from regional databases (Moine *et al.* 2002). The technique requires the identification of specimens to either generic or species level (Moine *et al.* 2002).

Application of ostracod-based methods in Pliocene climate reconstruction

In climate reconstructions, an extensive range of data series and methods are essential to develop a more accurate regional temperature regime (Mann, Bradley and Hughes, 1998).

The MCR method is yet to be applied to Pliocene ostracods from the Coralline Crag Formation. This method is valuable for the Pliocene reconstruction due to the lack of direct modern analogues (Porch *et al.* 2009). A fossil-modern analogue technique has, however, been applied to ostracods of Late Pliocene age from the Red Crag Formation by Wood (2012). The results show a temperature range much lower than modern, approximately 4-5°C cooler (see figure 2.10).

Mean Winter Temperature at Depth (℃)

Figure 2.10. Recent (numbered points) and Fossil (un-numbered) mean summer and winter temperature envelopes for the North Sea and Red Crag Formation, with modern day bottom water temperatures shown (Wood, 2012).

Wood (2012) highlighted the potential dispersal of benthic ostracods during the Pliocene and how migration was influenced by watermass boundaries. Approximations for palaeotemperature and bathymetric conditions can be estimated based upon similarities of fossil and recent faunas (Wood, 2012).

Multivariate approaches to climate reconstruction using proxies

A multivariate approach using fossil proxies such as ostracod taxa allows for the statistical interpretation of the similarities in habitual temperature range (Shi, 1993). Binary similarity coefficients and cluster analysis are two multivariate methods; Wood (2012) utilised the binary similarity coefficient to approximate temperature in the Red Crag Formation. This new data can then be used to test existing theories and models of mid-Pliocene global warming.

Proxy data in climate modelling

Proxy data can be used either qualitatively or quantitatively to infer past climates (Kohfeld and Harrison, 2000). A statistical analysis requires the assumption that the modern and fossil assemblages inhabited the same conditions, which hinders computational modelling (Braconnot *et al.* 2012a). However, this is where non-climatic drivers such as carbon dioxide levels have an impact on climate modelling. Computational modelling using proxies of Pliocene age has been utilised and developed over the past 28 years (Haywood, Dowsett and Dolan, 2016).

2.8 Earth systems for climate modelling

The Earth can be divided into five systems: Atmosphere, hydrosphere, ice, land and organic matter (Stocker, 2013). These components can be modelled individually or coupled for a comprehensive overview of Earth systems. Variables such as carbon dioxide emissions can be applied to the model, to observe the possible effects on Earth climate systems over time (Stocker, 2013).

Pliocene Climate Modelling

Zubakov and Borzenkova (1988) were first to consider using the mid-Pliocene or 'Pliocene Optimum' as an analogue for 21st Century climate change (4.3-3.3 ma).

Their work on the mid-Pliocene warm period concluded that the climate was 4-5°C warmer than today (Haywood, Dowsett and Dolan, 2016). They sampled terrestrial and marine sections and reconstructed numerous superclimathems, of between 100,000 to 300,000 years. Their research lead to the establishment of the USGS (United States Geological Survey) PRISM project (Haywood, Dowsett and Dolan, 2016).

Pliocene Research Interpretation and Synoptic Mapping project (PRISM)

The PRISM project has investigated the mPWP since 1989 (Haywood, Dowsett, and Dolan 2016). The PRISM has undertaken a comprehensive global synthesis of the mPWP (3.29-2.97 ma) climate, this time slice has since been revised to (3.264-3.025 ma) (Dowsett *et al.* 2010; Haywood *et al.* 2016). Haywood *et al.* (2011) hypothesised that the palaeoclimate experienced during the mPWP correlates to the current warming trend and predictions for the 21st Century. PRISM has pooled data from around the world, using different proxies and sedimentological facies, with a focus on surface ocean and land temperatures using: oxygen isotopes, floral and faunal assemblages and isotopic composition of carbonates and biomarkers (Haywood, Dowsett and Dolan, 2016).

The reconstruction of mid-Pliocene sea surface temperatures (SST) was carried out by Dowsett, Barron and Poore (1996) as part of the early PRISM project. Their work indicates that North Atlantic and Pacific SST were warmer than those of today, however, the data sets for the South Pacific, Indian Ocean and Arabian Sea were small.

It is suggested that the similar positioning of the continents and comparable carbon dioxide concentrations make the mPWP a reliable analogue (Dowsett, Chandler and Robinson, 2009: Bartoli, Hönisch, and Zeebe, 2011).

Temperatures are suggested to have been 1.8-3.6°C higher during the mPWP, compared to the IPCC (Intergovernmental Panel on Climate Change) B1 projections which suggest 1.1-2.9°C of warming for the Late 21st Century (IPCC, 2013).

PRISM3D

PRISM3D is the fourth generation in Pliocene temperature reconstructions, bringing together the research from the previous three generations.

PRISM3D provides the most comprehensive reconstruction of any previous warm interval in Earth's history (Dowsett *et al.* 2010). This research indicates that temperatures increased considerably with latitude, while at low latitudes the temperatures were comparative to present. The PRISM3D modelled climate parameters such as SST, bottom water temperatures, vegetation, ice sheets, orography and sea level change (Dowsett *et al.* 2010).

The latest PRISM modelling (PRISM4) is at a pilot stage, however, this version aims to better define regional climatic regimes (USGS, 2015). Further research by PRISM4 has led to the better prediction of the strength and frequency of El Niño Southern Oscillation (ENSO) (USGS, 2015). The use of a multi-proxy analysis and regional climate processes will produce a finer geological timeline for the mPWP.

Community Climate System 4 model

The Community Climate System 4 model (CCS4) is an Atmosphere-Ocean Global Circulation Model (AOGCM), used to study the mPWP (Gent *et al.* 2011). AOGCMs use linked atmospheric, oceanic and sea ice model, resulting in greater accuracy of SST, sea ice systems and model evolution. Together this provides greater accuracy in surface heat fluctuations when reconstructing temperatures (Gordon *et al.* 2000).

2.9 Climate modelling comparison projects

Climate model intercomparison projects are an important method for measuring the uncertainty and capability of individual models (Giorgetta *et al.* 2013). Using models highlighted in PRISM3D, along with other climate models, it is possible to simulate short and long term climate change effectively.

Hibbard *et al.* (2007) outlined a strategy for successful coupled model experiments, which focussed on short term (2030) and long term (2100) projections for climate change, with parameters such as emissions, pollutants and socio-economic changes.

Pliocene Model Intercomparison Project

PlioMIP aim was to compare climate models to create a comprehensive overview of changing climatic conditions during the Pliocene (Hill *et al.* 2014). This project is part of the much larger PMIP (Palaeoclimate Model Intercomparison Project), which provides an overview of longer palaeoclimate change (Hill *et al.* 2012).

Initial comparison of the Hadley centre and Goddard Institute for space studies climate models (HadAM3 and GCMAM3) resulted in similarities and differences in the accuracy of the models, encouraging the further development of PlioMIP (Haywood *et al.* 2009a). The PlioMIP based its experiments upon the boundaries defined by PRISM3D, allowing for analysis of SST, vegetation cover and ice extent mapping (Dowsett *et al.* 2010).

PlioMIP finished its first phase in 2015 the second phase is at its design and planning stage (Haywood *et al.* 2016). Phase 1 of PlioMIP became the first palaeoclimate intercomparison project to require vegetation distributions, leading to vegetation-climate feedbacks as an output of the comparisons. The outputs of the first phase identified inaccuracies in PlioMIP data for the Tropics, however, climatic drivers such as clear-sky albedo and greenhouse gas emissions lead to increased Polar amplification of higher surface temperatures (Hill *et al.* 2014).

Pliocene Ice Sheet Intercomparison Project

The Pliocene Ice Sheet Intercomparison Project (PLISMIP) was initiated as part of PlioMIP; its aim, to develop a better understanding of ice sheet responses during the mPWP (Dolan *et al.* 2012). Work on Pliocene Arctic ice has been conducted by Howell *et al.* (2016), exploring modern and Pliocene Arctic ice variation using PlioMIP and CMIP5 (Climate Model Intercomparison Project 5) data as part of PLISMIP.

The geographical mapping of ice coverage during the Pliocene is limited (Haywood *et al.* 2009; Fielding *et al.* 2009; Dwyer and Chandler 2009; Naish and Wilson, 2009). It is suggested that Pliocene Arctic ice coverage was perennial or seasonal; Darby (2008) supports a perennial theory based upon iron fragments found in an Arctic marine core from the Arctic Coring Expedition (ACEX). Cronin *et al.* (1993) and Polyak *et al.* (2010) support a seasonal ice coverage based upon ostracod assemblages and ice-rafted debris sediments in the Meighan Islands.

2.10 Limitations of Pliocene Data

The limitations of the Pliocene as an analogue for late 21st Century climate change range from uniformitarian assumptions to climatic conditions (Haywood *et al.* 2009). In particular, the THC produces issues in modelling the mPWP with respect to oceanic basins and hemispheric temperature distribution, however, regional regimes have the ability to override global trends in oceanic circulation (Haywood, Sellwood and Valdes, 2000).

Hill (2015) suggested that a lack of geographic changes *i.e.* the closing of the Isthmus of Panama, hinders the reliability for the Pliocene as a climate analogue, conversely, changes in geography and orography are not going to be a factor in late 21st Century warming.

AGCM have a usefulness and consequent inaccuracy due to the application of prescribed SST and/ or slab ocean-models, as such, they are unable to simulate thermohaline and ocean heat circulation (Haywood and Valdes, 2004). The solution to this issue was the development of the Hadley Centre for Climate Prediction and Research Model 3 (HadCM3) (Haywood and Valdes 2004; Haywood *et al.* 2016).

Orbital forcing throughout the Neogene has been calibrated with geological data, however, correlation errors can result, thus creating disagreements between models and data (Haywood *et al.* 2013a).

2.11 Improving the reliability of Pliocene modelling

Lunt *et al.* (2010) suggests that the reliability of Pliocene modelling can be improved by focussing upon the boundary conditions and their impacts on Earth system sensitivity. This would reduce temperature gradient variability in modelling and factor in changes such as orography, vegetation distribution and ice sheet presence.

Hill (2015) notes that the Pliocene is the best palaeoclimate analogue for an Earth system functioning with carbon dioxide levels at 400ppm. While mentioning that North Atlantic temperatures during the Pliocene are not going to be a factor in the late 21st Century as geographical changes will be limited during this period.

Haywood *et al.* (2016) outlines four criteria that enhance the reliability of mPWP data and models: 1) a more precise chronology; 2) creating local and regional based palaeoenvironmental reconstructions, which can be compared to models; 3) producing climate models with greater time interval consistency; 4) developing climate models that produce more accurate orbital and environmental variability during the mPWP.

The work in this thesis will focus on point 2 by Haywood *et al.* (2016), reconstructing the Coralline Crag Formation palaeoenvironment around Sutton Knoll, Suffolk.

2.12 Summary

The Pliocene period offers a significant period of warming much akin to our 21st Century climate. The studies of Coralline Crag Formation ostracods can help to contribute to our understanding of the mPWP and thus 21st Century warming.

3. Methodology

This chapter aims to provide a detailed description and review of techniques using fossil proxies in palaeoenvironmental reconstruction with a particular emphasis on ostracods and bottom water temperatures.

3.1 Field Data Collection

Figure 3.1. Location of sample sites in Suffolk, United Kingdom (Google, 2017).

The six Coralline Crag sites were sampled in November 2016 (see table 3.1).

Site	Latitude and longitude coordinates	Ordnance Survey coordinates
Sutton Knoll site 1	52°2'47.46"N 1°21'32.46"E	TM305440
Sutton Knoll site 2	52°2'49.58"N 1°21'38.31"E	TM305440
The Cliff, Gedgrave	52°5'2.67"N, 1°29'50.85"E	TM39724863
Broom Hill	52°5'43.90"N, 1°30'41.92"E	TM40634995
Richmond Farm	52°5'19.39"N, 1°31'11.01"E	TM41224922
Gedgrave Farm	52°4’59.81”N, 1°30’34.67”E	TM40534859

Table 3.1. Locations of the Coralline Crag sites with latitude and longitude co-ordinates and Ordnance Survey co-ordinates.

At each locality, the sedimentary section was cleaned and photographed; a one-metre wide section was identified for sedimentary logging: grain size, sorting and sedimentary structures were recorded. The members of the Coralline Crag were identified and samples collected.

100g sediment samples were collected at 50cm intervals up to a height of 2.5 m, 32 samples were collected in total.

Site abbreviations for this research:

Sutton Knoll	**SK**
Broom Pit (Broom Hill)	**BP**
Gedgrave Farm	**GF**
Orford 'The Cliff' (The Cliff, Gedgrave)	**OC**
Richmond Farm	**RF**

Table 3.2. Site abbreviations for this thesis.

3.2 Laboratory Data Collection

Laboratory work was undertaken to supplement the observations in the field. Boomer, Horne and Slipper (2003) outline the parameters for accurate sampling and preparation of an ostracod assemblage. It is suggested that a sample size of moderate diversity should contain 30-40 species per 200-300 specimens, while appropriate sieving and disaggregation of the ostracods is essential to include both juveniles and adults with clean specimens of each.

Ostracod identification was carried out from December 2016 through to April 2017. Initially, each sample was sieved through a 60ɸ/ 0.25 mm mesh. Ostracods were picked using a sable hair 00-gauge brush and a Kyowa optical SDZ-PL model microscope with an active light source.

The ostracods were then placed onto covered and labelled slides, up to 50 ostracods per sample were recovered due to time constraints. Cemented or fragmented ostracods were not picked due to the difficulty in accurate identification, 806 specimens in total were recovered from sampling.

Once sampled the ostracods were photographed using a Bresser Mikrokular Full HD microscope lens camera. The photographs were then used to aid species identification. Species were identified from the observations of Wood *et al.* (1993), with their collection containing a large sample of ostracods from the southern North Sea.

3.3 Sedimentary logs

Sedimentary logs were used to summarise and identify the analysis of contemporary and historical facies and environments. Digital versions of the sections were created using Sed Log 3.1 software which allows for the input of features and structures present in the stratigraphy (see figure 3.2).

Some materials have been removed due to 3rd party copyright. The unabridged version can be viewed in Lancester Library - Coventry University.

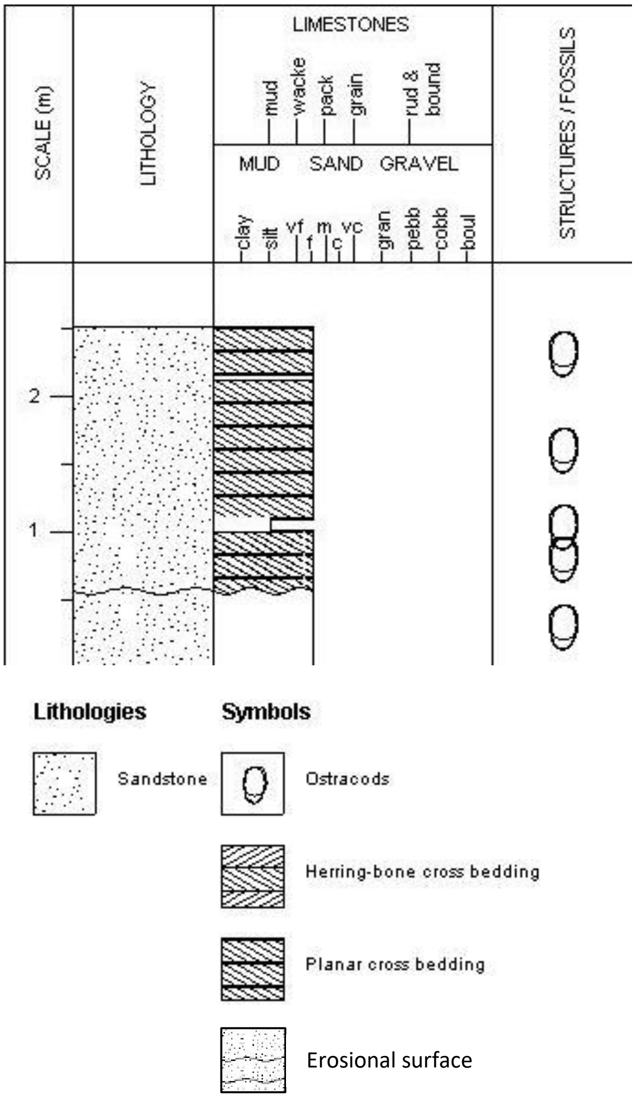

Figure 3.2. Cross bedded section from Richmond Farm used for sediment logging showing the Sudbourne Member, tape measure for scale at 2 m with digitised log and key adjacent.

3.4 Approaches in Climatic Reconstruction

Of the three approaches used in climate reconstructions - indicator species, assemblages and multivariate calibration - the first two will be used to help reconstruct conditions during the deposition of the Coralline Crag Formation (Birks *et al.* 2010).

The indicator species approach requires the development of bio-climate envelopes to identify areas of climate overlap, most commonly referred to as the Mutual Climatic Range method (Birks *et al.* 2010). This method uses the fossil taxa to help develop the envelopes and identify overlaps of mutuality.

The assemblage approach requires a statistical analysis of the abundance of available fossil taxa (Birks and Birks, 1980). The main method of analysis is the modern analogue technique (MAT) which compares numerically the similarity or dissimilarity between fossil and modern assemblages (Birks *et al.* 2010). The MAT was used for southern North Sea ostracoda temperature reconstructions by Wood *et al.* (1993) and Wood (2012).

Multi-model approaches in climate reconstruction

Johnson and Omland (2004) highlight the major advantages of using two or more approaches in reconstruction, these are:

1) Intercomparison between models can occur to evaluate the observed trends from the taxa, by considering what each model defines and the outcomes they produce;
2) The models can be given a rank to define how successful at producing values and boundaries they are; and
3) If the outcomes from the models are similar, then averages from them can be produced to make significant and prominent estimates and inferences.

Multi-model approaches increase the margins of error due to additional numerical analyses; however, the homogeneity of the data sets from the taxa allows for a better understanding of the errors that may arise (Birks *et al.* 2010).

3.5 Mutual Climatic Range method (MCR)

Calculating the mean winter (T_{MIN}) and mean summer (T_{MAX}) temperatures allows for the development of an 'envelope' which represents the tolerance of each ostracod species or genera found in the fossil assemblage. Temperature envelopes are required to show a range (T_{RANGE}) of tolerances for each taxon which then provides a mutual climatic range of past climate for each location (Elias, 1997; Frenzel *et al.* 2010).

Wood binary database (unpublished data)

The Wood binary database (unpublished data) contains over 220 ostracod species from over 270 locations ranging from the Atlantic Ocean to the Arctic Ocean (see figure 3.3).

Figure 3.3. *Aurila* localities from the Wood binary database (unpublished data) where temperatures were sampled.

The locations provided the temperatures upon which temperature plots for each genus were produced from the 33 identified across all sites.

Ostracod genera temperature ranges

Once the ostracod taxa had been identified these were used at the generic level for the development of Mutual Climatic ranges. Genera were used because few species were recovered (see Appendix A). The photos of each genus identified can be found in Appendix C. Modern genera temperatures and locations were taken from the Wood Binary (2014) North East Atlantic database (unpublished data) (see figure 3.4).

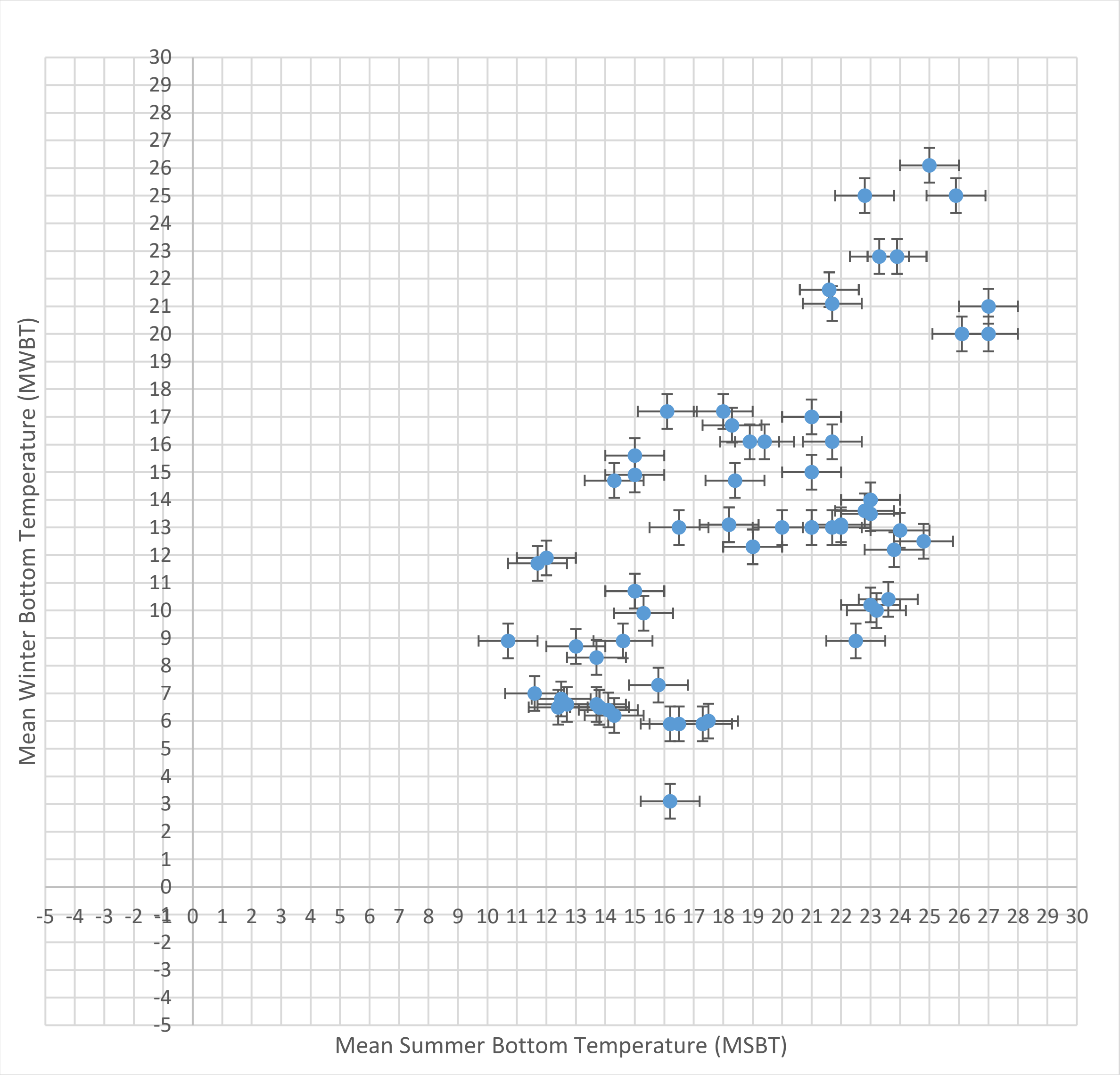

Figure 3.4. Example of genera T_{MIN} and T_{MAX} with ± 1°C boundary, temperature plot for *Aurila*.

The axis names used herein are the same for every style of graphic produced (Temperature plot, MCR and statistical plot).

The temperature envelope was produced by adding one standard error that represents 30 years of variance in ocean temperatures at depth; this is equivalent to 1°C (see figure 3.5).

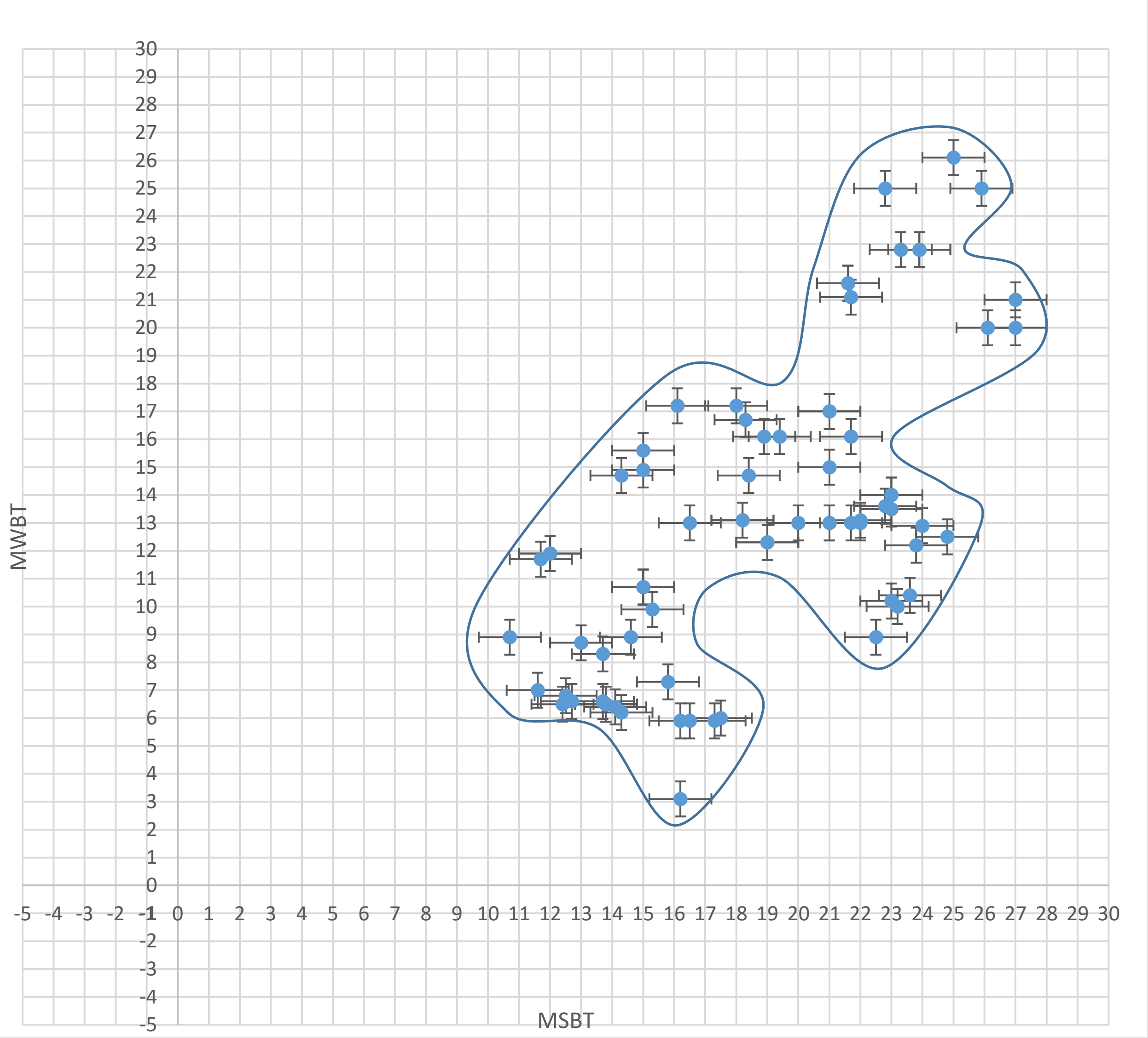

Figure 3.5. Temperature range with ± 1°C boundary applied for *Aurila*.

This method, of course, offers a broader temperature envelope than for a species level analysis, however, the validity of this method can by comparison with other techniques, *i.e*. assemblage-level recent-fossil analogue techniques, provide useful information (see section 2.7). Wood (2012) applied the same approach by applying a one standard deviation error boundary to the temperature ranges, which accounted for the natural fluctuation in mean annual summer and winter temperatures.

Mann, Bradley and Hughes (1998), applied this method on a global scale to data from the past six centuries but using a 5° x 5° longitude and latitudinal scale, which was supplemented by statistical calibration to apply a standard error to each of the temperature values. This is similar to the approach taken with the temperature ranges prior to the development of the MCR but on a much larger scale.

3.6 Mutual Climate Range

The benefits of this technique are that it allows for the identification of mutual tolerances irrespective of recent geographical location. Furthermore, it removes the assumption that fossil assemblages must be similar to modern in order to match analogues (Elias, 1997; Horne, 2007).

To further develop the generic level MCRs the temperature envelopes are overlain onto a simple 1 x 1°C grid (see figure 3.6).

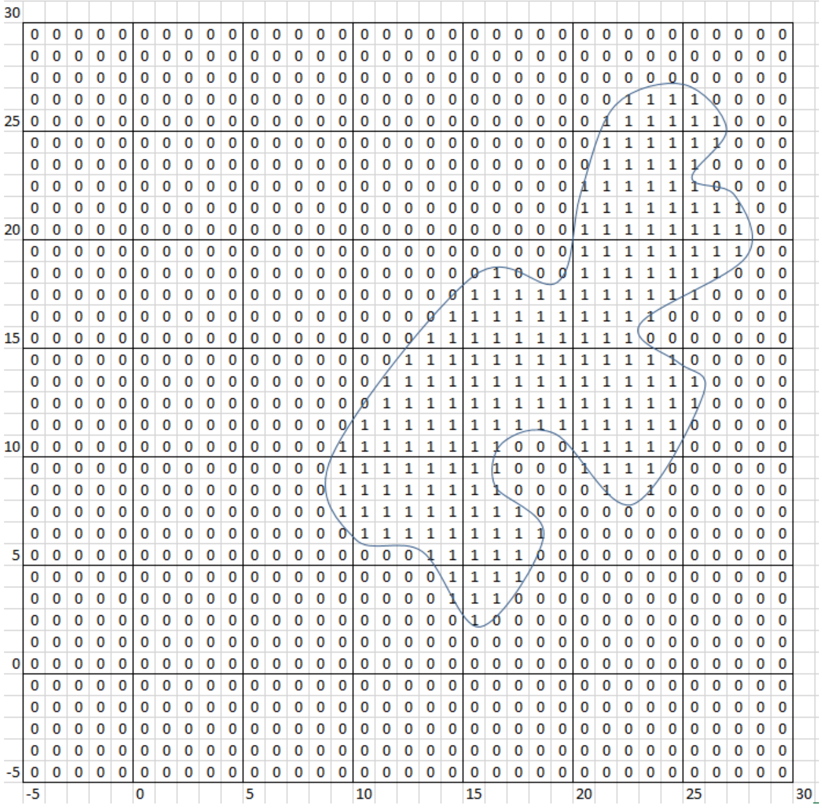

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Figure 3.6. *Aurila* MCR grid.

Individual genus MCR are compiled together for each sample, site and member to then produce the generic MCRs. This is achieved by formulating sums of presence to provide integer numbers as a representation of abundance (see figure 3.7).

This provides an alternative graphical representation of the temperature zonation that can be added to and overlain on additional genera envelopes. The most clustered zone, with the greatest overlap, is then defined as the mutual temperature zone.

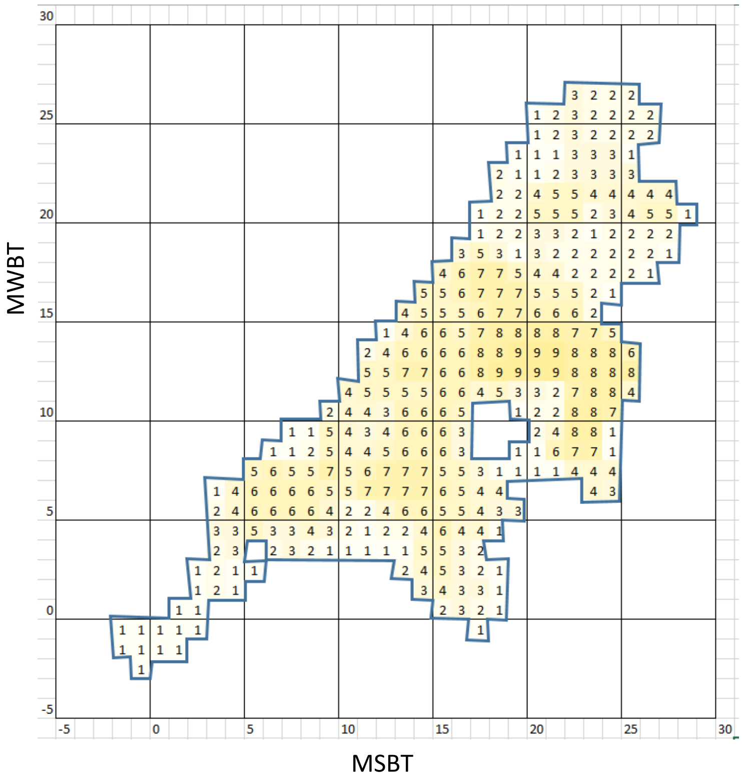

Figure 3.7. MCR for genera identified in a sample from Sutton Knoll.

The area of greatest overlap has been highlighted, however for a more accurate representation of mutuality, percentage mutuality has been used. This process takes the total genera in a sample and the number of genera in the area of greatest overlap; see equation below, using values from figure 3.7:

$$Percentage\ Mutuality = \frac{Highest\ value\ of\ overlap}{Total\ number\ of\ genera\ in\ sample}$$

$$Percentage\ Mutuality = \frac{9}{11}$$

$$Percentage\ Mutuality = 81.8\%$$

From this, the MCR can be adapted to show zones of mutuality at varying degrees, for the purpose of simplifying the results and allowing for a comparison between each MCR based upon a defined parameter. The percentage mutuality envelope that will be used will be >75%. This value was chosen based upon the number of genera in each sample and the mutuality values produced (see figure 3.8).

Mutuality values

🟥 >75%

Total genera in sample	11
Greatest overlap value	9

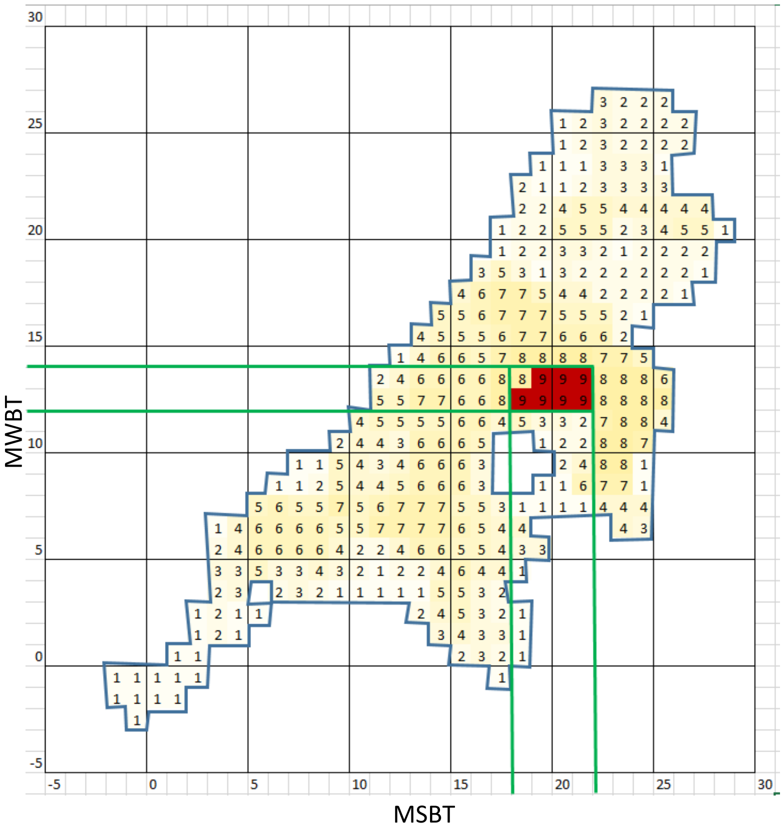

Figure 3.8. MCR with highlighted mutuality envelopes for a sample from Sutton Knoll, with green lines highlighting temperature range.

This method will be applied to the sites where the Ramsholt and Sudbourne members have been identified, as well as for composite MCRs of each member. This will then allow for an accurate comparison of the temperature envelopes produced, while also identifying samples with unique temperature ranges. Composite MCRs assume that the stratigraphical changes between the Ramsholt and Sudbourne members are negligible to the temperature reconstruction. This is in part, due to post depositional mixing of Ramsholt sediments into the Sudbourne Member.

Extant species

Two extant species *Bythocythere bradii* and *Eucythere prava* were identified during sampling (see figure 3.9) and separate temperature envelopes and MCR were developed for them individually. Separate temperature envelopes and MCR were created due to these species having modern analogues, therefore differentiating them from the assemblage.

Figure 3.9. *Bythocythere bradii* (left) and *Eucythere prava* (right) identified from sampling.

3.7 Multivariate methods of analysis

There are two important methods for multivariate analysis in palaeobiogeography, classification and ordination (Shi, 1993). The classification method uses the binary similarity coefficient technique. To reduce error both the binary similarity coefficient technique and hierarchical cluster analysis were used (Zenetos, 1991).

Binary similarity coefficient technique and cluster analysis both analyse data sets, using assemblage approaches for palaeoclimatic reconstruction (Birks *et al.* 2010). One of the main differences between the methods is the graphical representation of numerical values for binary similarity coefficient (see section 3.8) and an overall dendrogram for a cluster analysis (Shi, 1993).

Both methods can be used in an ostracodal analysis, with binary values for presence and absence of species and genera, and integer values for the abundance of each species.

3.8 Binary Similarity Coefficient method

The binary similarity coefficient method is a quantitative method for comparing modern and fossil assemblage similarity. Cocks and Fortey (1982) first used this method for the comparison of fauna across the Iapetus Ocean during its closure. It was noted that faunas of similar habitats were required during comparison to ensure a constant variable, for this thesis, climatic conditions.

The method compares the presence/ absence of taxa in an assemblage where 1 = presence/ 100% similarity and 0 = absence/ 0% similarity. The most commonly used coefficient is Jaccard, which emphasises the samples with the greatest difference (see figure 3.10) (Hazel, 1970).

Values that are closer to 1 would be preferable to show near identical similarity, however, due to the size of the database, this may be unlikely. Wood (2012) calculated Jaccard values ranging from 0.25-0.33, this suggests that if values similar to this are achieved from the binary similarity coefficient then approximations for a temperature range can be determined.

$$S_{ij} = \frac{a}{a + b + c}$$

Figure 3.10. Jaccard binary coefficient formula, where 'S_{ij}' is similarity between two values (Chhipi *et al.* 2013).

Alternatively, the Dice coefficient provides similar values highlighting the more significant samples by doubling the values of samples that are dissimilar, compared to the Jaccard coefficient, which allows for a comparison (Hall, 1969; Hazel, 1970).

$$S_{ij} = \frac{2a}{2a + b + c}$$

Figure 3.11. Dice binary coefficient formula (Meyer *et al.* 2004).

Presence/ absence data for fossil and recent faunas are compared at the generic level with the Wood binary database (unpublished data). For the purposes of this work, the Dice method will be utilised, due to the higher correlation values it produces, which will allow for a more accurate analysis of the genera.

3.9 Cluster analysis

A wide variety of clustering techniques were initially proposed by Sokal and Sneath (1963), the most common methods are weighted and unweighted pair group, WPGM and UPGM. The pair group methods work by plotting individual objects into a cluster during a single computational cycle. Based on the highest average of similarities to the group of the cluster, equal weighting is given to each sample, WPGM applies equal weighting at the start of each cluster, while UPGM applies equal weighting throughout the entire cluster (Hazel, 1970).

Hierarchical or agglomerative clustering can use the centroid technique to calculate the similarity of two clusters using the cosine correlation of the centroids of those clusters (Steinbach, Karypis and Kumar, 2000). The nearest neighbour technique applies a class to each value and assigns a cluster and is similar to the centroid method. Errors in clustering may occur if the nearest neighbour is unreliable (Guha, Rastogi and Shim, 2000).

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Figure 3.12. Processes and procedures for a multivariate analysis of palaeontological data (Shi, 1993).

Outliers in the data set may not be identified from hierarchical clustering, as the value may be put in a cluster of nearest significance (Shi, 1993). While the resulting dendrogram may not be affected in distribution by outliers, making them harder to identify through this method.

Hierarchical clustering is represented as a dendrogram displaying inter-relationships between clusters (Bobisud and Bobisud, 1972; Podani, 1989). The dendrogram used herein is polytomous being applied to observe relationships between presence and abundance at the species level from each sample and site (see figure 3.13).

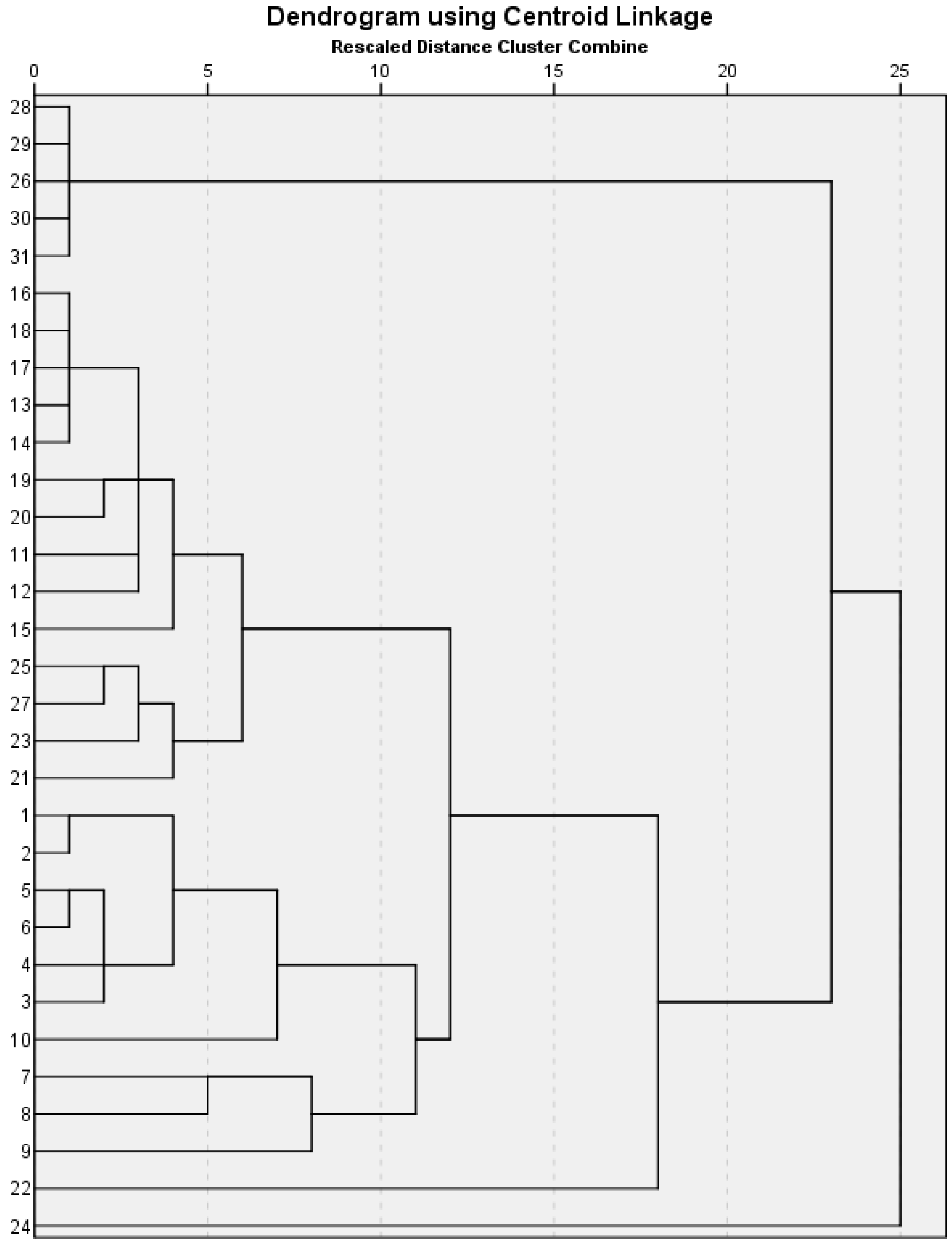

Figure 3.13. Centroid method dendrogram using species similarity and abundances from all samples.

3.10 Simpson and Margalef indices

Biodiversity of the ostracod species was calculated using two indices: Simpson and Margalef. The Simpson Index highlights more dominant species in a sample and is calculated using the formula below (Viehberg and Pienitz, 2017):

$$D = \sum \frac{n(n-1)}{N(N-1)}$$

Where D = Simpson Index, n = number of individual species and N = total number of individual specimens in the sample. The value 'D' is then converted into its reciprocal form to reflect the index increasing with diversity:

$$Reciprocal = \frac{1}{D}$$

The Margalef Index determines the species richness/ density in a sample, which is affected by the sample size, the formula for this index is below. Where Dmg = Margalef Index, S = Species abundance in the sample and N = total number of individual specimens in sample (Gamito, 2010):

$$Dmg = \frac{S-1}{\ln N}$$

The values from both indices will reveal the diversity and density of each sample and site as well as a composite calculation, which will allow for an intercomparison. It will then be possible to deduce depositional environments of the sites.

4. Results

This chapter presents the field and laboratory data used to reconstruct watermass temperature and other environmental conditions for the Coralline Crag Formation of Suffolk. In the first instance, sedimentary logs provide a summary of the local stratigraphy, sedimentary structures and thus palaeoenvironmental conditions during the deposition of the Ramsholt and Sudbourne members.

Generic temperature envelopes were developed for the application in MCR analysis. The process of MCR construction is reviewed and errors with acceptance values defined. For the Ramsholt and Sudbourne members, ostracod-based MCRs are developed with inter-site and member comparisons made, and a cluster analysis was undertaken.

4.1 Sedimentary logs

Sedimentary logs were drawn from photographs and data collected in the field. Sed Log 3.1 was used to create the digital versions of the sedimentary logs seen in this chapter, displaying petrology, sedimentary structures, fossils and the transition between the Ramsholt and Sudbourne members, and allow for inter site comparison of the Coralline Crag Formation.

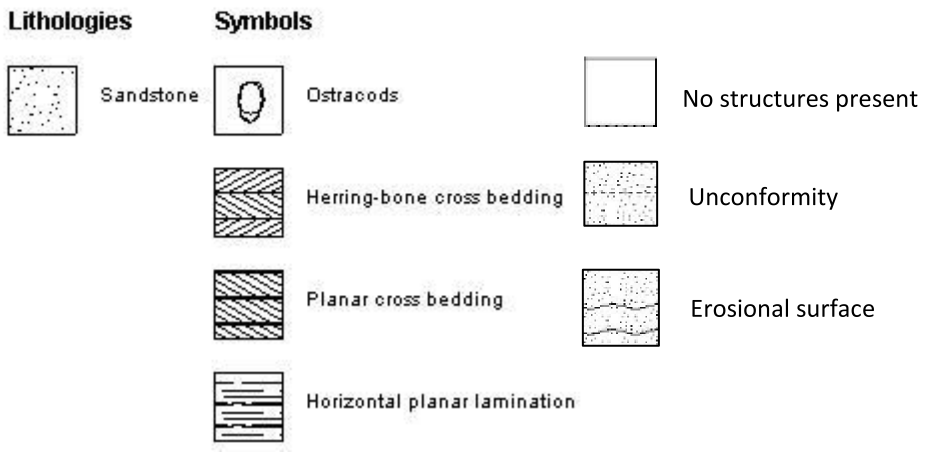

Figure 4.1. Sedimentary logs key.

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Figure 4.2. Lithostratigraphic relationships between the six sample sites, black lines showing similar lithostratigraphy between sites, red line highlighting the unconformity between the deposition of the Ramsholt and Sudbourne members and scale bar (Balson et al. 1993; Lisiecki and Raymo, 2005).

4.2 Genera temperature envelopes and MCR

Temperature envelopes for each genus were produced using the Wood binary database (unpublished data) which details mean summer (MSBT) and winter (MWBT) bottom water temperature for genera from the Equator to the North Pole from 3˚N to 80˚N.

Figure 4.3. Location of *Aurila* genus ostracods in the North Atlantic from the Wood binary database (unpublished data), averaged temperature values for these locations are used to create the generic temperature envelopes.

After the temperature values have been calculated, a bivariate plot of MSBT and MWBT is produced (see figure 4.4).

Figure 4.4. *Aurila* temperature envelope (left) and binary plot on MCR (right) developed from Wood binary database (unpublished data).

The temperature envelope includes a 1 sigma error (see section 3.5) calculated as *c.* +/- 1°C, based on 90 years of temperature data at each site. This was then converted to a simple presence and absence Excel plot (see figure 4.5).

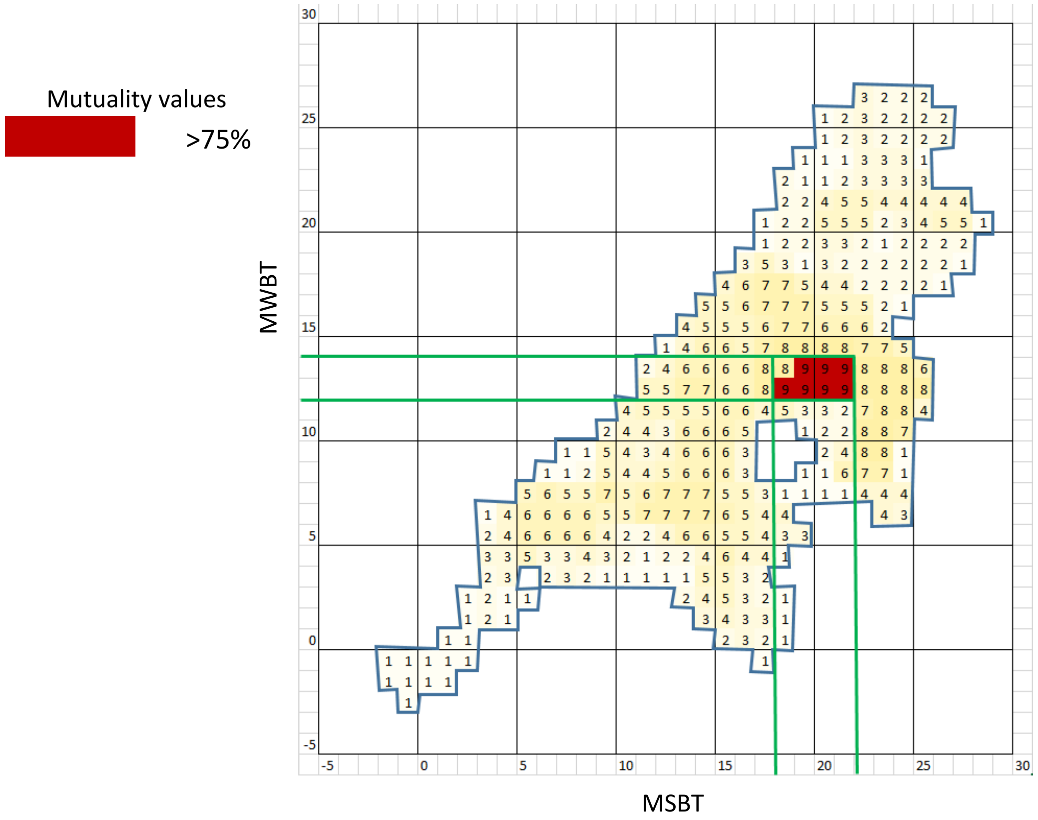


Figure 4.5. Generic MCR for sample 1 at Sutton Knoll Site 1, with area of greatest mutuality (overlap) highlighted.

A MCR plot is then produced by overlapping the temperature envelopes for all genera in any given sample. The 9 of the 11 total genera of the Sutton Knoll site 1 sample 1 display a mutual overlap of 81.8%.

Example of mutuality using figure 4.5:

$$\%mutuality = \frac{highest\ value\ of\ overlap}{total\ genera\ in\ sample}$$

$$\%mutuality = \frac{9}{11}$$

$$\%mutuality = 81.8\%$$

4.3 Mutual Climatic Ranges and temperature reconstruction

The generic-level MCRs help define the temperature range for each sample and site assemblage, in addition, temperature envelopes can be constructed for the Ramsholt and Sudbourne members, and Coralline Crag Formation as a whole using composite samples.

Following the mutuality calculation, one percentage range was used to highlight zones of mutuality, >75%. Genera are used herein as only two extant species were discovered from sampling. Consequently, 33 genera were identified and used to develop the MCR for individual samples and members. All sample MCRs can be found in Appendix B.

Ramsholt Member MCR for the individual sites

MCRs were produced for the individual sites where the Ramsholt Member occurs (see figures 4.6-4.9).

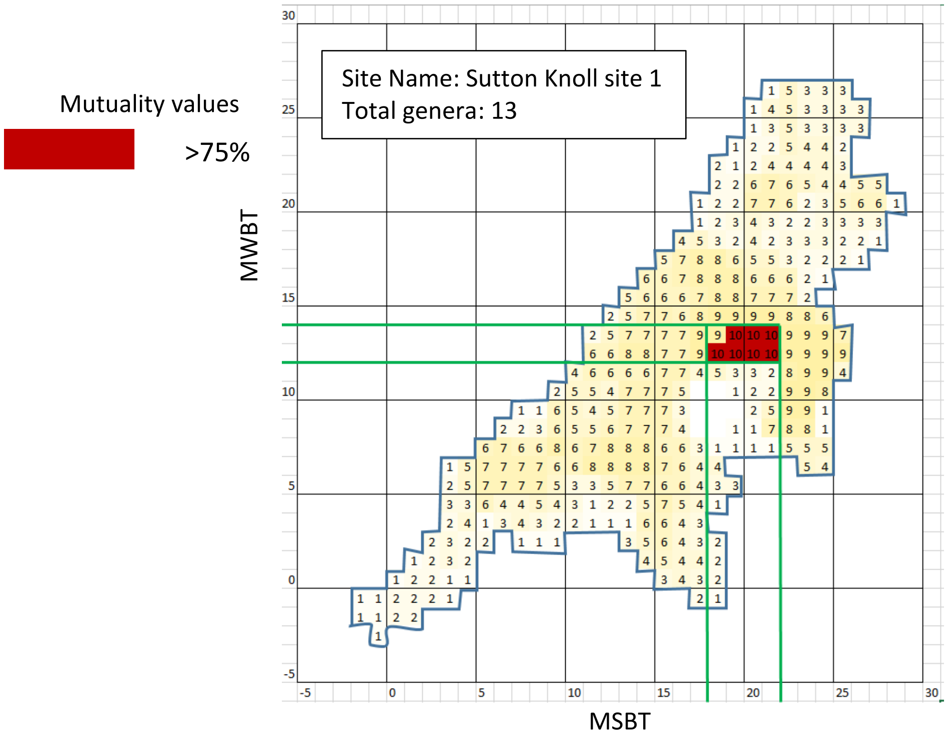


Figure 4.6. MCR plot for the Ramsholt Member at Sutton Knoll site 1 with mutuality values of >75% highlighted. Temperature ranges are defined by green intersecting lines.

The >75% envelope constrains the temperature range to 18-20°C MSBT and 12-13°C MWBT, with the generic mutuality percentage for this site being 76.9%.

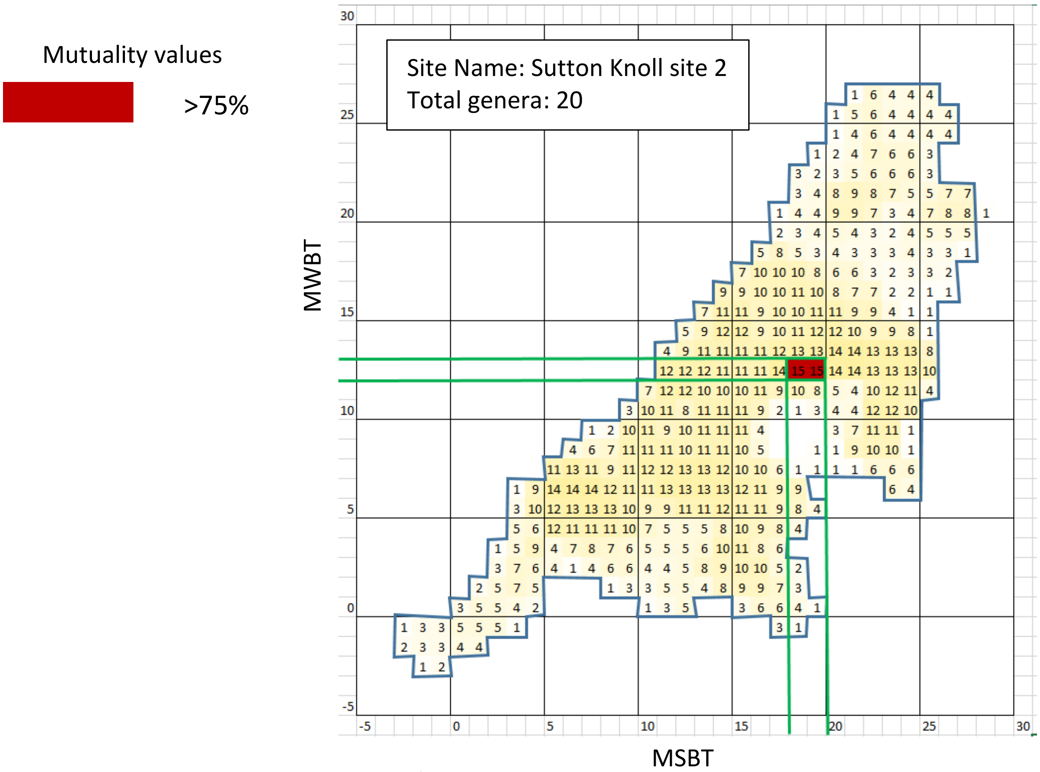


Figure 4.7. MCR plot for the Ramsholt Member at Sutton Knoll site 2 with mutuality values of >75% highlighted. Temperature ranges are defined by green intersecting lines.

The temperature range for the Ramsholt Member at Sutton Knoll site 2 is narrower with a greater number of genera producing a temperature range of 18-20˚C MSBT, 12-13˚C MWBT with the mutuality percentage slightly lower at 75%.

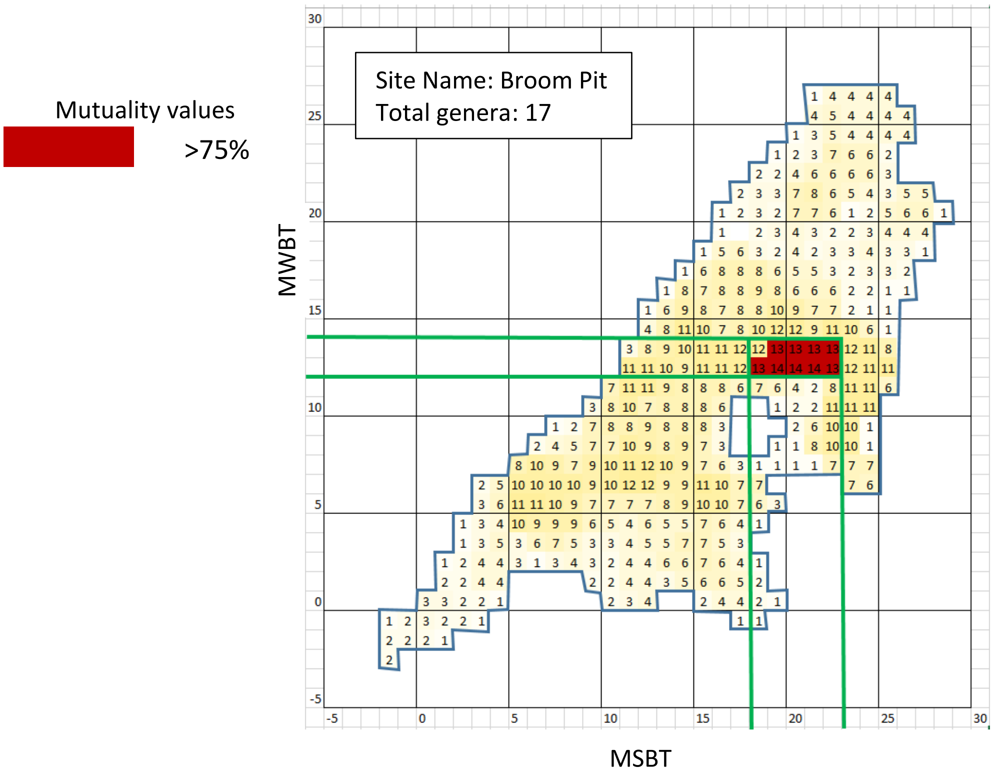


Figure 4.8. MCR plot for the Ramsholt Member at Broom Pit with mutuality values of >75% highlighted. Temperature ranges are defined by green intersecting lines.

The temperature envelope identified by the >75% mutuality has a temperature range of 18-23°C MSBT, 12-14°C MWBT. The number of genera at this site is similar to Sutton Knoll site 2 and a generic mutuality percentage ranging from 76.5-82.3%.

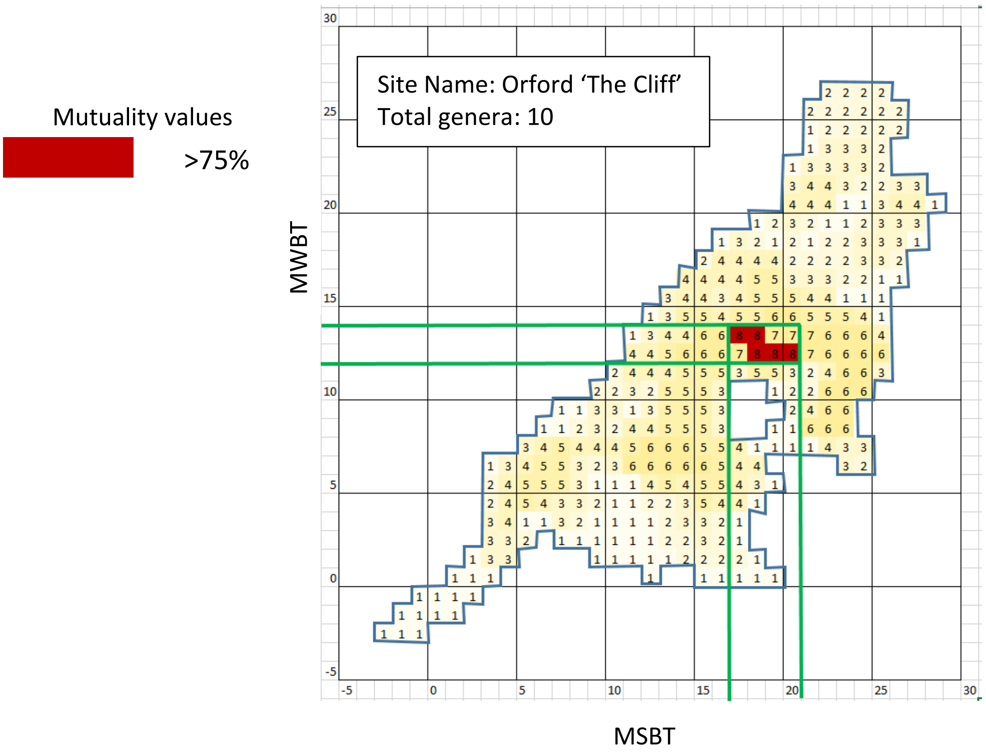


Figure 4.9. MCR plot for the Ramsholt Member at Orford 'The Cliff' with mutuality values of >75% highlighted. Temperature ranges are defined by green intersecting lines.

The >75% mutuality values at 80%, produce a temperature range of 17-21°C MSBT, 12-14°C MWBT, with 8 genera in the greatest overlap.

Ramsholt Member MCR

A composite MCR plot for the Ramsholt Member has been produced with the >75% mutuality level added.

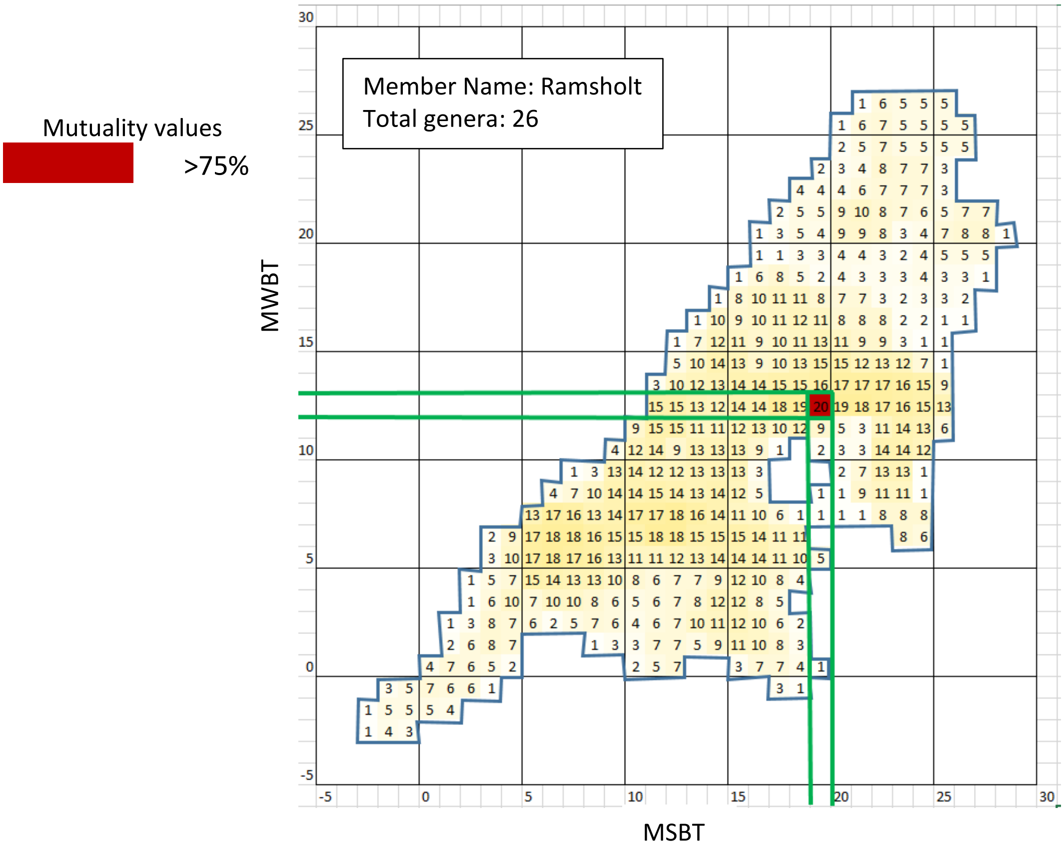


Figure 4.10. MCR plot for the Ramsholt Member with mutuality values of >75% highlighted. Temperature ranges are defined by green intersecting lines.

A total of 26 genera were identified in the Ramsholt Member with a maximum of 20 genera overlapping, producing a generic mutuality percentage of 76.9%. At the >75% mutuality a temperature range of 19-20°C MSBT, 12-13°C MWBT is identified.

Sudbourne Member MCR for individual sites

MCRs were produced for the individual sites where the Sudbourne Member occurs (see figures 4.11-4.14).

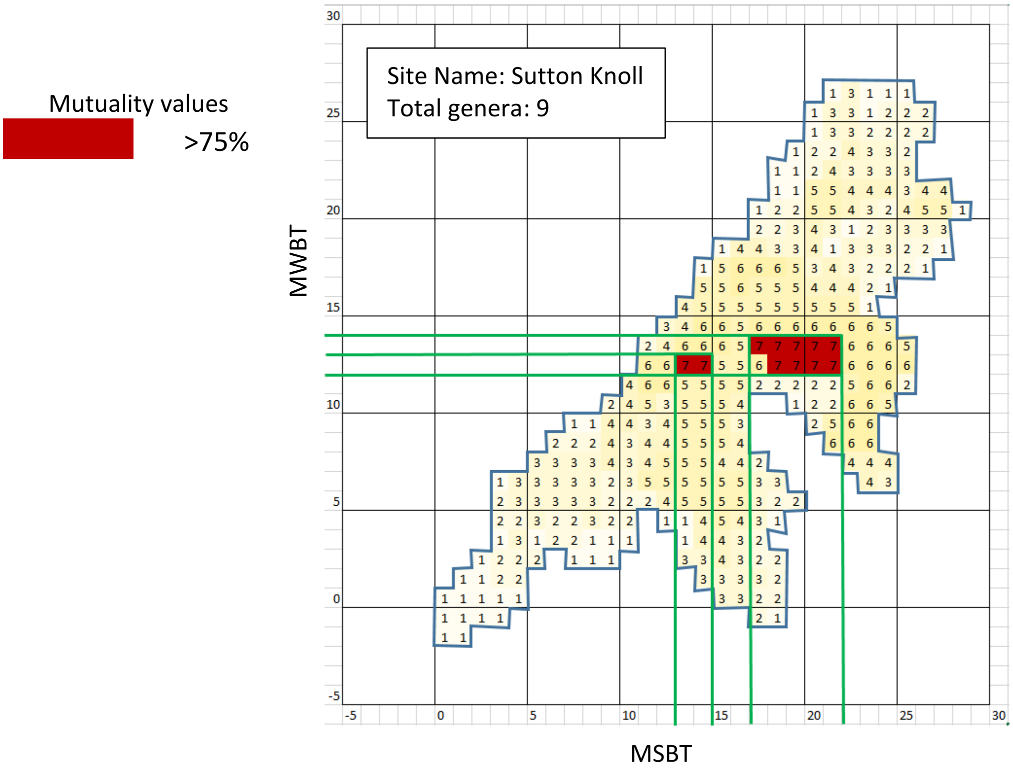


Figure 4.11. MCR plot for the Sudbourne Member at Sutton Knoll site 1 with mutuality values of >75% highlighted. Temperature ranges are defined by green intersecting lines.

Fewer genera are identified at the >75% mutuality with the temperature ranges defined at 13-15˚C MSBT, 12-13˚C MWBT for the small envelope and 17-22˚C MSBT, 12-14˚C MWBT for the larger envelope from a mutuality percentage of 77.7%.

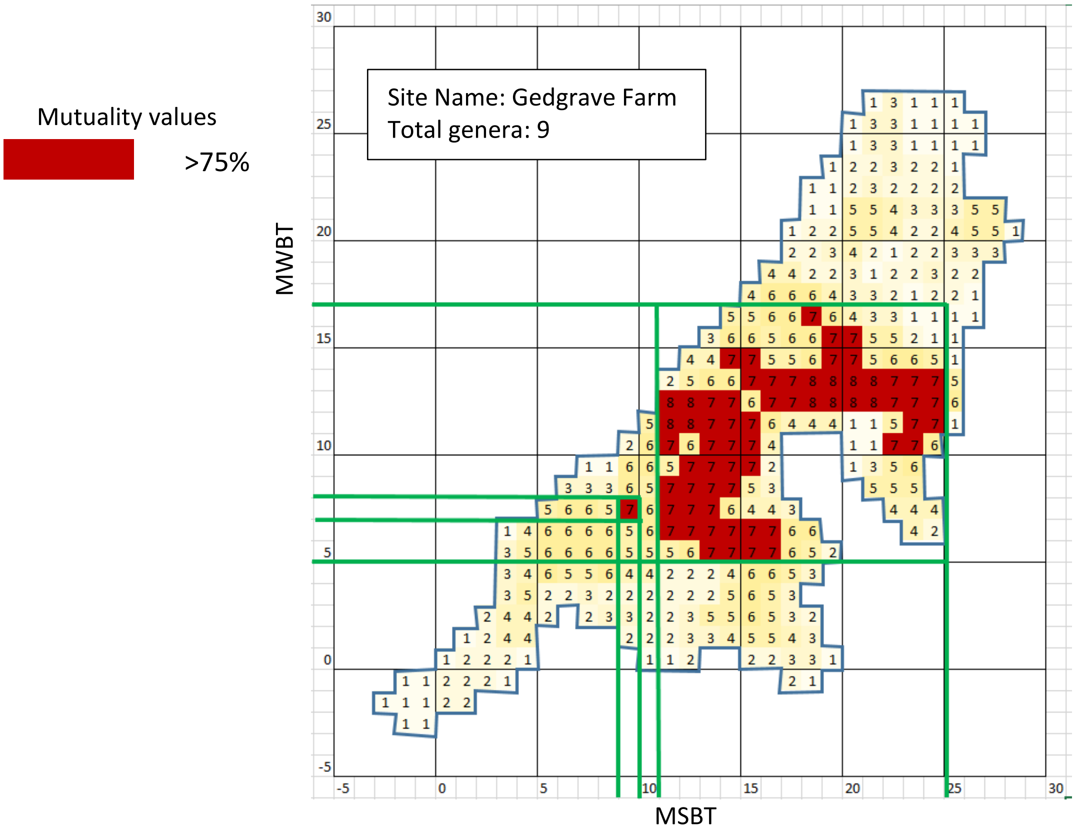


Figure 4.12. MCR plot for the Sudbourne Member at Gedgrave Farm with mutuality values of >75% highlighted. Temperature ranges are defined by green intersecting lines.

Gedgrave Farm identifies the largest temperature envelope from both the members at individual sites, with a generic mutuality percentage range of 77.7-88.8%. Values >75% highlighted, produced two envelopes with temperature ranges of 9-10˚C MSBT, 7-8˚C MWBT and 11-25˚C MSBT, 5-17˚C MWBT.

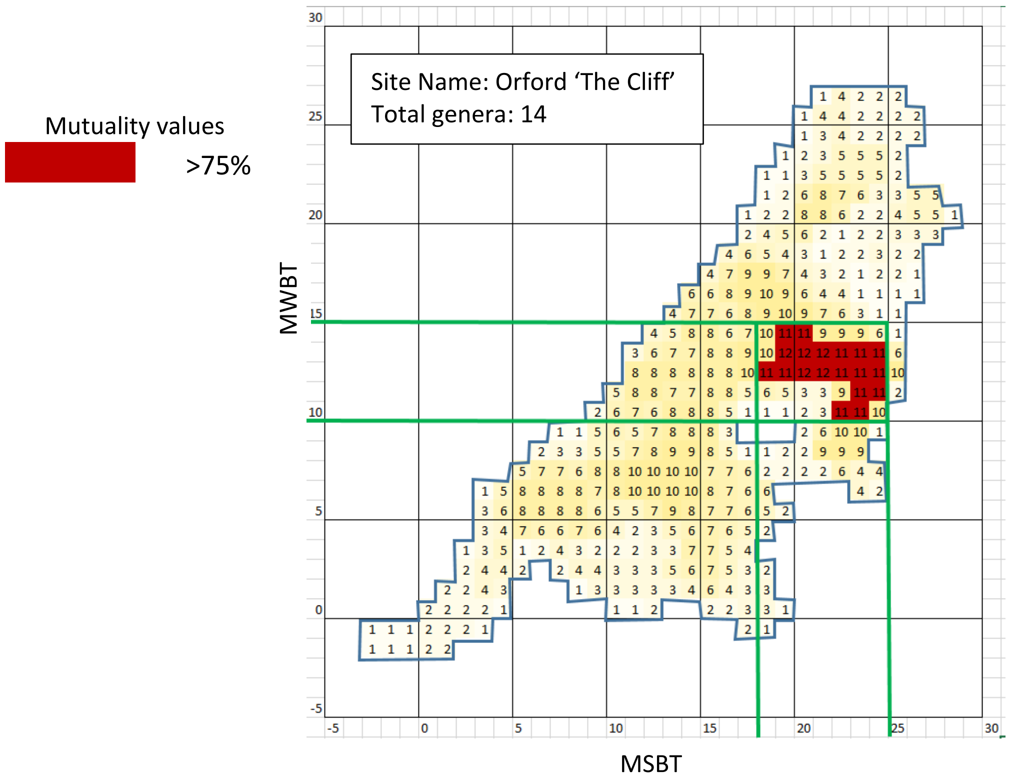


Figure 4.13. MCR plot for the Sudbourne Member at Orford ‘The Cliff’ with mutuality values of >75% highlighted. Temperature ranges are defined by green intersecting lines.

The >75% mutuality values produce the second largest temperature range from sampling of 18-25˚C MSBT, 10-15˚C MWBT, from a generic mutuality percentage range of 78.5-85.7%.

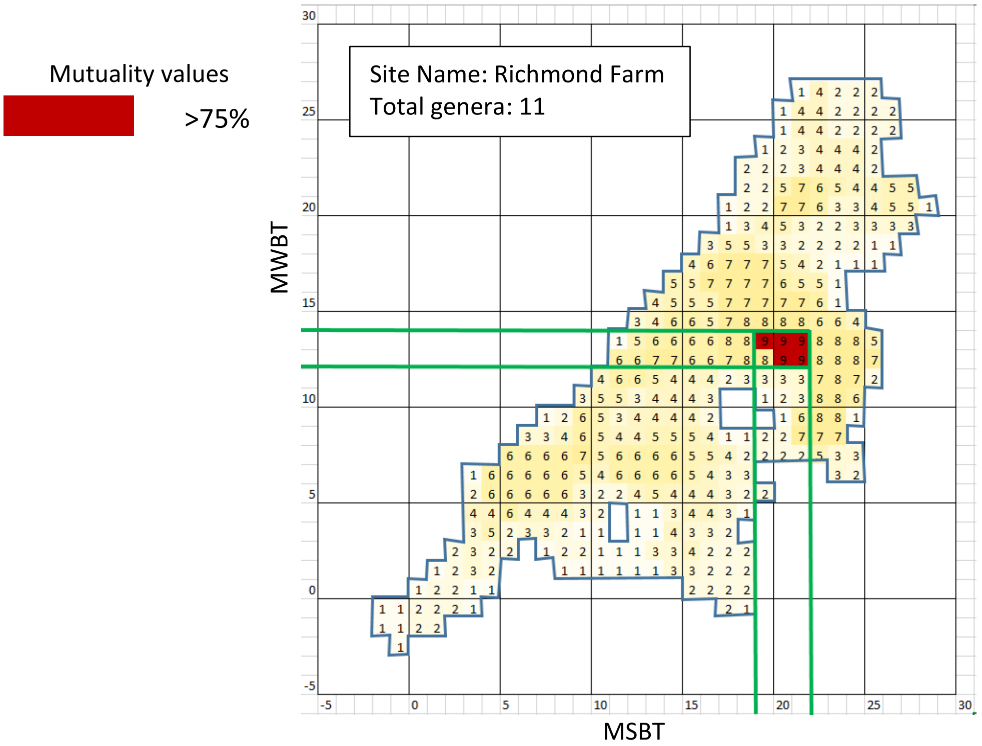


Figure 4.14. MCR plot for the Sudbourne Member at Richmond Farm with mutuality values of >75% highlighted. Temperature ranges are defined by green intersecting lines.

Richmond Farm produces a single temperature envelope with generic mutuality percentage of 81.8%. The mutuality values >75% produce a temperature range of 19-22˚C MSBT and 12-14˚C MWBT.

Sudbourne Member MCR

Similarly, to the Ramsholt Member, a composite MCR has been produced for the Sudbourne Member with the same >75% mutuality envelope identified, to produce a temperature envelope.

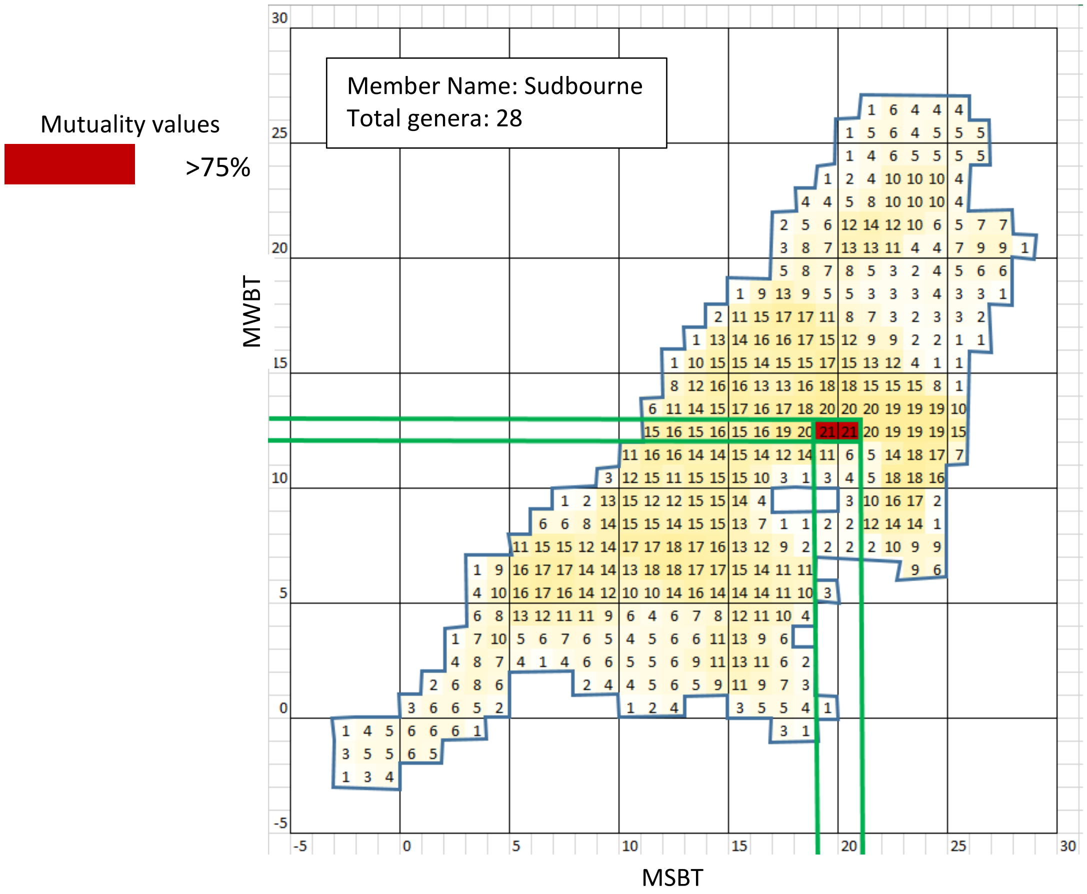


Figure 4.15. MCR plot for the Sudbourne Member with mutuality values of >75% highlighted. Temperature ranges are defined by green intersecting lines.

The >75% mutuality values produce a temperature range of 19-21˚C MSBT, 12-13˚C MWBT, with 21 genera from the 28 identified in the Sudbourne Member producing a generic mutuality percentage of 75%.

4.4 Multivariate Analysis

Two methods of multivariate analysis were applied to the ostracod data set: binary similarity coefficient and cluster analysis. The binary similarity coefficient generates values of correlation (similarity) between the fossil and recent generic-level assemblages.

The Dice method was used, it produces values between 0 (zero correlation) and 1 (100% correlation). This research produced values from 0 to 0.571 with an average 0.114 and a standard deviation of 0.012. The upper and lower bounds of the average have been calculated as below:

$$Upper\ bound = Avg. + 2\ x\ Standard\ Deviation$$

$$Upper\ bound = 0.138$$

$$Lower\ bound = Avg. - 2\ x\ Standard\ Deviation$$

$$Lower\ bound = \ 0.089$$

Values above 0.5 were used to highlight fossil and recent assemblages of similar faunal structure. The recent proxies thus provide MSBT and MWBT. The outcomes from the graphs will provide a first approximation of temperature for the Ramsholt and Sudbourne members.

Key	
●	Sutton Knoll
▲	Broom Pit
■	Orford 'The Cliff'
1-12	Sample Number

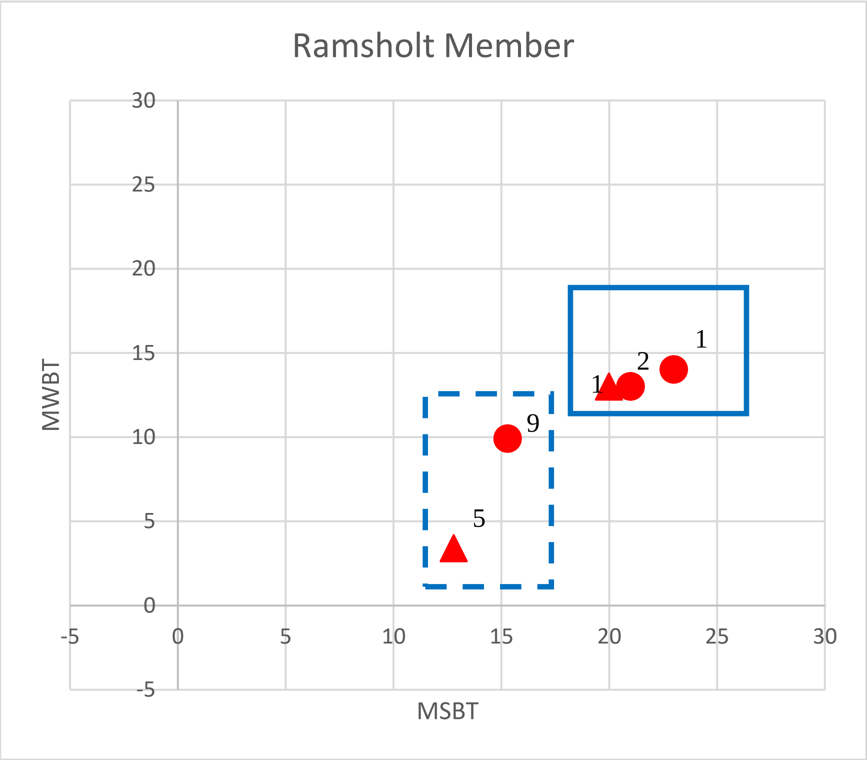


Figure 4.16. Dice binary similarity coefficient values >0.5 for the Ramsholt Member, solid blue box identifying warm zone, dashed blue box identifying colder zone. Temperature values are derived from the Recent-analogues.

Dice similarity values for the Ramsholt Member ranged from 0.5-0.563, with Sutton Knoll (sample 1) the highest value. There are three points [box] with a temperature range of 20-23˚C MSBT, 13-14˚C MWBT. Two points [dashed box], with similarity of 0.5 indicate cooler temperatures regions at 12.8˚C MSBT, 3.4˚C MWBT; 15.3˚C MSBT, 9.9˚C MWBT.

Key	
●	Sutton Knoll
■	Orford 'The Cliff'
✕	Gedgrave Farm
1-12	Sample Number

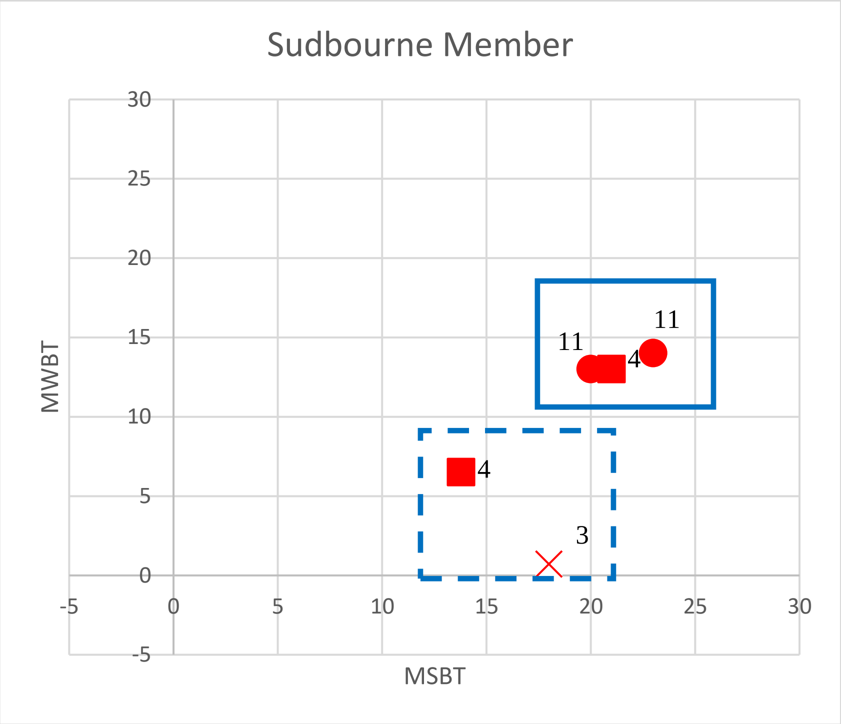


Figure 4.17. Dice binary similarity coefficient values >0.5 for the Sudbourne Member, solid blue box identifying warm zone, dashed blue box identifying colder zone. Temperature values are derived from the Recent-analogues.

The values of similarity between the recent database and the Sudbourne Member range from 0.5-0.571, with the highest values at Sutton Knoll (sample 11). There is a cluster of points in the temperature range of 20-23˚C MSBT, 13-14˚C MWBT [box]. While the two other points have correlation values of 0.5, with a narrow temperature range [dashed box].

Extant species for climatic comparison

Extant species, when compared to genera, are indicative of much more precise modern climate conditions, while their fossil counterparts represent conditions from a defined period (Cusminsky et al. 2011). *Bythocythere bradii* and *Eucythere prava* are recovered from the Coralline Crag Formation (Mezquita et al. 2005; Cusminsky et al. 2011).

4.5 Cluster Analysis

The second multivariate analysis utilised, was hierarchical clustering. An introduction to the methodology is outlined in section 3.9. The clustering determines the relationships based on the abundance of species.

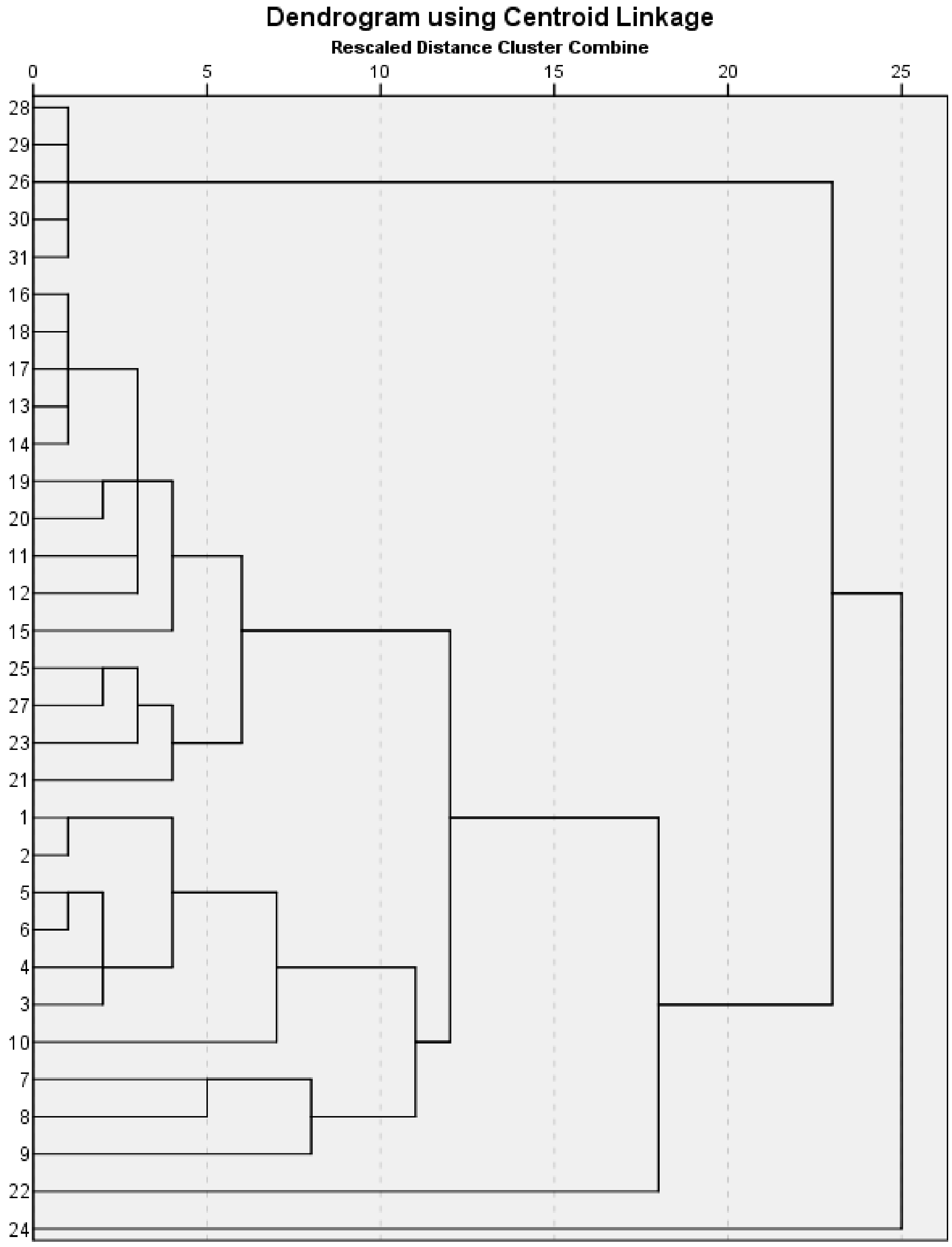


Figure 4.18. Cluster diagram of species assemblage from the Coralline Crag Formation, using the (Centroid clustering and the Squared Euclidian method).

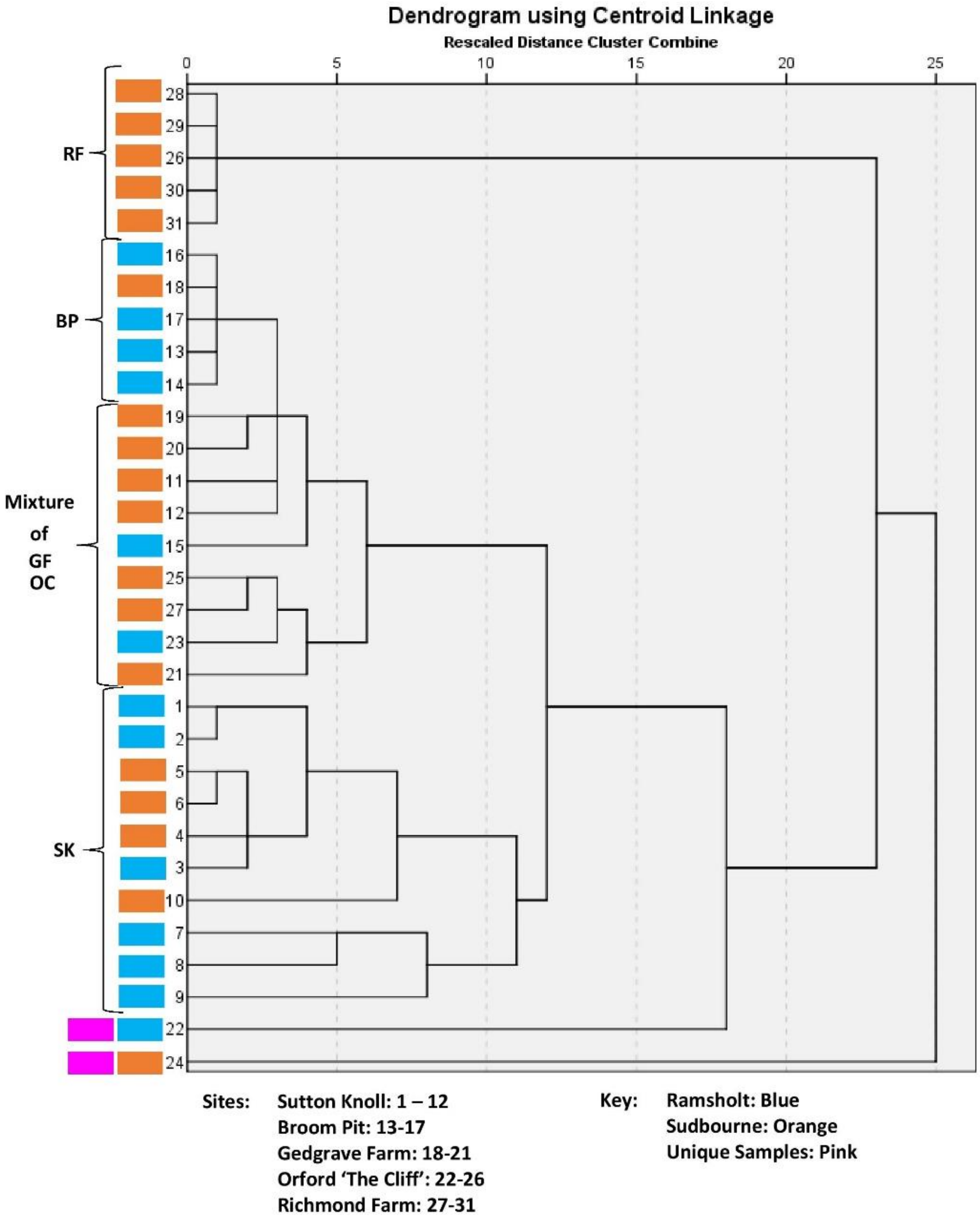


Figure 4.19. Annotated centroid cluster dendrogram.

Three of the five sample sites can be identified in the dendrogram, while assemblages from Gedgrave and Orford 'The Cliff' are intermixed. There are no definitive trends separating the Ramsholt or Sudbourne members. There are two unique samples (samples 22 and 24), both from Orford 'The Cliff', from each member.

4.6 Simpson and Margalef index values

The Simpson and Margalef values have been calculated for each sample and member at the sites. This has quantified the diversity of the ostracods and allowed for a comparison between the members to identify any trends.

Sample	Simpson Index Value	Margalef Index Values
SK1	8.28	4.75
SK2	3.78	2.58
SK3	9.62	2.91
SK4	5.00	2.52
SK5	26.25	4.06
SK6	14.00	2.40
SK7	12.25	5.65
SK8	5.77	4.28
SK9	3.38	3.23
SK10	12.23	3.78
SK11	7.23	4.28
SK12	10.58	5.38
BP1	4.43	3.18
BP2	5.51	3.05
BP3	4.79	4.21
BP4	4.13	3.00
BP5	4.06	3.37
GF1	2.47	2.11
GF2	3.50	1.84
GF3	9.42	2.81
GF4	5.04	3.34
OC1	7.98	3.94
OC2	5.05	3.52
OC3	2.69	3.23
OC4	5.52	3.28
OC5	15.60	3.11
RF1	4.28	3.10
RF2	2.00	0.72
RF3	0.00	3.64
RF4	10.90	3.60
RF5	3.71	2.33

Table 4.1. Simpson and Margalef index values for each sample rounded to 2 d.p.

There are trends between samples, particularly at the Sutton Knoll site where there are variations between the diversity values for the members. While the Broom Pit Simpson and Margalef values remain relatively constant with no significant change. At Gedgrave Farm and Richmond farm both indices produce sporadic values for diversity with no trend, while at Orford 'The Cliff' a trend may be discernible between the Ramsholt and Sudbourne member samples (see table 4.2).

Member	**Simpson Index Value**	**Margalef Index Value**
SK Site 1 Ramsholt	6.47	5.12
SK Site 1 Sudbourne	9.62	5.18
SK Site 2 Ramsholt	6.01	7.57
SK Site 2 Sudbourne	10.36	7.83
OC Ramsholt	7.43	5.09
OC Sudbourne	4.04	5.79

Table 4.2. Simpson and Margalef index values for members at sites where transitions occur rounded to 2 d.p.

The values for Table 4.2 were calculated by identifying the specimens present at each site and then producing the index values following the same formula used for the individual samples. At both Sutton Knoll sites, there is a clear increase in both indices from the Ramsholt to the Sudbourne Member, while Orford 'The Cliff' sees the opposite to this trend with a decrease from the Ramsholt to the Sudbourne Member with the Simpson index. However, Orford 'The Cliff' does see an increase in the Margalef index similar to both Sutton Knoll sites.

4.7 Summary

The results provide the foundation upon which a critical analysis of the methodologies and temperature ranges produced can be discussed in the following section.

5. Analysis and Discussion

This chapter provides an analysis and a discussion of the methodologies and results used to help determine bottom water mass temperature during the Pliocene of Suffolk.

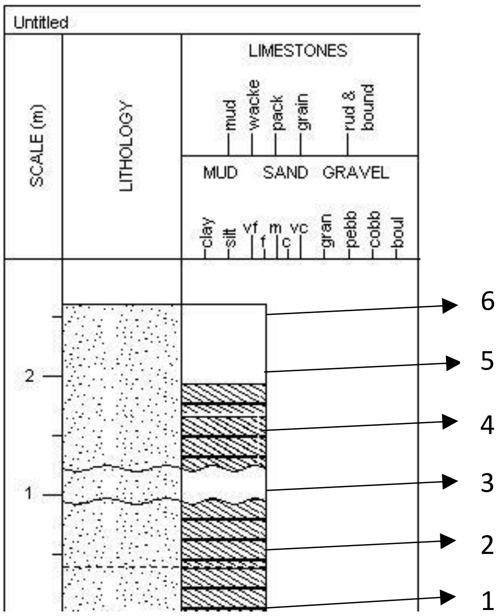
5.1 Sedimentary log locations and members

Sedimentary successions have been logged and sampled and an ostracodal analysis has been undertaken to reconstruct temperatures for the members of the Coralline Crag Formation. It will then be possible to determine any transitions within and between the Ramsholt and Sudbourne members. The Pliocene temperatures produced can be compared to the modern values for the southern North Sea of 16.6± 1˚C for summer and 6± 1˚C for winter (Wood, 2012).

Sutton Knoll site 1

Following the methodology outlined in section 3.5, the >75% generic mutuality values were applied to determine the temperature ranges at the sites. The average mutuality range from all samples was 80.1%, with a range from 66.6-100% for individual samples (see Appendix B).

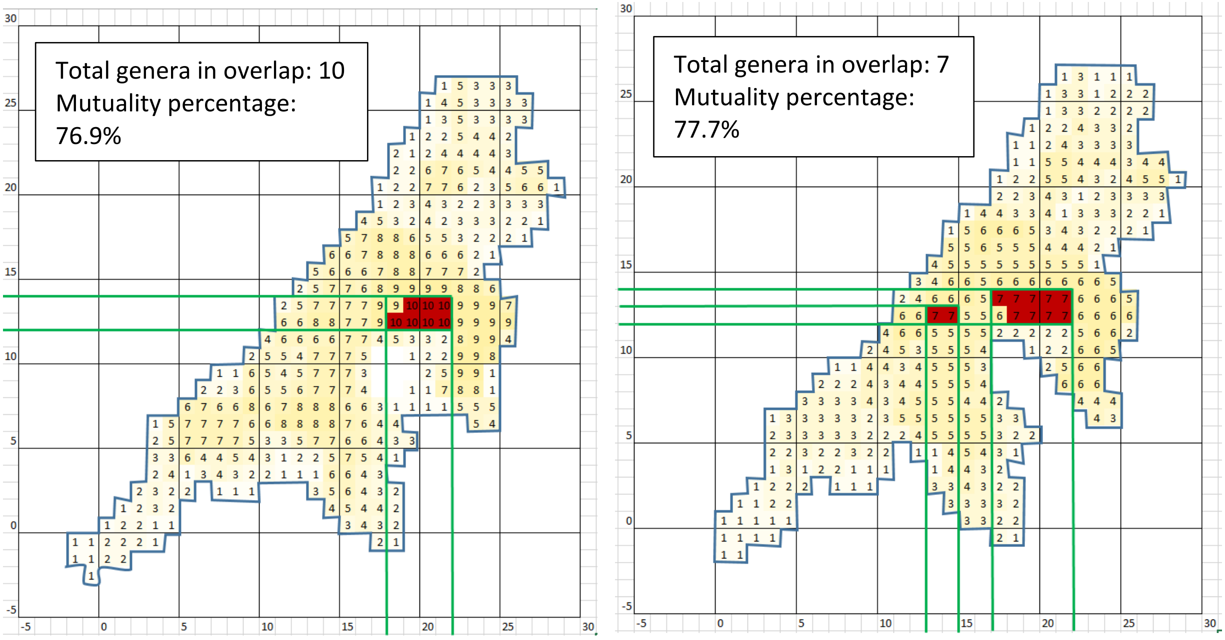
The sites provide a first approximation for the temperatures of the Ramsholt and Sudbourne members. The transitions between the members reflect any changes in genera density that occur between the Ramsholt and Sudbourne (Dowsett and Poore, 1991).



Sample numbers: 4, 5, 6
Member: Sudbourne
Temperature Ranges: 13-15˚C MSBT, 12-13˚C MWBT and 17-22˚C MSBT, 12-14˚C MWBT
Total genera: 9
Total species: 20
Genera mutuality value: 77.7%
Simpson Value: 9.62
Margalef Value: 5.18

Sample numbers: 1, 2, 3
Member: Ramsholt
Temperature Range: 18-22˚C MSBT, 12-14˚C MWBT
Total genera: 13
Total species: 23
Genera mutuality value: 76.9%
Simpson Value: 6.47
Margalef Value: 5.12

Figure 5.1. Sutton Knoll site 1 sedimentary log with sampled horizons, member names, temperature ranges, genera number, species number, genera mutuality values and Simpson and Margalef species values.


Total genera in overlap: 10
Mutuality percentage: 76.9%

Total genera in overlap: 7
Mutuality percentage: 77.7%

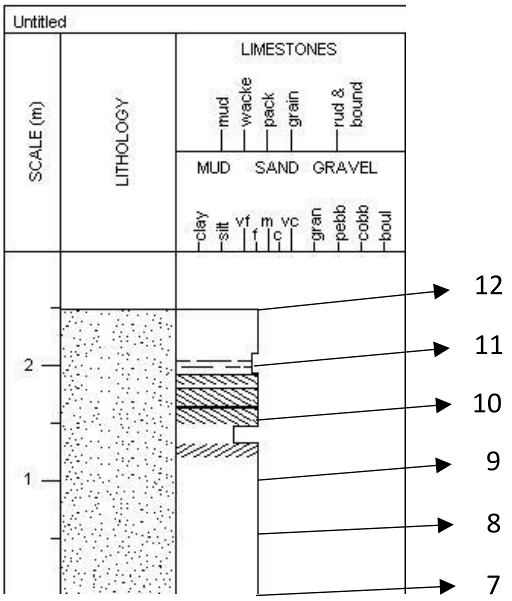
Figure 5.2. Ramsholt Member (left) and Sudbourne Member (right) at Sutton Knoll site 1 MCRs, with >75% mutuality values highlighted and temperature ranges identified by green lines.

The temperature ranges for the Ramsholt and Sudbourne members are nearly the same, with only a small envelope for the Sudbourne Member deviating from this trend. When compared to the modern temperatures it shows that the Ramsholt Member was warmer by 1.4-5.4˚C for summer temperatures and 6-8˚C for winter temperatures. While the Sudbourne Member is 0.4˚C-5.4˚C warmer for summer temperatures and 6-8˚C for winter temperatures, which suggests that the Ramsholt and Sudbourne are equally warmer than modern. This suggests that there is no discernible variance in temperature from the deposition of the Ramsholt to the Sudbourne.

The quantity of genera and species at this site suggests a decrease in number of species and genera from the Ramsholt to the Sudbourne, however, the Simpson and Margalef values suggest an increase in diversity of ostracods in the Sudbourne Member. This could be a result of the reworking of the Ramsholt sediments during the deposition of the Sudbourne, which is visible with the cross-bedded stratigraphy, indicative of a high-energy environment (Daley and Balson, 1999). Similarly, the reworking may have allowed adult species of more adaptable ostracods to be preserved from the Ramsholt in the Sudbourne, such as species of *Aurila*. It is assumed that the species are native to both the Ramsholt and Sudbourne due to similar climatic conditions.

It is observed at this site that the strata and cross beds present in the Ramsholt Member are particularly fine in texture, suggesting a low energy environment and prolonged depositional process. Conversely those present in the Sudbourne Member, with a trend from N.E-S.W. are much coarser in texture and larger at a height of approximately 75 cm. This suggests a potential tidal environment, with the unconformable layer between the Ramsholt and Sudbourne suggesting reworking or turbidity currents abrading the Ramsholt Member, thus resulting in the inclusion of species from the Ramsholt in the Sudbourne (Daley and Balson, 1999). From this it is possible to deduce that the Sudbourne Member was deposited in a similar climatic environment however, the energy levels were far greater, possibly due to the introduction of a stronger North Sea oceanic current.

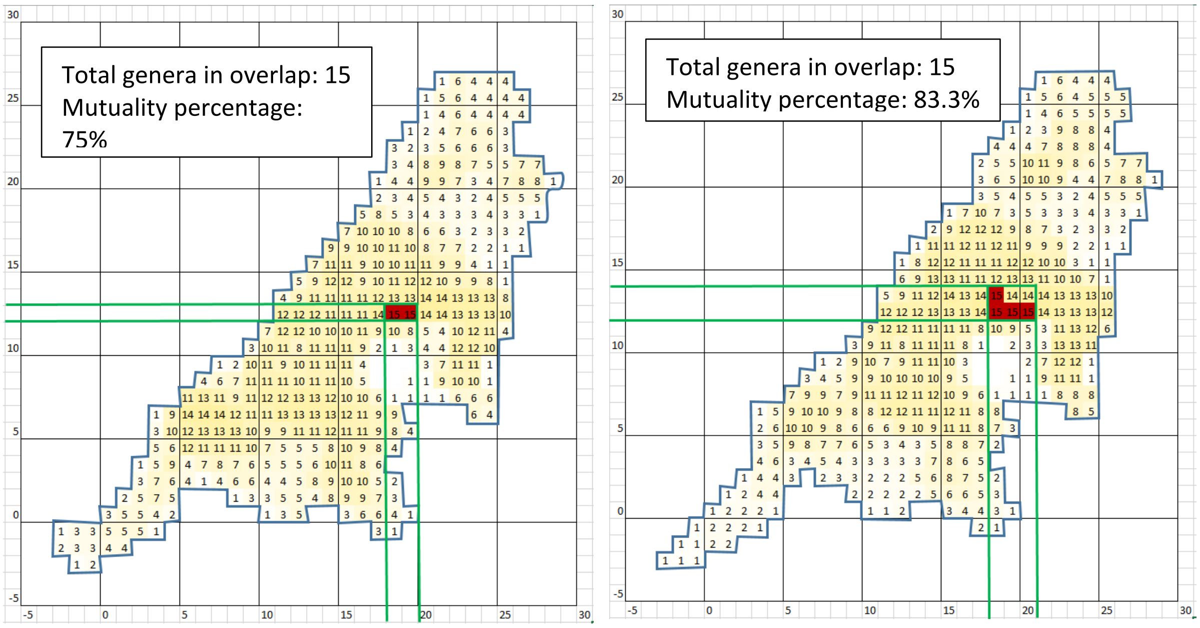
Sutton Knoll site 2



Sample numbers: 10, 11, 12
Member: Sudbourne
Temperature Range: 18-21˚C MSBT, 12-14˚C MWBT
Total genera: 18
Total species: 37
Genera mutuality value: 77.7%
Simpson Value: 10.3
Margalef Value: 7.83

Sample numbers: 7, 8, 9
Member: Ramsholt
Temperature Range: 18-20˚C MSBT, 12-13˚C MWBT
Total genera: 20
Total species: 38
Genera mutuality value: 75%
Simpson Value: 6.01
Margalef Value: 7.57

Figure 5.3. Sutton Knoll site 2 sedimentary log with sampled horizons, member names, temperature ranges, genera number, species number, genera mutuality values and Simpson and Margalef species values.


Total genera in overlap: 15
Mutuality percentage: 75%

Total genera in overlap: 15
Mutuality percentage: 83.3%

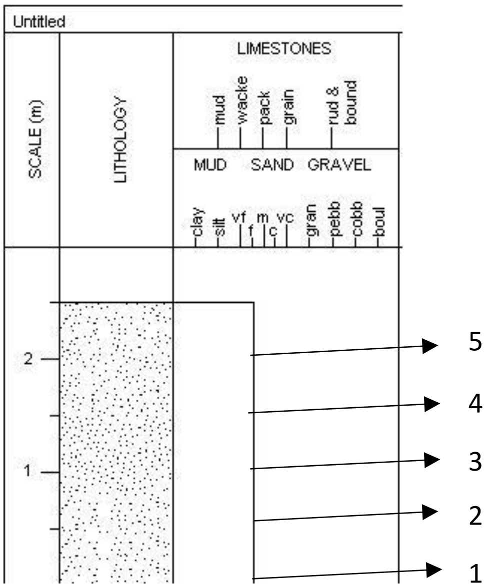
Figure 5.4. Ramsholt Member (left) and Sudbourne Member (right) at Sutton Knoll site 2 MCRs, with >75% mutuality values highlighted and temperature ranges identified by green lines.

Sutton Knoll site 2 produces a similar temperature range to site 1 for both members however, the difference compared to the modern temperature is lower at 1.4-3.4˚C for summer and 6-7˚C for winter for the Ramsholt. While the Sudbourne Member produces temperatures that are 1.4-4.4˚C warmer for summer and 6-8˚C for winter. This suggests that both Sutton Knoll sites have similar temperature regimes, with a similar difference to modern temperatures.

Once more the cross bedded stratigraphy of the Sudbourne is present, however, no structures are present within the Ramsholt Member. This supports the evidence that the Ramsholt was deposited under low energy conditions, as inferred by the greater abundances of species and genera compared to the Sudbourne. While the laminated layer present in the Sudbourne suggests that there was a change in energy levels after the deposition of the cross beds, specifically a lower energy, possibly caused by a cooling event and receding of sea level, that may have coincided with the proposed 'intra Pliocene' event *c.* 3ma (Dowsett and Poore, 1991).

The main difference between the two Sutton Knoll sites is the number of species and genera being significantly greater at site 2, with 38 species and 20 genera in the Ramsholt and 37 species and 18 genera in the Sudbourne. The Simpson and Margalef values support this with a visibly greater diversity of ostracods. The species quantity may reflect the large diversity of ostracods from the *Aurila*, *Muellerina* and *Thaerocythere* genus similar to the findings by Wood *et al.* (1993). This would also suggest that there is no faunal evidence of the proposed Late Pliocene cooling *c.* 2.9ma in the Coralline Crag Formation (Wood *et al.* 1993).

Broom Pit



Sample numbers: 1, 2, 3, 4, 5
Member: Ramsholt
Temperature Range: 18-23˚C MSBT, 12-14˚C MWBT
Total genera: 17
Total species: 35
Mutuality Value: 76.5-82.3%
Simpson Value: 4.29
Margalef Value: 7.06

Figure 5.5. Broom Pit sedimentary log with sampled horizons, member names, temperature ranges, genera number, species number, genera mutuality values and Simpson and Margalef species values.

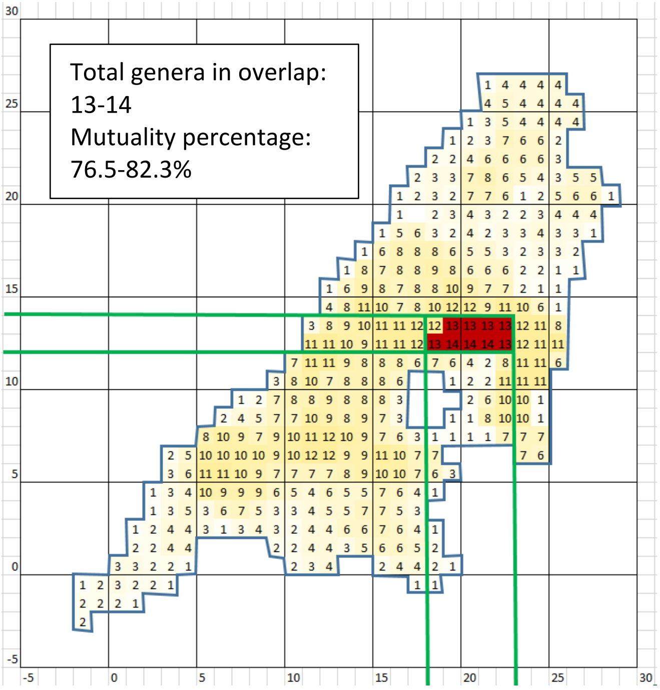

Total genera in overlap: 13-14
Mutuality percentage: 76.5-82.3%

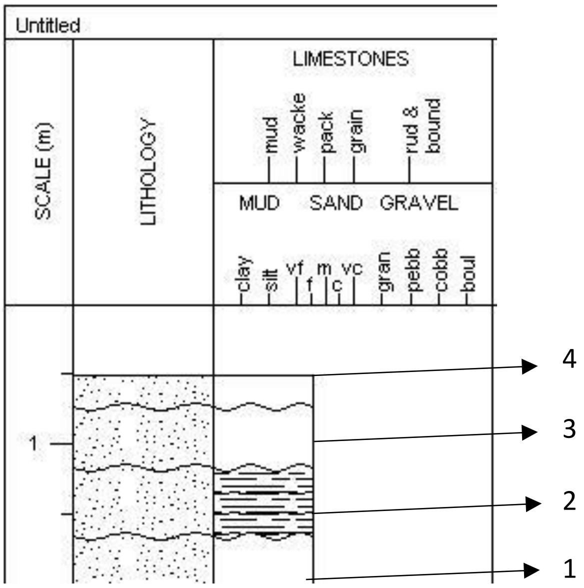
Figure 5.6. Broom Pit MCR for the Ramsholt Member with the >75% generic mutuality values highlighted, temperature ranges identified by green lines.

Broom Pit only contained samples from the Ramsholt which does not allow for a comparison between members. However, the temperature ranges produced show a similar trend being 1.4-6.4˚C and 6-8˚C warmer for summer and winter respectively for the Ramsholt Member at Sutton Knoll than modern. This site also shows similar numbers of species and genera to Sutton Knoll site 2, suggesting that these samples may occur in the geological column at the same depth.

The Simpson index value is the second lowest of the sites suggesting that there is a low level of diversity in the ostracod species, despite the high number, which is a result of a dominance of *Aurila* and *Muellerina* species. However, the Margalef value suggests a correspondence to the species diversity at Sutton Knoll site 2. This may infer that the specimens present at Broom Pit, although low in diversity, are high in number. From this, it can be inferred that Broom Pit produces similar temperature and ostracod diversity and abundance ranges as the other sites where the Ramsholt Member occurs.

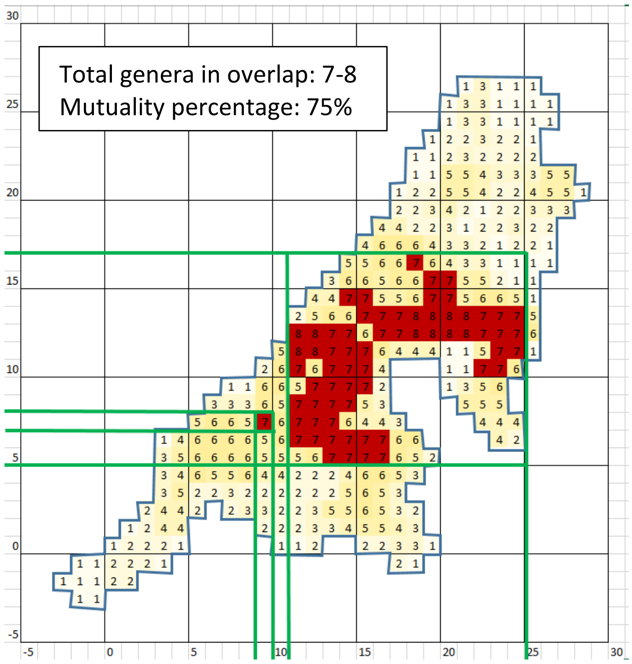
This site offers the best evidence that the Ramsholt was deposited in a low energy environment, possibly influenced by bioturbation, hence no structures being present in the stratigraphy (Daley and Balson, 1999). While the fine grain size of the sediment has allowed for the good preservation of a high number of ostracod specimens, once more suggesting that the Ramsholt was deposited in a low energy environment allowing for a successful preservation of the ostracod assemblage (Balson *et al.* 1993; Daley and Balson, 1999).

Gedgrave Farm



Sample numbers: 1, 2, 3, 4
Member: Sudbourne
Temperature Ranges: 9-10˚C MSBT, 7-8˚C MWBT and 11-25˚C MSBT, 5-17˚C MWBT
Total genera: 9
Total species: 19
Genera mutuality value: 77.7-88.8%
Simpson Value: 4.09
Margalef Value: 4.10

Figure 5.7. Gedgrave Farm sedimentary log with sampled horizons, member names, temperature ranges, genera number, species number, genera mutuality values and Simpson and Margalef species values.



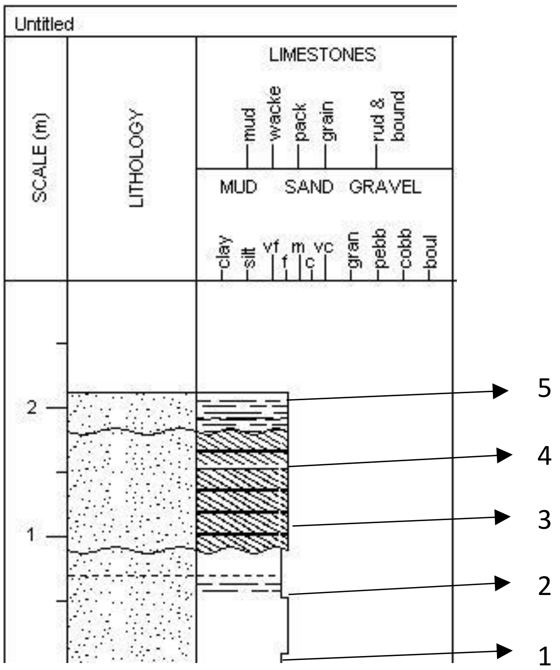
Total genera in overlap: 7-8
Mutuality percentage: 75%

Figure 5.8. Gedgrave Farm MCR for the Sudbourne Member with the >75% generic mutuality values highlighted, temperature ranges identified by green lines.

Gedgrave Farm produced the largest temperature envelope and subsequently the equal lowest genera and lowest species values. The temperature range produced for the Sudbourne Member here shows the widest range of warming and cooling compared to the modern levels. Summer temperatures are between 5.6˚C cooler and 8.4˚C warmer than modern levels, while winter temperatures are between 1˚C cooler and 11˚C warmer. The wide range is evidently a result of the low genera count and cooler inhabiting species of *Muellerina* and *Thaerocythere* abundant throughout the samples at this site.

The biodiversity index values are the lowest of all sites, suggesting a low diversity of ostracods as supported by the low quantity. The dominance of *Muellerina* and *Thaerocythere* throughout individual samples has resulted in the cooler temperature envelope. The site does have sampling issues with only one sample having above 35 specimens present, while the other three had less than 20. This may be a result of the environmental change, as shown with the cross bedded stratigraphy. Cross beds result from a higher energy depositional environment, which has potentially resulted in post depositional mixing of the Ramsholt Member sediments into the Sudbourne. Further to this, the higher energy depositional environment will have only allowed adult specimens to be preserved due to the greater erosional forces acting upon the sediments (Boomer *et al.* 1993; Nichols, 1999). However, despite this, it does provide an indication as to the temperature range of the Sudbourne Member.

Orford 'The Cliff'



Sample numbers: 3, 4, 5
Member: Sudbourne
Temperature Ranges: 18-25˚C MSBT, 10-15˚C MWBT
Total genera: 14
Total species: 26
Genera mutuality value: 78.5-85.7%
Simpson Value: 4.04
Margalef Value: 5.79

Sample numbers: 1, 2
Member: Ramsholt
Temperature Range: 17-21˚C MSBT, 12-14˚C MWBT
Total genera: 10
Total species: 23
Genera mutuality value: 80%
Simpson Value: 7.43
Margalef Value: 5.09

Figure 5.9. Orford 'The Cliff' sedimentary log with sampled horizons, member names, temperature ranges, genera number, species number, genera mutuality values and Simpson and Margalef species values.

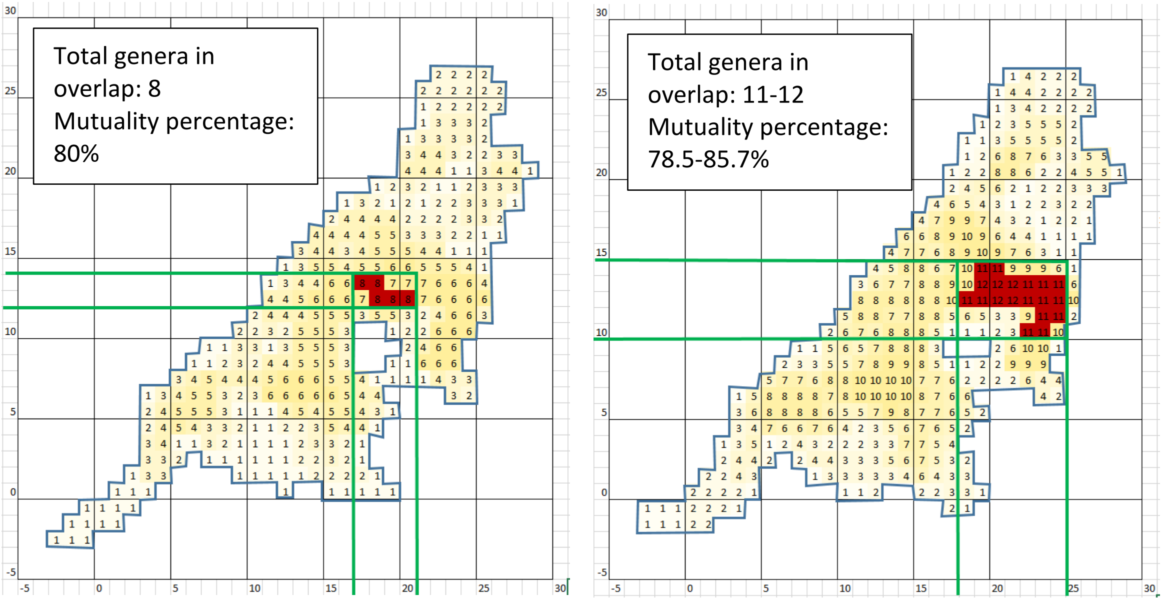


Figure 5.10. Ramsholt Member (left) and Sudbourne Member (right) at Orford 'The Cliff' MCRs, with >75% mutuality values highlighted and temperature ranges identified by green lines.

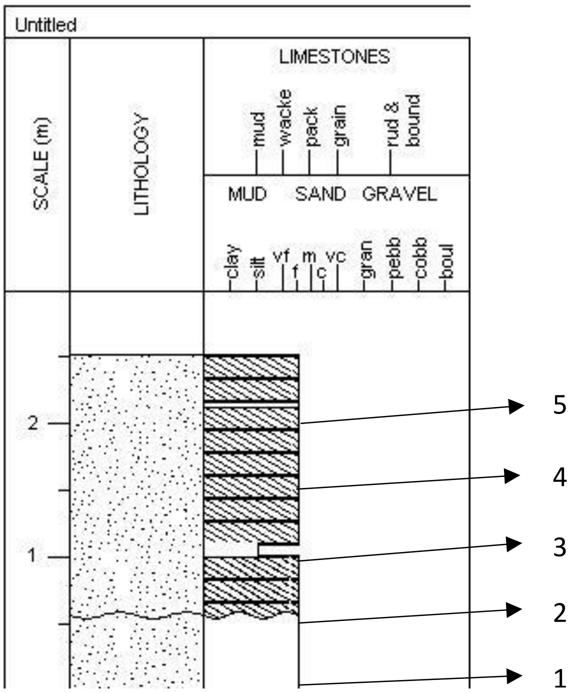
Orford 'The Cliff' is the other site to have both the Ramsholt and Sudbourne members present. The difference compared to both of the Sutton Knoll sites, is that this site sees a lower number of species and genera in the Ramsholt Member compared to the Sudbourne Member. Conversely, the Ramsholt Member Simpson index value suggests a greater diversity of ostracods compared to the Sudbourne Member. This is highlighted by the number of different species of key genera such as *Aurila, Muellerina* and *Thaerocythere* being greater in the Ramsholt Member compared to the Sudbourne.

The generic mutuality values also support this diversity with similar values for both members, which have produced temperature ranges 0.4-4.4˚C warmer than modern for summer and 6-8˚C warmer for winter from the Ramsholt Member, and 1.4-8.4˚C warmer for summer and 4-9˚C warmer for winter in the Sudbourne Member. It can be inferred that despite variations in biodiversity index values the temperature ranges produced are similar for the Ramsholt and Sudbourne as the other sites.

The transition from the Ramsholt to the Sudbourne at this site shows once more that there is little change in temperature, which would suggest that there is no change in climatic environment during the deposition of these members.

However, the distinct Sudbourne cross beds are present, along with an underlying laminated layer. The laminated layer suggests that there may have been a significant decrease in energy during the latter stages of the deposition of the Ramsholt, possibly linked to a period of cooling that lowered sea levels, depositing this layer. Furthermore, the cross beds are overlain by an additional laminated layer, similar to Sutton Knoll site 2, this may be indicative of a decrease in energy levels, possibly linked to a decrease in sea level after the high-energy period that deposited the cross beds (Daley and Balson, 1999). This theory is contradicted by the increase in the number of ostracods in the Sudbourne Member at this site. But, it could support evidence for post depositional mixing from the Ramsholt, leading to this increase in abundance.

Richmond Farm



Sample numbers: 1, 2, 3, 4, 5
Member: Sudbourne
Temperature Ranges: 19-22˚C MSBT, 12-14˚C MWBT
Total genera: 11
Total species: 27
Genera mutuality value: 81.8%
Simpson Value: 5.48
Margalef Value: 6.18

Figure 5.11. Richmond Farm sedimentary log with sampled horizons, member names, temperature ranges, genera number, species number, genera mutuality values and Simpson and Margalef species values.

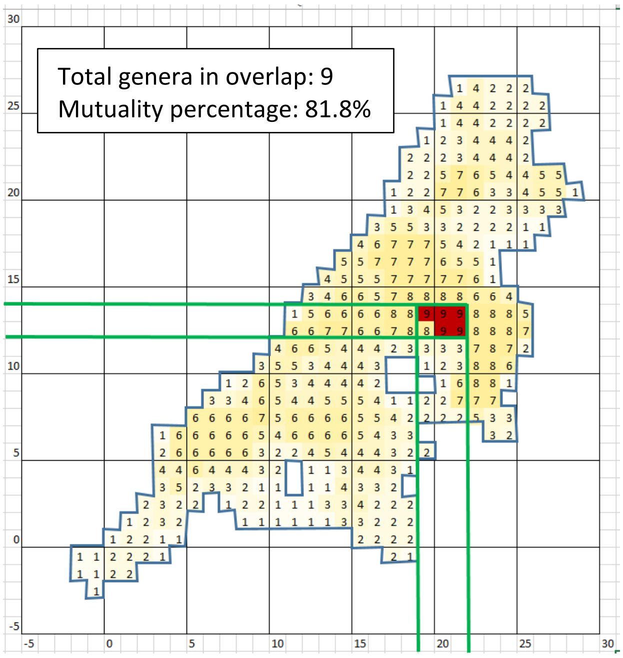


Figure 5.12. Richmond Farm MCR for the Sudbourne Member with the >75% generic mutuality values highlighted, temperature ranges identified by green lines.

Richmond Farm offers a similar temperature range for the Sudbourne Member as those produced at both Sutton Knoll sites. The temperatures at this site are between 2.4-5.4˚C warmer for summer and 6-8˚C warmer for winter than those of modern. The ranges produced here show once more that there is no discernible difference in the temperatures of the Ramsholt and Sudbourne. Which may be due to reworking of the Ramsholt sediments in the basal layer of the Sudbourne that have resulted in the lower ostracod numbers in this layer, which in turn has only preserved adult ostracod specimens, which have produced this temperature range. As for samples 4 and 5, these had much broader temperature ranges due to a lack of genera present (see Appendix B).

The genera and species numbers are similar to Orford 'The Cliff' and Sutton Knoll site 2, while the Simpson and Margalef values here, suggest a lower diversity compared to these two sites. This may be a result of the dominance of genera such as *Aurila, Muellerina* and *Pontocythere* at this site, thus resulting in a lower diversity value but the high number of specimens from these genera. As a consequence, this does not support evidence for a change in climatic conditions between the Ramsholt and Sudbourne members.

5.2 Comparison of Ramsholt and Sudbourne members MCRs

A comparison of the composite MCRs for the Ramsholt and Sudbourne will provide an indication of the temperatures for each member, which are then used to form the MCR for the Coralline Crag Formation.

Ramsholt and Sudbourne composite MCRs comparison

The composite MCRs pool all of the genera from the sites where they were identified. These have then been compared to provide an indication of the temperature of the Coralline Crag Formation. This assumes that the changes between the members are not of significance, due to post depositional mixing. However, this may result in a misinterpretation as to the true temperatures of the Ramsholt and Sudbourne members and consequently the Coralline Crag Formation.

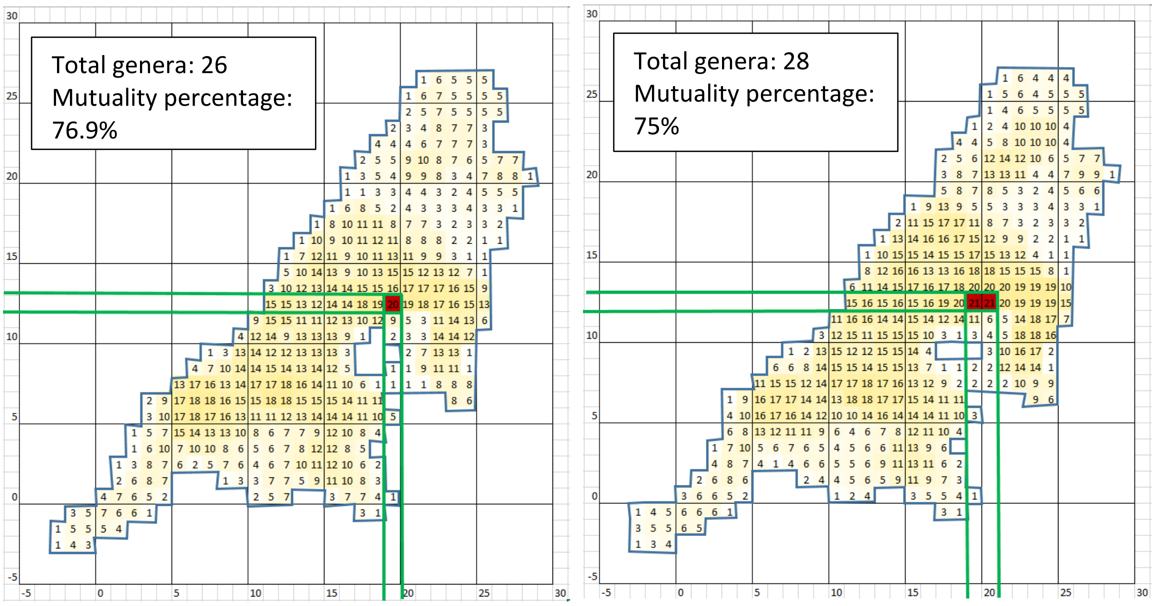


Figure 5.13. Ramsholt Member (left) and Sudbourne Member (right) composite MCRs, with >75% mutuality values highlighted and temperature ranges identified by green lines.

The temperature ranges produced for both members are the same when applying the >75% generic mutuality values. It must be considered that at lower generic mutuality values the transparency in temperature envelopes becomes distorted and lost, particularly at 65-70%, where an envelope with a temperature range of *c.* 5-15˚C MSBT, *c.* 5-10˚C MWBT becomes visible.

The temperatures for the Ramsholt are 2.4-3.4˚C warmer than modern for summer and 6-7˚C warmer for winter. While the Sudbourne is 2.4-4.4˚C warmer for summer and 6-7˚C for winter. The summer temperatures are similar to the global mean average temperatures produced by the PlioMIP for the mPWP (Haywood *et al.* 2013b). It must be considered, however, that PlioMIP focussed on SST and SAT rather than bottom-water temperatures, which does mean direct comparisons are difficult.

Simpson and Margalef values have been calculated for each member and these show little difference for either member, with values for the Ramsholt of 5.83 and 9.83, and 5.80 and 10.1 for the Sudbourne respectively. They do suggest, however, a relatively broad level of diversity of species, while the species numbers of 60 and 61 for the Ramsholt and Sudbourne respectively, are indicative of a high number of unique species at each site.

This is indicative of no significant change between the members in terms of temperature or diversity, the only noticeable change is in the stratigraphy with the cross bedded structures and laminated beds present in the Sudbourne Member. The cross bedded stratigraphy infers a change from a low energy, stable environment to a high-energy environment. The cross beds present in the Sudbourne Member are deposited facing a N.E – S.W direction, which is the modern flow direction for the southern North Sea (see figure 5.14) (Sündermann and Pohlmann, 2011).

Figure 5.14. The modern current direction of the North Sea shown by red arrows and Suffolk highlighted by green star (Sündermann and Pohlmann, 2011).

The flow regime for the modern North Sea is stronger in the summer at approximately 3 cm/s, compared to 1 cm/s in the winter. If a similar flow regime was present during the Pliocene for this region as suggested by the orientation of the cross beds, it would suggest that there has been no discernible difference in flow regime for the Sudbourne compared to present. Furthermore, this would account for the reason the cross beds exist, with this flow regime possibly being stronger during the Pliocene with the extensive cross bedding of the Sudbourne Member and presence of adult specimens of ostracods and proposed mixing of species from the Ramsholt (Sündermann and Pohlmann, 2011).

One consideration when identifying the origin of the cross beds is to observe their direction and lithology. Those present in the Sudbourne Member at both Sutton Knoll sites trend from N.E – S.W, while those present at the other sites trend in the opposite direction S.W – N.E. It can, therefore, be inferred that this is a tidal deposition, while the presence of laminations in the stratigraphy further supports this hypothesis (de Raff and Boersma, 2007).

Extant species MCRs

The two extant species *Bythocythere bradii* and *Eucythere prava*, have their own MCR which can be overlain on to the Ramsholt and Sudbourne member plots.

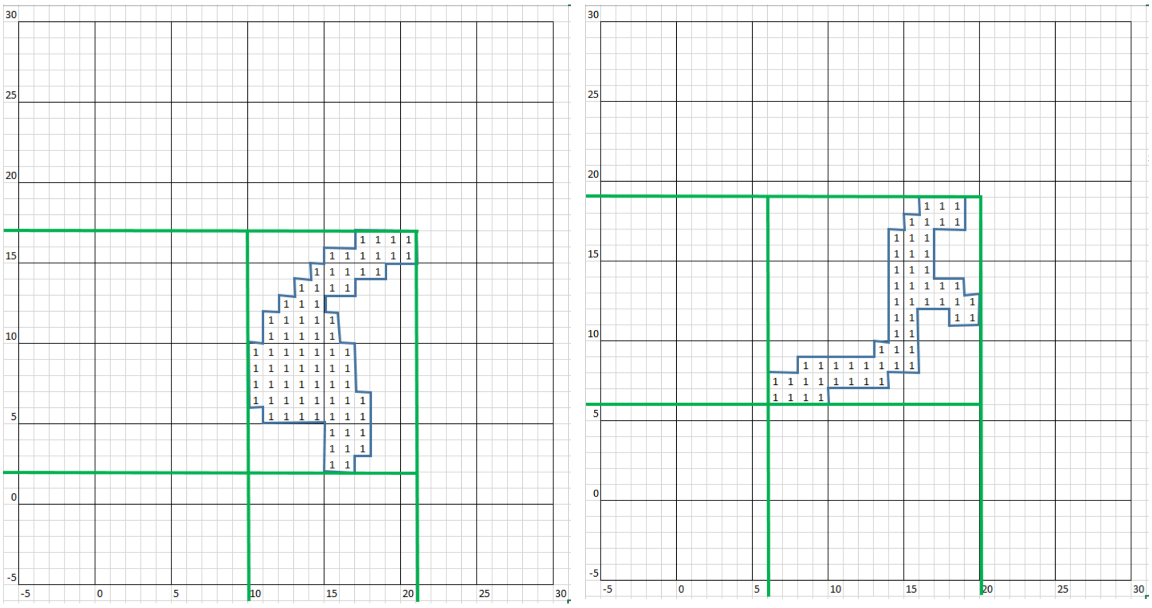


Figure 5.15. *Bythocythere bradii* (left) and *Eucythere prava* (right) individual temperature plots, temperature ranges identified by green lines.

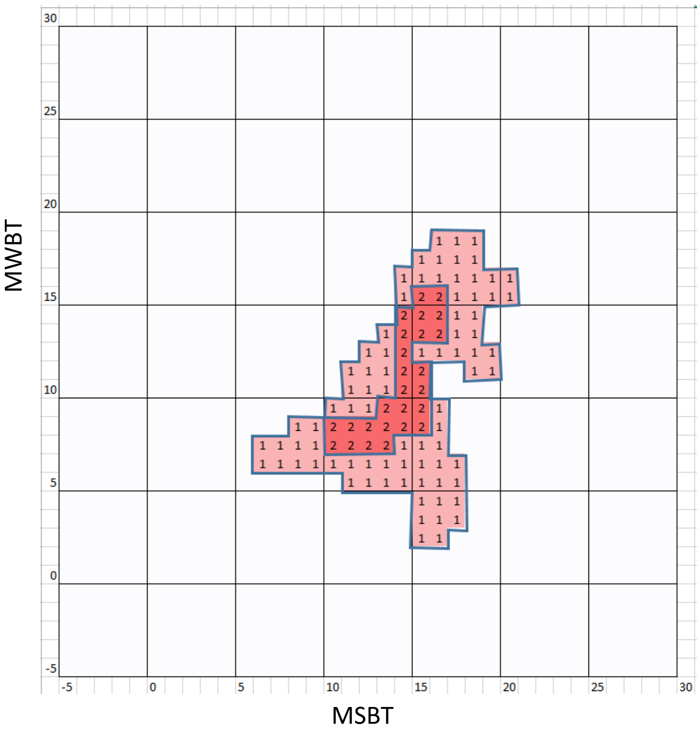


Figure 5.16. MCR for the extant species, area of greatest mutuality/ overlap highlighted.

The MCR is overlain and compared to the members at the >75% mutuality to determine any variations in temperature ranges.

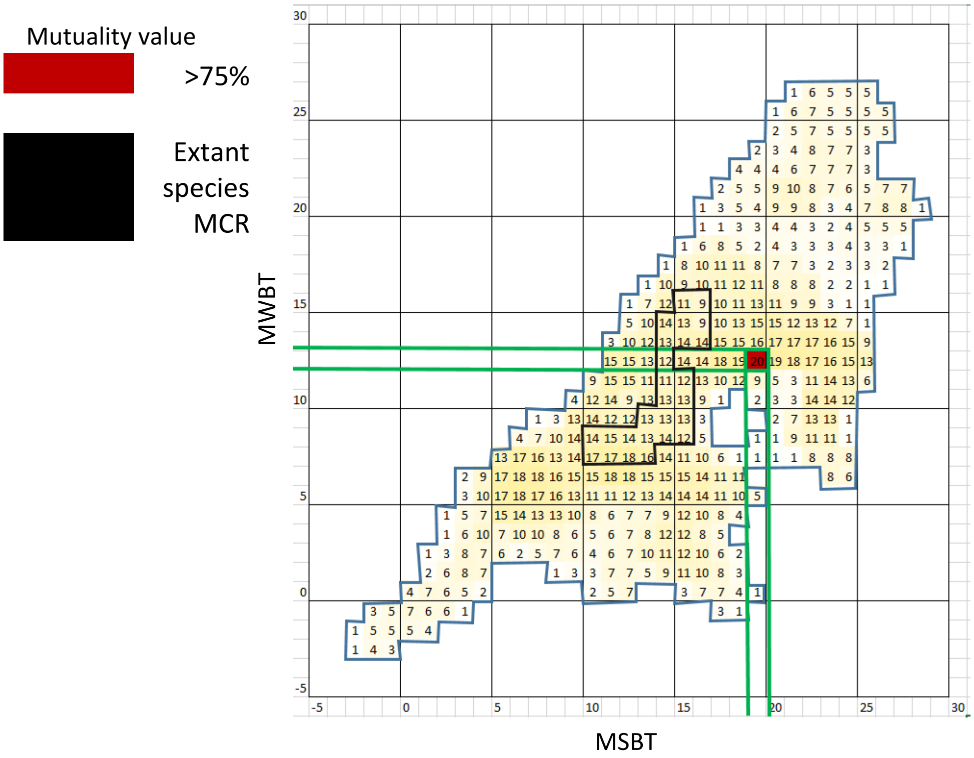


Figure 5.17. Extant species MCR overlain onto Ramsholt Member MCR, with >75% mutuality envelope highlighted and temperature range identified by green lines.

When considering the use of the extant species the six assumptions for climate reconstructions have to be applied (see section 2.6), in particular, the first three which are (Birks *et al.* 2010):

1) The modern taxa are related to the climate they inhabit
2) Climate variable/s that are to be reconstructed are either linearly or monotonically linked to an ecologically significant component of the system being examined.
3) The modern and fossil taxa have the same ecological responses and can, therefore, be used to reconstruct changes through time.

The extant species MCR overlay on the Ramsholt does not show any correlation but does overlie areas of 65-70% generic mutuality. However, it is only when the individual species temperature envelopes are observed that it is clear to see an overlap, with *Eucythere prava.* It overlies the >75% generic mutuality value, but also areas of 70-75% mutuality, which does suggest there is a correlation between modern and fossil samples. But, based upon the assumptions of climatic reconstruction this may be wrong entirely due to a change in ecological response and environmental habitat, with

Eucythere prava now found in Meditteranean environments Wood binary database (unpublished data). While the extant species may be misidentified, with their appearances similar to other species from their respective generas.

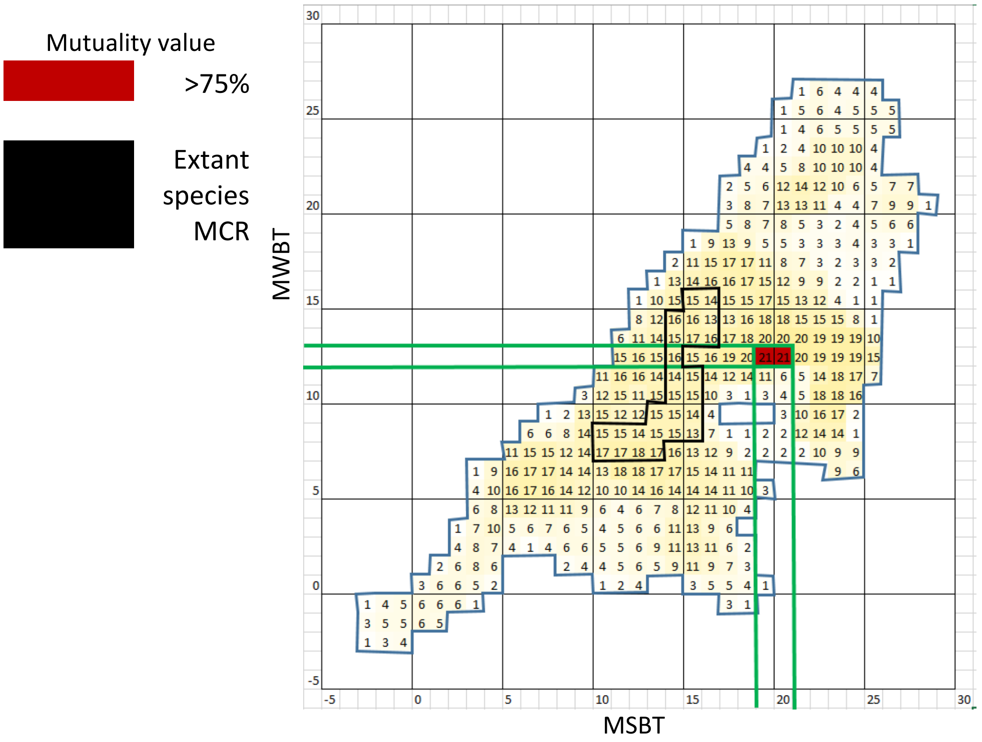


Figure 5.18. Extant species MCR overlain onto Sudbourne Member MCR, with >75% mutuality envelope highlighted and temperature range identified by green lines.

Similar to the Ramsholt Member, only the *Eucythere prava* temperature plot overlies the >75% mutuality values for the Sudbourne Member, which does suggest the modern and fossil correlate. It is important to remember, the same as with the Ramsholt Member, that the three assumptions need to be considered and general misidentification of the extant species.

5.3 Dice binary similarity coefficient

The Dice binary similarity coefficient values have been calculated and then compared to the MCRs to determine any correlation between the methodologies.

Key:

● – Sutton Knoll
▲ – Broom Pit
■ – Orford 'The Cliff'
✕ – Gedgrave Farm

1-12 - Sample Number

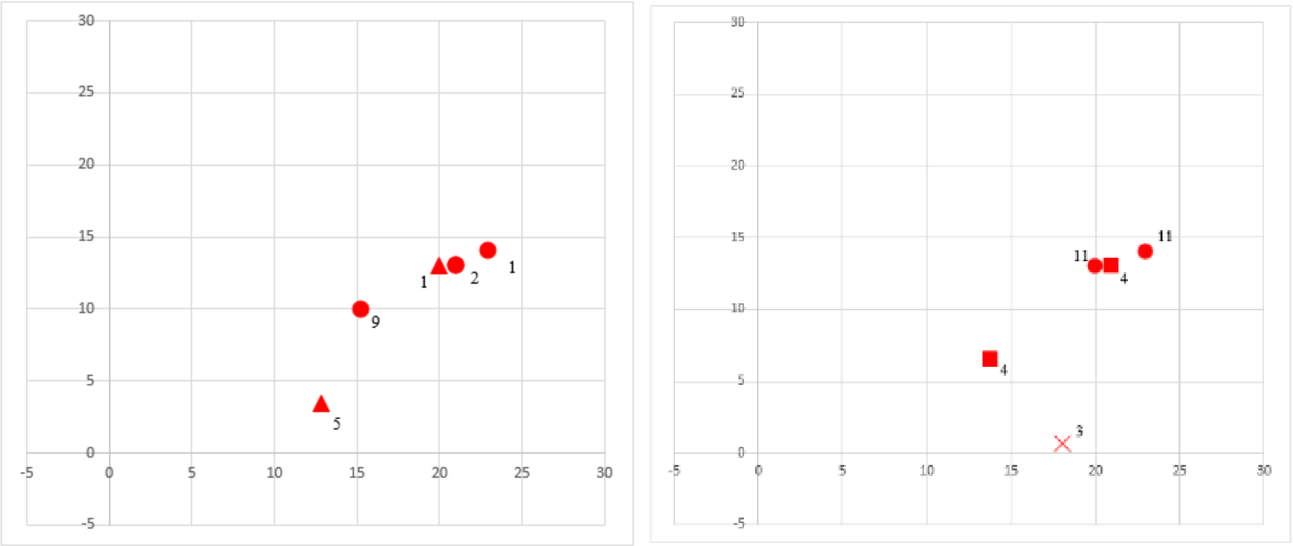


Figure 5.19. Dice binary similarity coefficient values >0.5 for the Ramsholt Member (left) and Sudbourne Member (right), where temperature values have been derived from recent analogues.

The two binary similarity coefficient plots have then been overlain onto the respective MCRs to determine any overlaps in temperature trends (see figures 5.20-5.21).

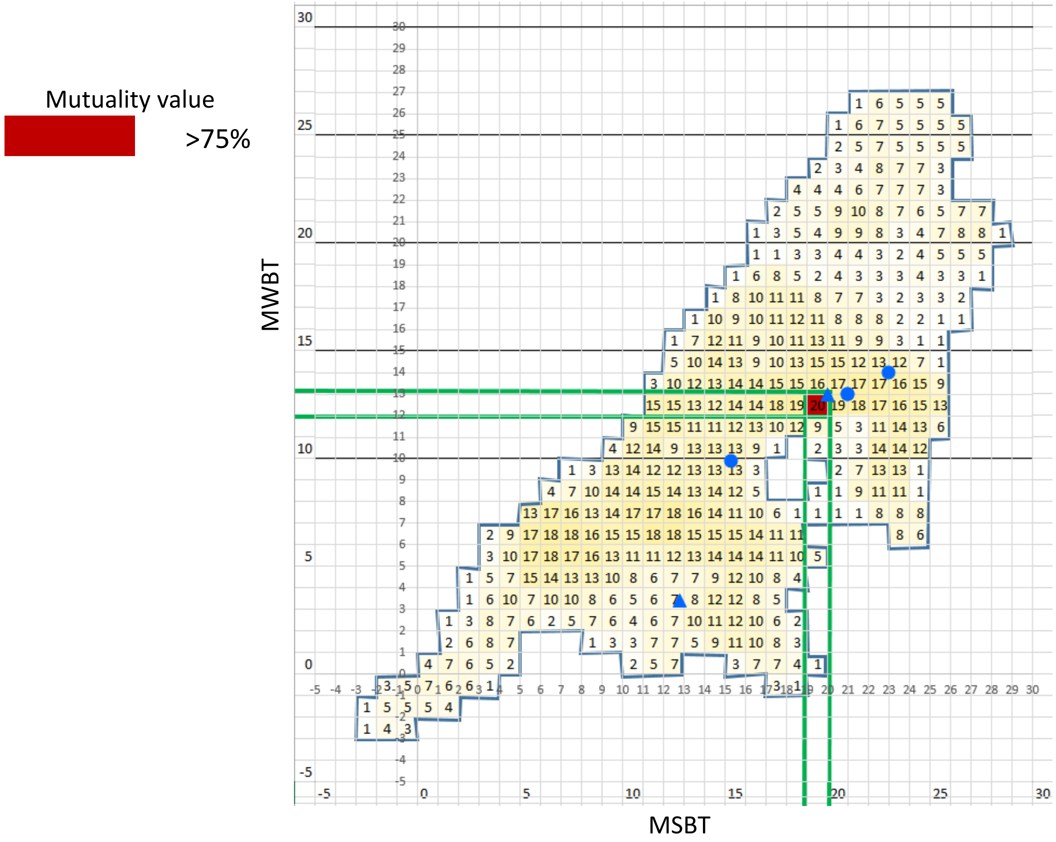


Figure 5.20. Dice binary similarity coefficient values >0.5 for Ramsholt Member MCR [blue points] overlain on Ramsholt Member MCR >75% mutuality value and temperature values defined by green lines.

Three Dice values overlie the areas of greatest overlap, in particular, those with values >75% generic mutuality, covering a temperature range of 19-23˚C MSBT and 12-15˚C MWBT. These areas suggest a similarity to the recent database, which would support evidence for this being the temperature range for Ramsholt Member. The two unique samples; one from Sutton Knoll and one from Broom Pit, suggest the presence of species which currently inhabit cooler regions, namely *Muellerina* and *Thaerocythere* taxa.

Furthermore, there were no genera from Orford 'The Cliff' with >0.5 similarity for the Ramsholt Member, suggesting genera at this site are not similar to the recent database.

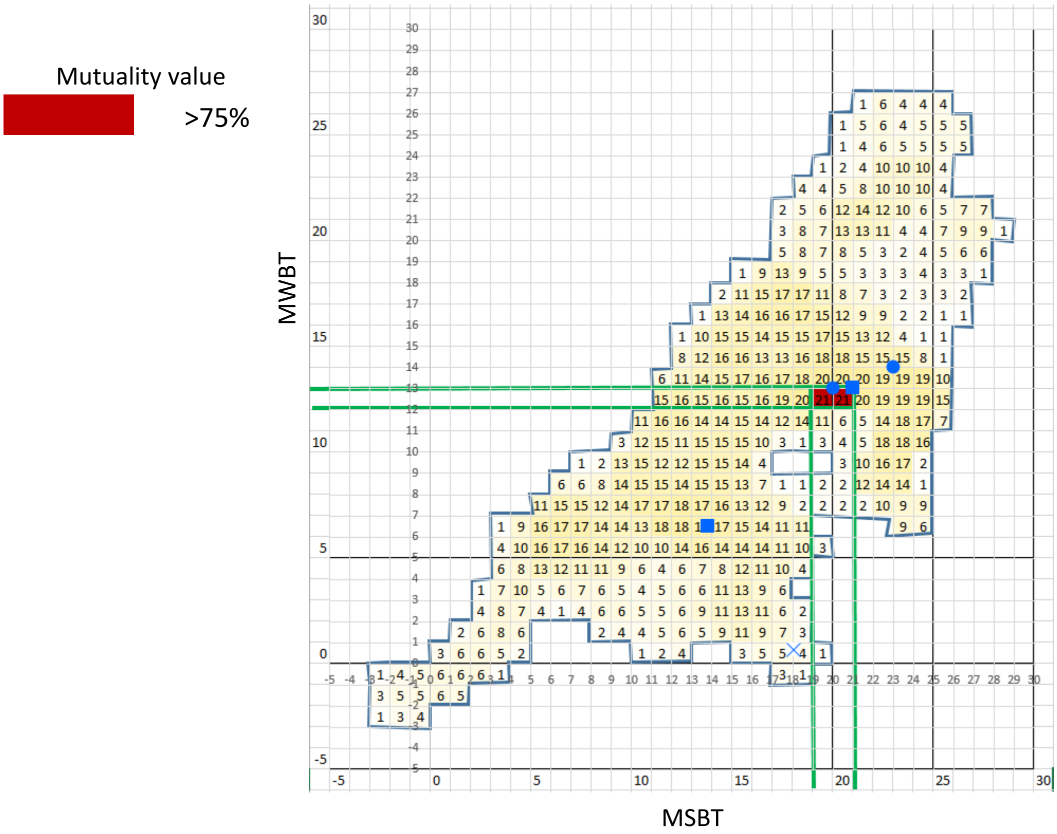


Figure 5.21. Dice binary similarity coefficient values >0.5 for Sudbourne Member [blue points], overlain on Sudbourne Member MCR with >75% mutuality values and temperature values defined by green lines.

The Sudbourne Member has a temperature zone of 19-23˚C MSBT, 12-14˚C MWBT suggested by the binary similarity coefficient plots, while there are two unique samples from Orford 'The Cliff' and Gedgrave Farm. This suggests that the Ramsholt and the Sudbourne share a similar temperature range with no significant change between members.

The unique samples are similar to those of Sutton Knoll, suggesting species of *Muellerina* and *Thaerocythere* inhabiting cooler regions are accountable. Hazel (1970), identifies two species from these genera, suggesting that they inhabited Sub-Arctic to Scandinavian temperatures. This would offer an explanation for the Gedgrave Farm unique sample in particular, with the exceptionally colder winter temperature, indicating a cooler environment (18°C MSBT, 0.7°C MWBT).

5.4 Species hierarchical clustering analysis

Species level hierarchical clustering provides an indication as to the similarity of ostracod assemblages.

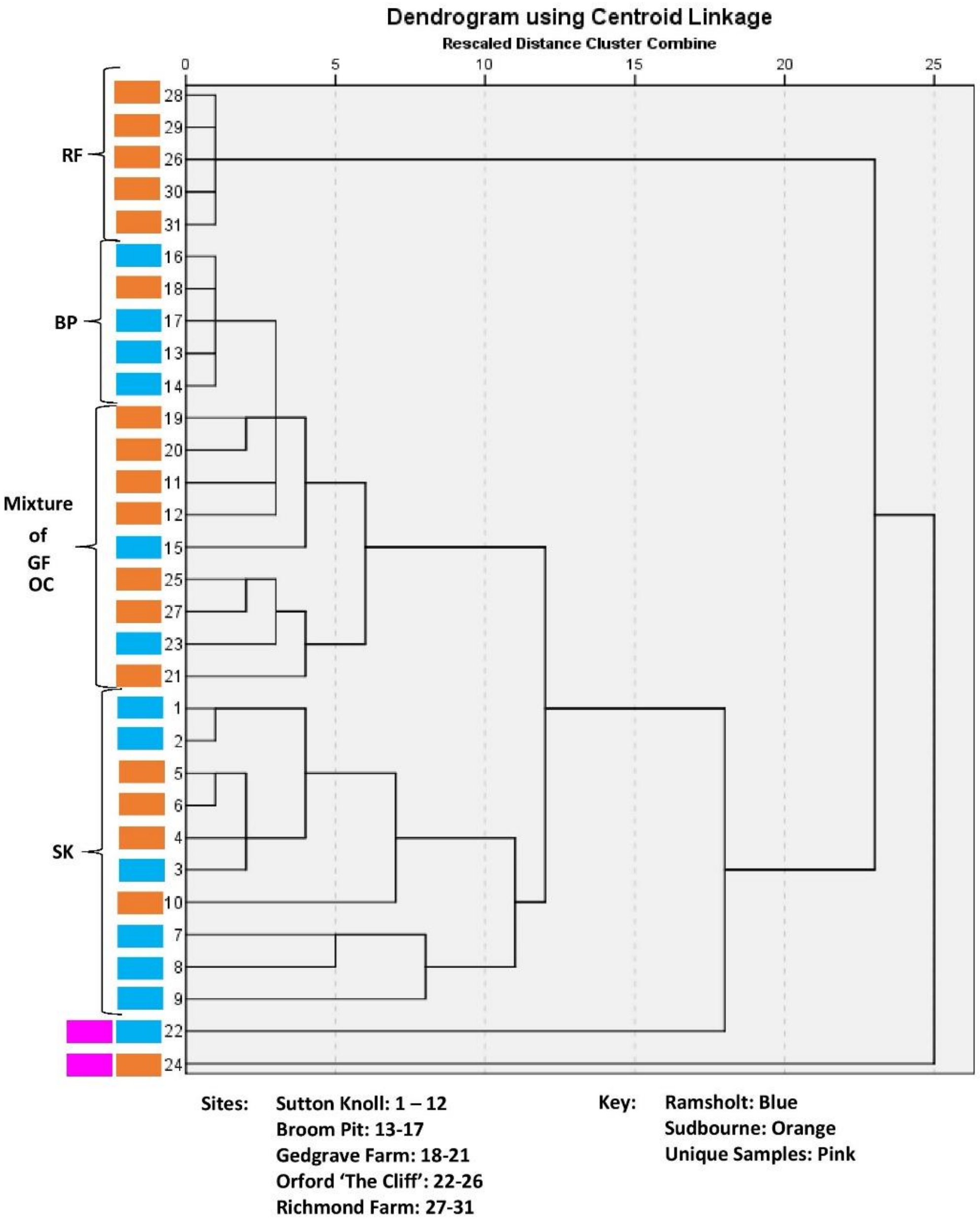


Figure 5.22. Annotated centroid cluster dendrogram with key trends outlined.

Three of the five sampled sites appear as clusters; Sutton, Broom Pit and Richmond Farm. Furthermore, assemblages from Gedgrave Farm and Orford 'The Cliff' are mixed which may infer that the depositional environments were similar and species present are alike. The two assemblage unique samples present are from 'The Cliff' at Orford, a reason for this may be the occurrence of rare species: *Falunia retifastigata* and *Microcytherura devenustata.*

The Broom Pit and Richmond Farm clusters suggest a transition from the Ramsholt to the Sudbourne, however, this is inconclusive as the clusters do not link. The cluster analysis does provide evidence that the species do not appear to be similar across sites. However, the Simpson and Margalef values suggest similar trends in diversity of the ostracods, which may mean that the Euclidian method of clustering has lost the trends that may be visible between species assemblages.

5.5 Coralline Crag Formation temperature range from MCR

The MCRs for the Ramsholt and Sudbourne members have been compiled using all 33 genera, to produce a composite MCR for the Coralline Crag Formation.

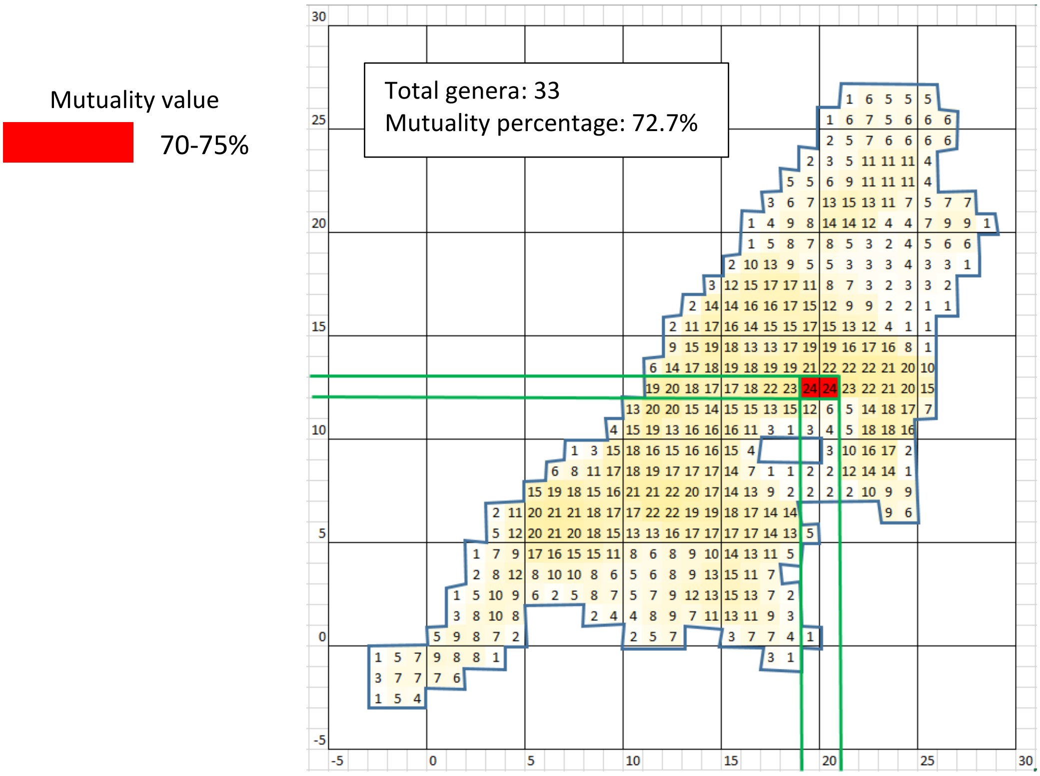


Figure 5.23. Coralline Crag Formation MCR with 70-75% mutuality values shown, temperature values defined by green lines.

The highest generic mutuality percentage values indicate temperatures between 19-21˚C MSBT and 12-13˚C MWBT. The temperatures produced are comparable to those identified by Wilkinson (1980) and Wood *et al.* (1993) at 10-24˚C for the Pliocene in Suffolk, with a lower total range and seasonal differentiation. There is also an abundance of genera [19-22] in a cooler region with temperatures of approximately 5-13°C MSBT and 5-10°C MWBT, this suggests that despite not being the area of greatest mutuality, there is an abundance of genera inhabiting this cooler region. This might indicate either an ubiquity trait of the genera or a preference towards colder waters, which is true for *Muellerina* and *Thaerocythere* as these are abundant throughout both the Ramsholt and Sudbourne.

The temperature range produced shows that the Ramsholt and Sudbourne have no change in climatic conditions. The stratigraphical differences with the presence of the cross beds and similar genera suggest that there has been post depositional mixing of the Ramsholt into the Sudbourne Member. This may result in this temperature reconstruction being warmer than what the Coralline Crag Formation actually was due to specimens from the Ramsholt, which inhabited waters approximately 5°C warmer than modern, being introduced to the Sudbourne, which may not have lived during the deposition of this member (Daley and Balson, 1999).

5.6 Comparison with published palaeotemperature reconstructions

A comparison of the Coralline Crag data produced and that of other research allows for an approximation as to where this data series correlates into Pliocene temperature reconstructions. Williams *et al.* (2009) compiles the data collected from some fossil proxies to reconstruct temperatures of the Coralline Crag Formation (see table 5.1).

Table 5.1. Temperature ranges for Suffolk and the Coralline Crag Formation based upon microfossil reconstructions (Williams *et al.* 2009).

Temperature reconstructions produced from this work suggest warmer conditions than the modern SST temperature, conversely the use of SST makes direct comparisons very difficult (Johnson *et al.* 2000; Wilkinson, 1980; Wood *et al.* 1993). It can also be seen that the temperature range correlates to the temperature estimates produced by the other work, in particular, the temperature range produced for the Coralline Crag by Wilkinson (1980) and Wood *et al.* (1993) of 10-24˚C.

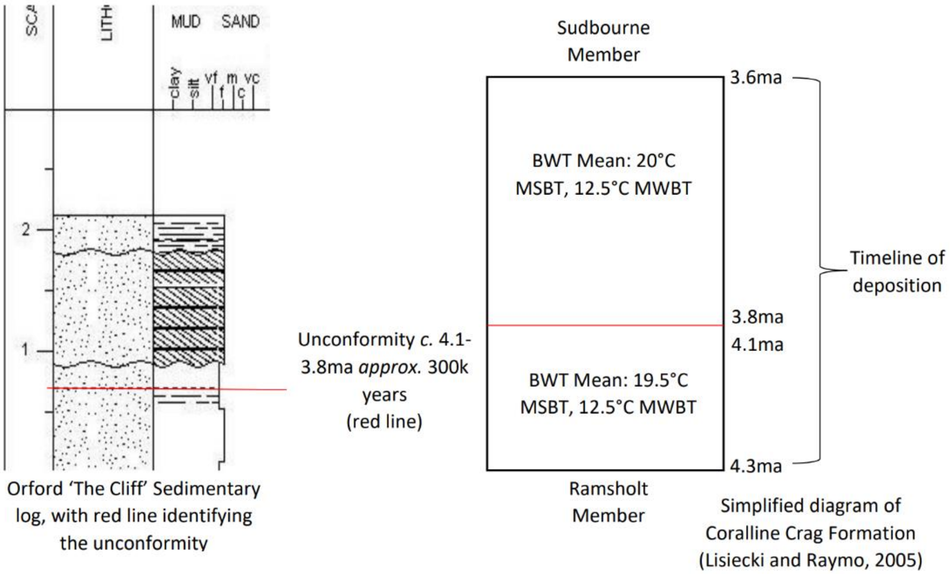


Figure 5.24. Summary diagram of the Coralline Crag Formation with mean BWT for summer and winter highlighted, chronostratigraphic timeline, lithostratigraphy, unconformity (red line) and key depositional characteristics from Orford 'The Cliff' site as a representation of each member.

When compared to the multi-proxy maximum temperature range of the Pliocene, the reconstructions produced by this work are comparable with a narrower range 12-21˚C and an annual mean of 16.5˚C ± 1°C. This suggests that the temperatures produced by this work agree with the published ranges, however, the comparison with the PRISM temperatures will test their true validity.

PRISM3D produces temperatures for deep ocean ranging in depths from 0-5500m, for the purpose of comparison, the depth of samples from a depth of 30m will be used based upon this being the average change in sea level from Pliocene to modern (Dwyer and Chandler, 2009; Dowsett *et al.* 2009). The temperature deduced is 13.21˚C ± 1°C for 54˚N 2.5˚E from a 4˚x 5˚ resolution, which is north of the current location of the Coralline Crag Formation (Dowsett *et al.* 2009). Comparison to the mean produced from this reconstruction of 16.5˚C ± 1°C suggests a slightly cooler temperature (Dowsett *et al*. 2009). The temperature at the lowest depth for this locality, 75 m, provides a temperature of 12.45°C ± 1°C, while the nearest locality at a 30 m depth, to produce a temperature close to the mean of this research is at 54°N -18°W, with a temperature of 16.44°C ± 1°C. One difference to consider is the timescale that the temperatures are identified from, with the PRISM3D focussing on *c.*3.26-3.02 ma, while the deposition of the Coralline Crag Formation occurred *c.*4.3-3.6 ma (Haywood *et al.* 2016; Wood *et al.* 1993). This may indicate that the deposition of the Coralline Crag Formation occurred during a warmer climate than that of the mPWP.

Alternatively, a three-degree variance between these temperature reconstructions and PRISM3D data suggests errors in these reconstructions linked to the use of a single proxy to determine temperature ranges. Whereas PRISM3D takes a multi-proxy approach which has allowed a more accurate determination of BWT.

5.7 Summary

The temperature reconstructions produced, when compared to those of published literature, suggest similar temperatures for the deposition of the Coralline Crag Formation. When compared to PRISM3D however, it suggests a warmer environment of deposition for the Coralline Crag Formation than the mPWP, which may suggest either the generic level is not sensitive enough or further work is required to determine a more accurate temperature range for the Coralline Crag Formation.

6. Conclusion

Temperature reconstructions have deduced a temperature range for the Coralline Crag Formation and two of its respective members, the Ramsholt and the Sudbourne. There is no discernible change in temperature between the Ramsholt and Sudbourne members, which suggests that they were deposited in similar climatic environments. However, the cross bedded strata of the Sudbourne, suggest a high energy tidal environment that acted in a N.E-S.W orientation, with evidence of this present at all of the sites sampled containing this member.

Possible reworking of the Ramsholt may have introduced species from this member into the Sudbourne sediments, while the similar temperatures may have resulted in similar species presence. Furthermore, the supporting evidence provided by the statistical analyses suggest that the temperature ranges for both members are similar. The influence of cold water inhabiting genera *Muellerina* and *Thaerocythere* are identified by the Dice binary similarity coefficients, with the significantly colder winter temperatures for both members, this supplements the findings of Wood *et al.* (1993).

The modern temperature values for the southern North Sea when compared to these temperature reconstruction support evidence that the Coralline Crag Formation was deposited in warmer waters of approximately 0.5-5.7˚C in summer and 5-8.3˚C in winter. Albeit these temperatures are exaggerated in the maximum range due to the ranges produced from the MCRs focussing on areas of greatest mutuality and not accounting for regions where <75% mutuality occurs.

In terms of the validity of the Coralline Crag Formation as an indicator of late 21st Century climate change, it can be inferred that the temperatures produced are warmer than modern for the southern North Sea. The IPCC B1 projections suggest a range of 1.1-2.9˚C warming for the late 21st Century (IPCC, 2013). The average difference between the summer and winter to modern produced here are 3.1˚C and 6.6˚C respectively. This suggests these temperature values could be potential maximum temperature increase if CO_2 levels increased to >500ppm, this hypothesis is contradicted, however, by the Pliocene CO_2 emission level being 400ppm, the same as they are today (NASA, 2017).

Hill (2015) argues that non-analogue characteristics of the Pliocene such as palaeogeography and orbital forcing can influence temperature reconstructions and should be regarded carefully to accurately simulate climatic conditions. The reconstructions produced in this work consider faunal conditions, which does mean they can be used as part of a larger climatic model such as PRISM. Furthermore, the implications of warming on regional palaeoenvironments supports the framework produced by Haywood *et al.* (2016) of developing small scale reconstructions that can enhance the global effort.

The work has supported the criteria outlined by Haywood *et al.* (2016) to provide a regional palaeoenvironmental reconstruction that can improve the accuracy of Pliocene reconstructions.

This work has provided an updated palaeoenvironmental reconstruction of the Coralline Crag Formation after the prior work carried out by Wilkinson (1980) and Wood *et al.* (1993). While it has also provided a first MCR of the benthic ostracods from the Coralline Crag Formation, with a comprehensive palaeoclimatic reconstruction having been carried out to provide a reassessment of the temperatures of the Coralline Crag Formation produced by Wood *et al.* (1993).

6.1 Avenues for future research and improvements

The research carried out has provided an indication as to the temperature of the Coralline Crag Formation and its ability to indicate future climate change. In future examinations of the Coralline Crag Formation, a multi-proxy approach would allow for composite temperature ranges to be produced to provide better estimates of the palaeoclimate.

An abundance of foraminifera and bryozoans are available in the Coralline Crag sediments, which could be used to determine temperature (Hodgson and Funnell, 1987; Daley and Balson, 1999). Additionally, greater accuracy of identification of specimens may have increased the specimens available to determine the temperature ranges more accurately. Furthermore, samples from sites containing the Aldeburgh Member would have offered comprehensive coverage of the Coralline Crag Formation and potentially allowed for observations of any temperature change in the latter part of the deposition of this member.

For future research, an understanding of the unconformity between the Coralline Crag and Red Crag would be invaluable in observations of the proposed ‘intra Pliocene’ cooling event *c.* 3 ma (Dowsett and Poore, 1991). This would then provide greater coverage of the palaeoenvironment and palaeoclimate of eastern England during the Pliocene, while this would allow for a better regional reconstruction of the southern North Sea as part of the PRISM and PlioMIP.

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APPENDICES

APPENDIX A
SUTTON KNOLL SPECIES LIST

Species	SK – Clay layer	SK1	SK2	SK3	SK4	SK5	SK6	SK7	SK8	SK9	SK10	SK11	SK12	SK Total species
Ambocythere sp.			1											1
Aurila anterocostata						1			1		1	2	1	6
Aurila sherborni		1				2		1	3			2		9
Aurila sp.														
Aurila stronglya	11	10	11	6	7	3	2	13	17	22	6	12	10	130
Aurila trigonula	2	1	1	1		1		3	4		1	3		17
Bairdoppilata fusca					1							1		2
Beatmoosina cuxhavenensis												1		1
Bythocythere bradyi										1				1
Bythocythere sp.														
Callistocythere lagaaji													1	1
Callistocythere multituberculata	1	1			1		1							4
Callistocythere sp.									1					1
Campylocythere sp.		1	1					1						3
Candona angulata							1							1
Carinocythereis senelis													1	1
Cletocythereis jonesi	3													3
Cyprideis sp.														
Cyprois marginata								1						1
Cytherella compressa														
Cytherella elliptica										1				1
Cytherella sp.												1		1
Cytheretta woodiana	1													1
Cytheridea amphisparsa														
Cytheridea muelleri											1			1
Cytheridea hoerstgenensis		1				1		3		1		1		7

Cytheromorpha sp.													1	1
Cytheropteron nodosum														
Cytherura atra														
Echinocythereis laqueta	2													2
Eucythere declivis												1		1
Eucythere prava										1				1
Eucythere sp.								1						1
Eucythere triangularis														
Falunia retifastigata														
Falunia sphaerulolineata										1				1
Haplocytheridea cypridiodes														
Haplocytheridea pinguis								1						1
Haplocytheridea sp.														
Haplocytheridea robusta										1		1		2
Hermanites paijenborchiana sensu	2			3				2	1	4	1		1	14
Hiltermanncythere cf. emaciata	1										1			2
Hirschmannia viridis	1							1						2
Krithe stemerdinkensis														
Kuiperiana subelliptica										1				1
Leptocythere psammophila												1		1
Leptocythere recurata								1	2					3
Leptocythere recurata								1	2	2				5
Loxoconcha rhomboidea	1													1
Loxoconcha parahombiodea	3	1		2	1	1		3	2	1	3		1	18
Microcytherura broekiana		1												1
Microcytherura devenustata														
Microcytherura sp.	1												1	2
Muellerina dolabrata									1		1		1	3
Muellerina lacunosa	2				1	1			1			1		6
Muellerina latimarginata						1	1	3	2		2	2	4	15
Muellerina metabyssicola	1	3	4	1	1			2	1	3		2	2	20

Muellerina pliocenia			1	1		1				2	3		2	10
Muellerina orygyma	1			2				1			5		1	10
Normanicythere leiderma		1							1					2
Neocytherideis sp.	1													1
Neonesidea rhomboidea		1						2					1	4
Palmoconcha bitruncata													1	1
Palmoconcha laevata		1							1					2
Palmoconcha sp.											1			1
Palmoconcha tamarindus	1	1												2
Pontocythere bacesoi sensu														
Pontocythere botellina	3	1	1	1	3	1		2			4		1	17
Pontocythere curvata								1				1	1	3
Pontocythere denticulata														
Pontocythere elongata													1	1
Pontocythere sp.	2	1		3			2							8
Robertsonites tuberculatus														
Sarsicytherida robusta	1													1
Schizocythere hollandica														
Schizocythere pliocenica													1	1
Sclerochilus contortus									1					1
Thaerocythere biformis													1	1
Thaerocythere hoptonensis														
Thaerocythere mayburyae														
Thaerocythere oedichilus														
Thaerocythere regulae sensu														
Thaerocythere sp.		1	1	2		1		2						7
Thaerocythere trachypora	2													2
Thaerocythere wittei	1													1
Triginglymus petrosa		2							1					3
Xestoleberis broeckiana								1						1
Xestoleberis depressa			1			1		2			1			5

Xestoleberis sp.							1	1				1		3
Xiphichilus sp.					1									1
TOTAL	44	29	22	22	16	15	8	49	42	41	31	33	34	

BROOM PIT SPECIES LIST

Species	BP1	BP2	BP3	BP4	BP5	BP Total Species
Ambocythere sp.						
Aurila anterocostata				1	1	2
Aurila sherborni		1		1		2
Aurila sp.						
Aurila stronglya	11	8	16	10	13	58
Aurila trigonula	2	3	2	1	2	10
Bairdoppilata fusca						
Beatmoosina cuxhavenensis						
Bythocythere bradyi						
Bythocythere sp.						
Callistocythere lagaaji						
Callistocythere multituberculata			1			1
Callistocythere sp.				1		1
Campylocythere sp.			1			1
Candona angulata						
Carinocythereis senelis						
Cletocythereis jonesi						
Cyprideis sp.	1					1
Cyprois marginata						
Cytherella compressa						
Cytherella elliptica						
Cytherella sp.						
Cytheretta woodiana	1		1			2
Cytheridea amphisparsa	1					1

Cytheridea muelleri						
Cytheridea hoerstgenensis	1	1				2
Cytheromorpha sp.						
Cytheropteron nodosum						
Cytherura atra				1		1
Echinocythereis laqueta						
Eucythere declivis						
Eucythere prava						
Eucythere sp.						
Eucythere triangularis	1					1
Falunia retifastigata						
Falunia sphaerulolineata						
Haplocytheridea cypridiodes			1			1
Haplocytheridea pinguis						
Haplocytheridea sp.						
Haplocytheridea robusta						
Hermanites paijenborchiana sensu		1	2		1	4
Hiltermanncythere cf. emaciata			1			1
Hirschmannia viridis						
Krithe stemerdinkensis		1				1
Kuiperiana subelliptica						
Leptocythere psammophila						
Leptocythere recurata			1			1
Leptocythere recurata				1		1
Loxoconcha rhomboidea						
Loxoconcha parahombiodea						
Microcytherura broekiana						
Microcytherura devenustata						
Microcytherura sp.						
Muellerina dolabrata						
Muellerina lacunosa	1					1

Muellerina latimarginata			1			1
Muellerina metabyssicola	2	1	2	2	1	8
Muellerina pliocenia		1	1		2	4
Muellerina orygyma						
Normanicythere leiderma						
Neocytherideis sp.						
Neonesidea rhomboidea					1	1
Palmoconcha bitruncata	1	1				2
Palmoconcha laevata						
Palmoconcha sp.						
Palmoconcha tamarindus						
Pontocythere bacesoi sensu						
Pontocythere botellina	1	1				2
Pontocythere curvata			1			1
Pontocythere denticulata					1	1
Pontocythere elongata						
Pontocythere sp.					1	1
Robertsonites tuberculatus				1		1
Sarsicytherida robusta						
Schizocythere hollandica			2			2
Schizocythere pliocenica						
Sclerochilus contortus						
Thaerocythere biformis			1	1	1	3
Thaerocythere hoptonensis						
Thaerocythere mayburyae						
Thaerocythere oedichilus					1	1
Thaerocythere regulae sensu						
Thaerocythere sp.						
Thaerocythere trachypora						
Thaerocythere wittei						
Triginglymus petrosa			1			1

Xestoleberis broeckiana					1	1
Xestoleberis depressa						
Xestoleberis sp.						
Xiphichilus sp.						
TOTAL	23	19	35	20	26	

GEDGRAVE FARM SPECIES LIST

Species	GF1	GF2	GF3	GF4	GF Total Species
Ambocythere sp.					
Aurila anterocostata		2	1	6	9
Aurila sherborni		2	1		3
Aurila sp.					
Aurila stronglya	11	8	4	15	38
Aurila trigonula	1	1	1	3	6
Bairdoppilata fusca					
Beatmoosina cuxhavenensis					
Bythocythere bradyi					
Bythocythere sp.					
Callistocythere lagaaji					
Callistocythere multituberculata					
Callistocythere sp.					
Campylocythere sp.	1				1
Candona angulata					
Carinocythereis senelis					
Cletocythereis jonesi					
Cyprideis sp.					
Cyprois marginata					
Cytherella compressa					
Cytherella elliptica					

Cytherella sp.					
Cytheretta woodiana					
Cytheridea amphisparsa					
Cytheridea muelleri					
Cytheridea hoerstgenensis					
Cytheromorpha sp.					
Cytheropteron nodosum		1			1
Cytherura atra					
Echinocythereis laqueta					
Eucythere declivis					
Eucythere prava					
Eucythere sp.	1				1
Eucythere triangularis					
Falunia retifastigata					
Falunia sphaerulolineata					
Haplocytheridea cypridiodes					
Haplocytheridea pinguis					
Haplocytheridea sp.					
Haplocytheridea robusta					
Hermanites paijenborchiana sensu					
Hiltermanncythere cf. emaciata					
Hirschmannia viridis					
Krithe stemerdinkensis					
Kuiperiana subelliptica					
Leptocythere psammophila					
Leptocythere recurata					
Leptocythere recurata recurata		1			1
Loxoconcha rhomboidea					
Loxoconcha parahombiodea			2	2	4
Microcytherura broekiana					
Microcytherura devenustata					

Microcytherura sp.					
Muellerina dolabrata					
Muellerina lacunosa					
Muellerina latimarginata			1	1	2
Muellerina metabyssicola	1		1	1	3
Muellerina pliocenia			1	2	3
Muellerina orygyma					
Normanicythere leiderma					
Neocytherideis sp.					
Neonesidea rhomboidea					
Palmoconcha bitruncata					
Palmoconcha laevata					
Palmoconcha sp.					
Palmoconcha tamarindus					
Pontocythere bacesoi sensu					
Pontocythere botellina				1	1
Pontocythere curvata					
Pontocythere denticulata					
Pontocythere elongata					
Pontocythere sp.					
Robertsonites tuberculatus					
Sarsicytherida robusta					
Schizocythere hollandica					
Schizocythere pliocenica	1				1
Sclerochilus contortus					
Thaerocythere biformis	1			1	2
Thaerocythere hoptonensis				1	1
Thaerocythere mayburyae					
Thaerocythere oedichilus					
Thaerocythere regulae sensu					
Thaerocythere sp.				1	1

Thaerocythere trachypora					
Thaerocythere wittei					
Triginglymus petrosa				1	1
Xestoleberis broeckiana					
Xestoleberis depressa				1	1
Xestoleberis sp.					
Xiphichilus sp.					
TOTAL	17	15	12	36	

ORFORD 'THE CLIFF' SPECIES LIST

Species	OC1	OC2	OC3	OC4	OC5	OC Total Species
Ambocythere sp.						
Aurila anterocostata	12	2	2	2		18
Aurila sherborni	3		2	1	1	7
Aurila sp.						
Aurila stronglya	10	13	25	9	3	60
Aurila trigonula	3		1	1		5
Bairdoppilata fusca						
Beatmoosina cuxhavenensis						
Bythocythere bradyi				1		1
Bythocythere sp.					1	1
Callistocythere lagaaji						
Callistocythere multituberculata	1					1
Callistocythere sp.						
Campylocythere sp.						
Candona angulata						
Carinocythereis senelis						
Cletocythereis jonesi						
Cyprideis sp.	1					1
Cyprois marginata						

Cytherella compressa						
Cytherella elliptica						
Cytherella sp.						
Cytheretta woodiana						
Cytheridea amphisparsa	1				2	3
Cytheridea muelleri muelleri						
Cytheridea hoerstgenensis		1			1	2
Cytheromorpha sp.	1					1
Cytheropteron nodosum						
Cytherura atra						
Echinocythereis laqueta						
Eucythere declivis						
Eucythere prava					1	1
Eucythere sp.						
Eucythere triangularis						
Falunia retifastigata	1					1
Falunia sphaerulolineata						
Haplocytheridea cypridiodes						
Haplocytheridea pinguis		1				1
Haplocytheridea sp.						
Haplocytheridea robusta						
Hermanites paijenborchiana sensu		1			1	2
Hiltermanncythere cf. emaciata						
Hirschmannia viridis						
Krithe stemerdinkensis						
Kuiperiana subelliptica						
Leptocythere psammophila						
Leptocythere recurata						
Leptocythere recurata recurata		1	1			2
Loxoconcha rhomboidea						
Loxoconcha parahombiodea			1			1

Microcytherura broekiana						
Microcytherura devenustata			1			1
Microcytherura sp.						
Muellerina dolabrata	1					1
Muellerina lacunosa		4		1		5
Muellerina latimarginata				1		1
Muellerina metabyssicola	1	2		1		4
Muellerina pliocenia	1	1			2	4
Muellerina orygyma	2					2
Normanicythere leiderma						
Neocytherideis sp.			1			1
Neonesidea rhomboidea		1	2			3
Palmoconcha bitruncata						
Palmoconcha laevata						
Palmoconcha sp.						
Palmoconcha tamarindus						
Pontocythere bacesoi sensu					1	1
Pontocythere botellina	3	1	1	2		7
Pontocythere curvata						
Pontocythere denticulata						
Pontocythere elongata						
Pontocythere sp.						
Robertsonites tuberculatus						
Sarsicytherida robusta						
Schizocythere hollandica			1			1
Schizocythere pliocenica						
Sclerochilus contortus						
Thaerocythere biformis	3	1	2			6
Thaerocythere hoptonensis						
Thaerocythere mayburyae				1		1
Thaerocythere oedichilus						

Thaerocythere regulae sensu	1		1			2
Thaerocythere sp.						
Thaerocythere trachypora						
Thaerocythere wittei						
Triginglymus petrosa		1				1
Xestoleberis broeckiana						
Xestoleberis depressa						
Xestoleberis sp.				1		1
Xiphichilus sp.						
TOTAL	45	30	41	21	13	

RICHMOND FARM SPECIES LIST

Species	RF1	RF2	RF3	RF4	RF5	RF Total Species
Ambocythere sp.						
Aurila anterocostata	1					1
Aurila sherborni						
Aurila sp.					1	1
Aurila stronglya	12	3	1	5	7	28
Aurila trigonula	2			1		3
Bairdoppilata fusca						
Beatmoosina cuxhavenensis						
Bythocythere bradyi						
Bythocythere sp.						
Callistocythere lagaaji						
Callistocythere multituberculata						
Callistocythere sp.						
Campylocythere sp.			1	1		2
Candona angulata						
Carinocythereis senelis						
Cletocythereis jonesi						

Cyprideis sp.						
Cyprois marginata						
Cytherella compressa			1			1
Cytherella elliptica						
Cytherella sp.						
Cytheretta woodiana						
Cytheridea amphisparsa						
Cytheridea muelleri muelleri				1		1
Cytheridea hoerstgenensis			1	1		2
Cytheromorpha sp.						
Cytheropteron nodosum						
Cytherura atra						
Echinocythereis laqueta						
Eucythere declivis						
Eucythere prava						
Eucythere sp.						
Eucythere triangularis						
Falunia retifastigata						
Falunia sphaerulolineata						
Haplocytheridea cypridiodes						
Haplocytheridea pinguis						
Haplocytheridea sp.					1	1
Haplocytheridea robusta	1					1
Hermanites paijenborchiana sensu						
Hiltermanncythere cf. emaciata						
Hirschmannia viridis						
Krithe stemerdinkensis						
Kuiperiana subelliptica						
Leptocythere psammophila						
Leptocythere recurata						
Leptocythere recurata recurata						

Loxoconcha rhomboidea						
Loxoconcha parahombiodea	3		1	1	1	6
Microcytherura broekiana						
Microcytherura devenustata						
Microcytherura sp.						
Muellerina dolabrata						
Muellerina lacunosa	1					1
Muellerina latimarginata	1					1
Muellerina metabyssicola	1		1			2
Muellerina pliocenia					1	1
Muellerina orygyma				1		1
Normanicythere leiderma				1		1
Neocytherideis sp.		1				1
Neonesidea rhomboidea				2		2
Palmoconcha bitruncata						
Palmoconcha laevata						
Palmoconcha sp.						
Palmoconcha tamarindus						
Pontocythere bacesoi sensu				1		1
Pontocythere botellina			1	1	1	3
Pontocythere curvata						
Pontocythere denticulata						
Pontocythere elongata	1					1
Pontocythere sp.					1	1
Robertsonites tuberculatus						
Sarsicytherida robusta						
Schizocythere hollandica						
Schizocythere pliocenica						
Sclerochilus contortus						
Thaerocythere biformis			1			1
Thaerocythere hoptonensis						

Thaerocythere mayburyae						
Thaerocythere oedichilus	1					1
Thaerocythere regulae sensu						
Thaerocythere sp.						
Thaerocythere trachypora						
Thaerocythere wittei						
Triginglymus petrosa			1			1
Xestoleberis broeckiana						
Xestoleberis depressa	1					1
Xestoleberis sp.						
Xiphichilus sp.						
TOTAL	25	4	9	16	13	

GENERA PRESENCE/ ABSENCE

SUTTON KNOLL GENERA PRESENCE/ ABSENCE

Genera	SK Clay Layer	SK1	SK2	SK3	SK4	SK5	SK6	SK7	SK8	SK9	SK10	SK11	SK12
Aurila	1	1	1	1	1	1	1	1	1	1	1	1	1
Bairdoppilata					1							1	
Bythocythere										1			
Callistocythere	1	1			1		1		1				1
Carinocythereis													1
Cletocythereis	1												
Cytherella										1		1	
Cytheretta	1												
Cytheridea		1				1		1		1	1	1	
Cytheromorpha													1
Cytheropteron													
Cytherura													
Echinocythereis	1												

Eucythere								1		1		1	
Hermanites	1			1				1	1	1	1		1
Hiltermannicythere	1										1		
Hirschmannia	1							1					
Krithe													
Kuiperiana										1			
Leptocythere								1	1	1		1	
Loxoconcha	1	1		1	1	1		1	1	1	1		1
Microcytherura	1	1											1
Muellerina	1	1	1	1	1	1	1	1	1	1	1	1	1
Neocythereideis	1												
Neonesidea		1						1					1
Normanicythere		1							1				
Palmoconcha	1	1							1		1		1
Pontocythere	1	1	1	1	1	1	1	1			1	1	1
Robertsonites													
Sarsicytheridea	1							1			1		
Sclerochilus									1				
Thaerocythere	1	1	1	1		1		1					1
Xestolebris			1			1	1	1			1	1	

BROOM PIT GENERA PRESENCE/ ABSENCE

Genera	BP1	BP2	BP3	BP4	BP5
Aurila	1	1	1	1	1
Bairdoppilata					
Bythocythere					
Callistocythere			1	1	
Carinocythereis					
Cletocythereis					
Cytherella					

Cytheretta	1		1		
Cytheridea	1	1			
Cytheromorpha					
Cytheropteron					
Cytherura				1	
Echinocythereis					
Eucythere	1				
Hermanites		1	1		1
Hiltermannicythere			1		
Hirschmannia					
Krithe		1			
Kuiperiana					
Leptocythere			1	1	
Loxoconcha					
Microcytherura					
Muellerina	1	1	1	1	1
Neocythereideis					
Neonesidea					1
Normanicythere					
Palmoconcha	1	1			
Pontocythere	1	1	1		1
Robertsonites				1	
Sarsicytheridea			1		
Sclerochilus					
Thaerocythere			1	1	1
Xestolebris					1

GEDGRAVE FARM GENERA PRESENCE/ ABSENCE

Genera	GF1	GF2	GF3	GF4
Aurila	1	1	1	1
Bairdoppilata				

Bythocythere				
Callistocythere				
Carinocythereis				
Cletocythereis				
Cytherella				
Cytheretta				
Cytheridea				
Cytheromorpha				
Cytheropteron		1		
Cytherura				
Echinocythereis				
Eucythere	1			
Hermanites				
Hirschmannia				
Krithe				
Kuiperiana				
Leptocythere		1		
Loxoconcha			1	1
Microcytherura				
Muellerina	1		1	1
Neocythereideis				
Neonesidea				
Normanicythere				
Palmoconcha				
Pontocythere				1
Robertsonites				
Sarsicytheridea				
Sclerochilus				
Thaerocythere	1			1
Xestolebris				1

ORFORD ‘THE CLIFF’ GENERA PRESENCE/ ABSENCE

Genera	OC1	OC2	OC3	OC4	OC5
Aurila	1	1	1	1	1
Bairdoppilata					
Bythocythere					1
Callistocythere	1				
Carinocythereis					
Cletocythereis					
Cytherella					
Cytheretta					
Cytheridea	1	1			1
Cytheromorpha	1				
Cytheropteron					
Cytherura					
Echinocythereis					
Eucythere					1
Hermanites		1			1
Hirschmannia					
Krithe					
Kuiperiana					
Leptocythere		1	1		
Loxoconcha			1		
Microcytherura			1		
Muellerina	1	1		1	1
Neocythereideis			1		
Neonesidea		1	1		
Normanicythere					
Palmoconcha					
Pontocythere	1	1	1	1	1
Robertsonites					
Sarsicytheridea					

Sclerochilus					
Thaerocythere	1	1	1	1	
Xestolebris				1	

RICHMOND FARM GENERA PRESENCE/ ABSENCE

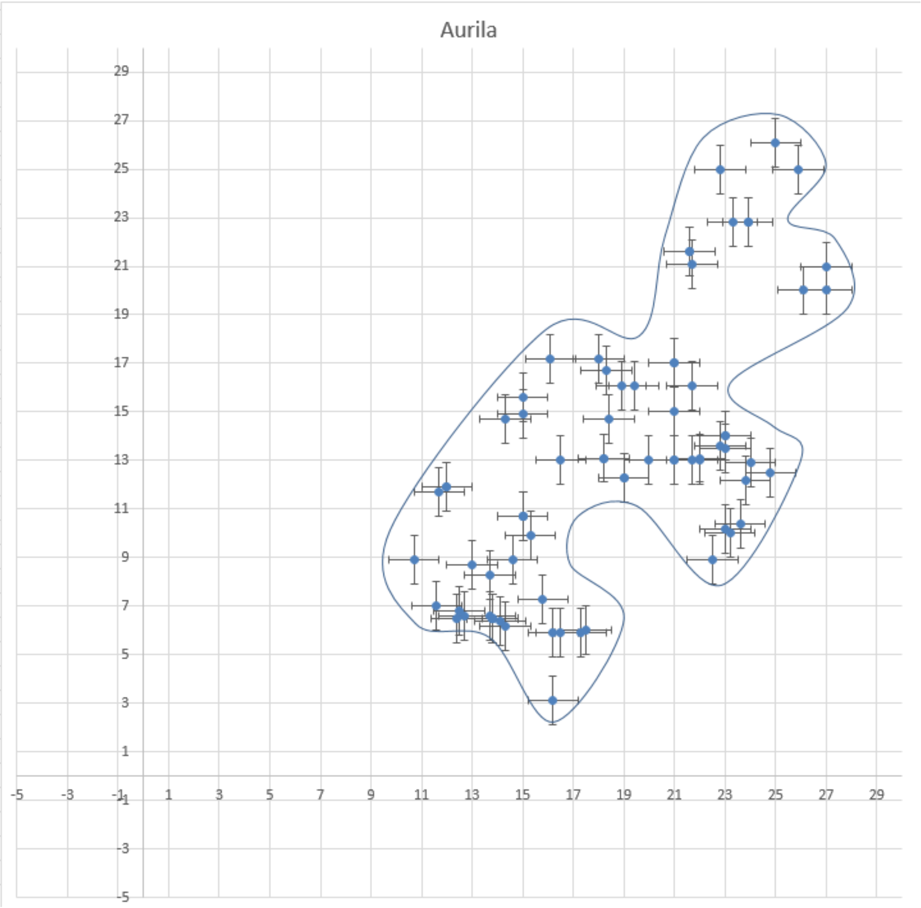
Genera	RF1	RF2	RF3	RF4	RF5
Aurila	1	1	1	1	1
Bairdoppilata					
Bythocythere					
Callistocythere					
Carinocythereis					
Cletocythereis					
Cytherella			1		
Cytheretta					
Cytheridea			1	1	
Cytheromorpha					
Cytheropteron					
Cytherura					
Echinocythereis					
Eucythere					
Hermanites					
Hirschmannia					
Krithe					
Kuiperiana					
Leptocythere					
Loxoconcha	1		1	1	1
Microcytherura					
Muellerina	1		1	1	1
Neocythereideis		1			
Neonesidea				1	

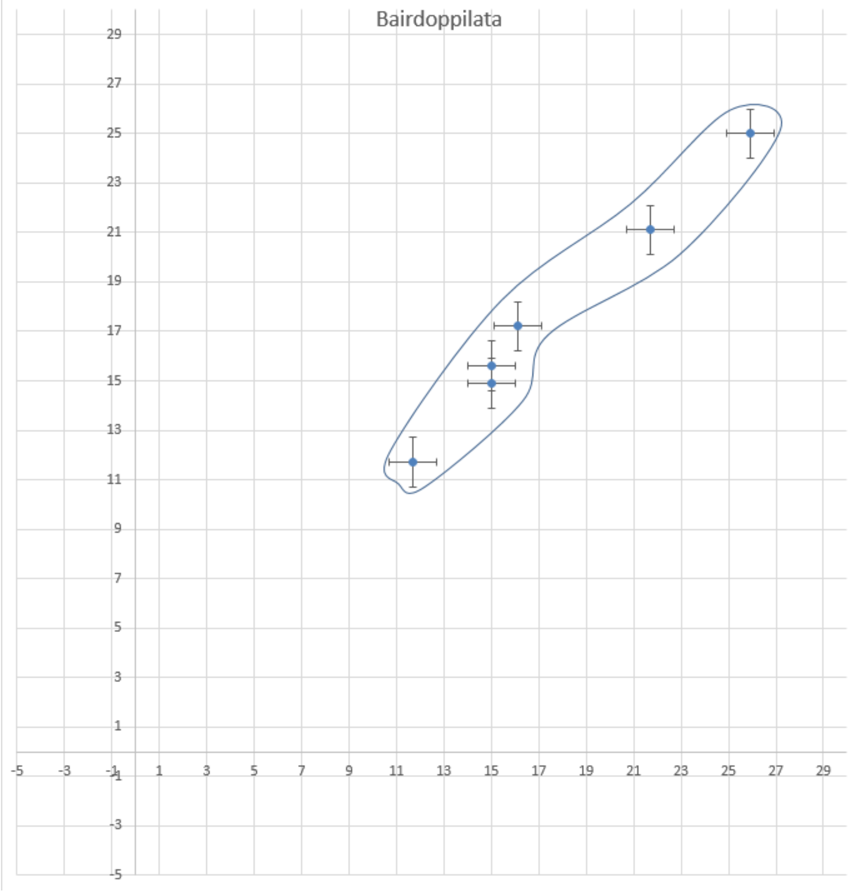
Normanicythere				1	
Palmoconcha					
Pontocythere	1		1	1	1
Robertsonites					
Sarsicytheridea					
Sclerochilus					
Thaerocythere	1		1		
Xestolebris	1				

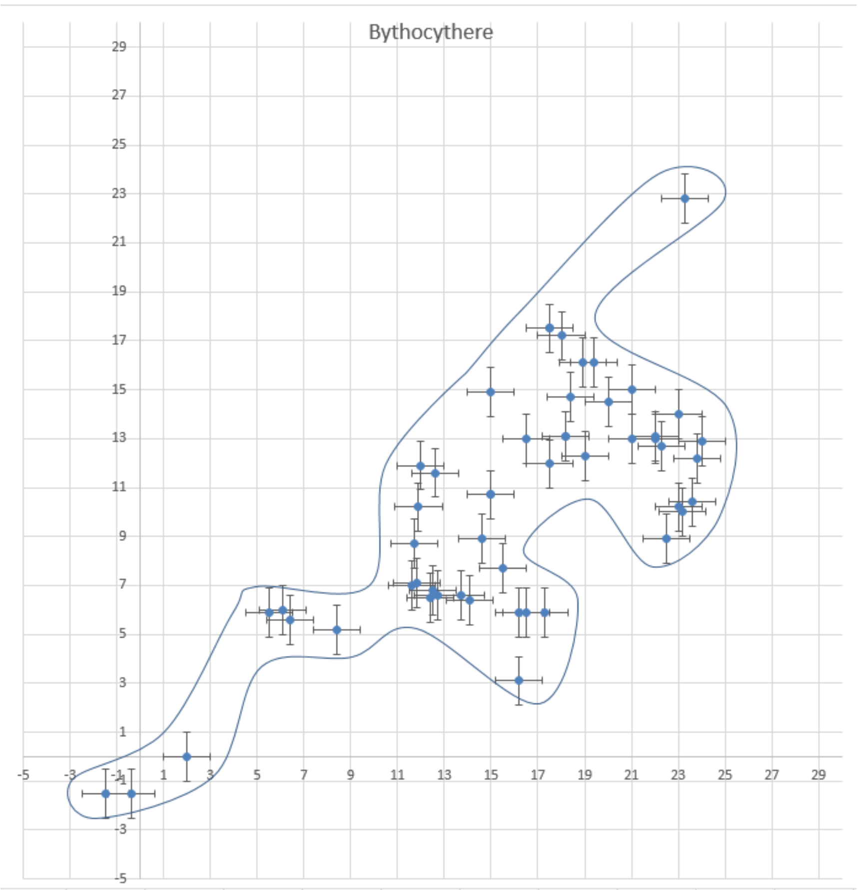
APPENDIX B

GENERA TEMPERATURE PLOTS

All temperature plots have the MSBT along the x-axis and MWBT along the y-axis.



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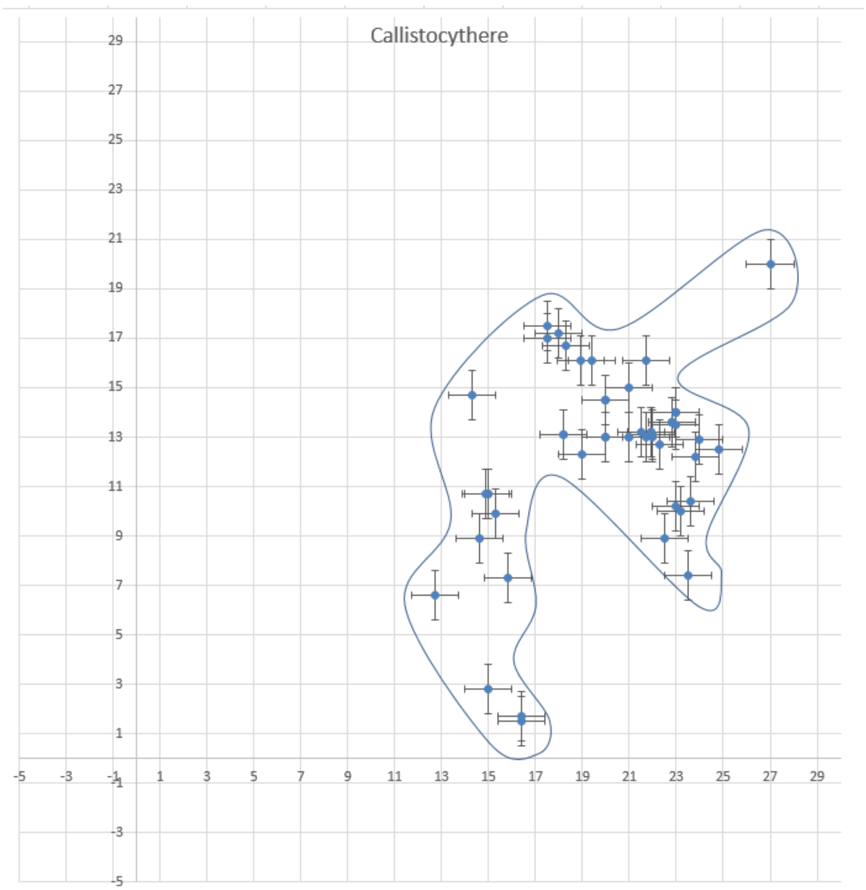
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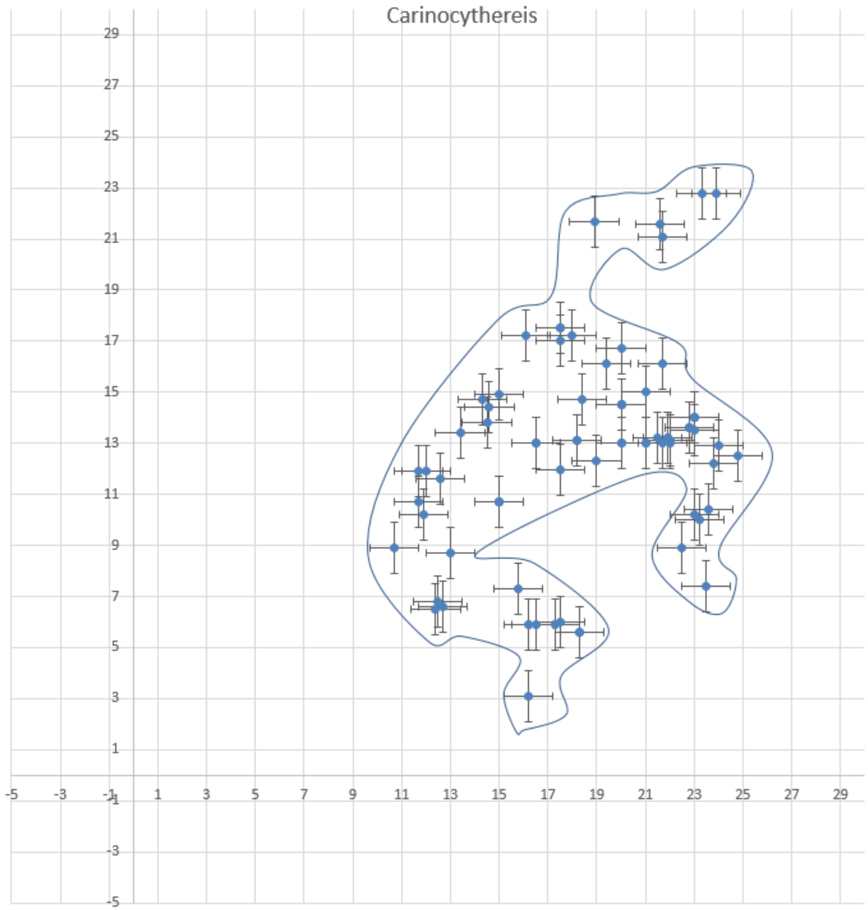
Carinocythereis
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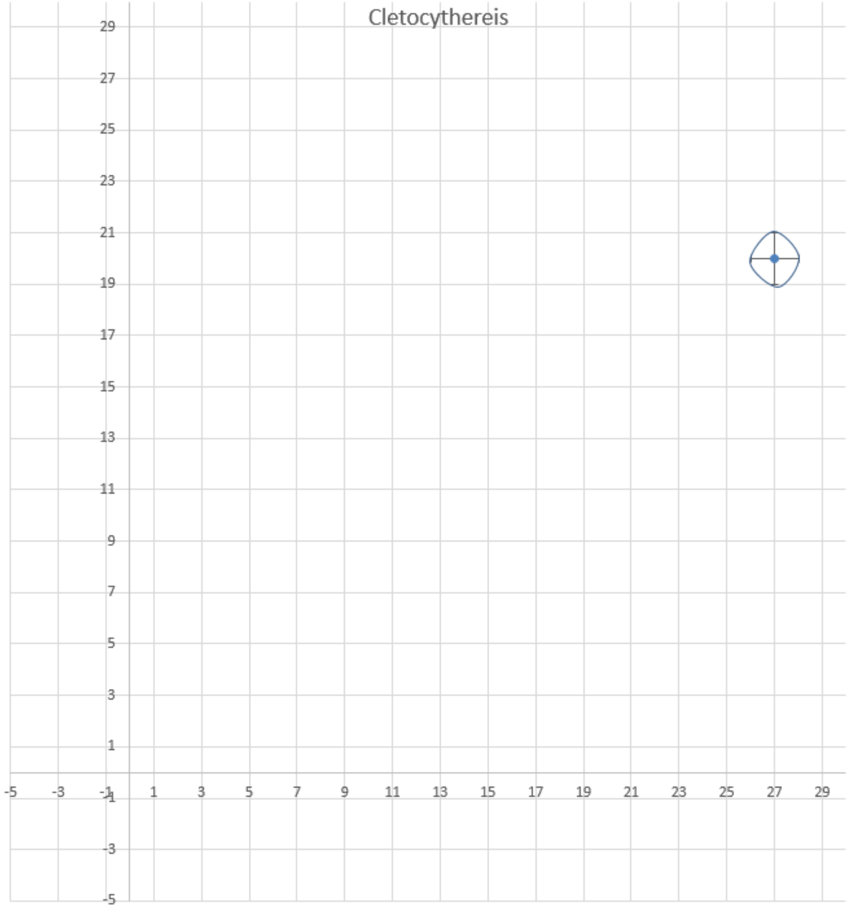
Cletocythereis
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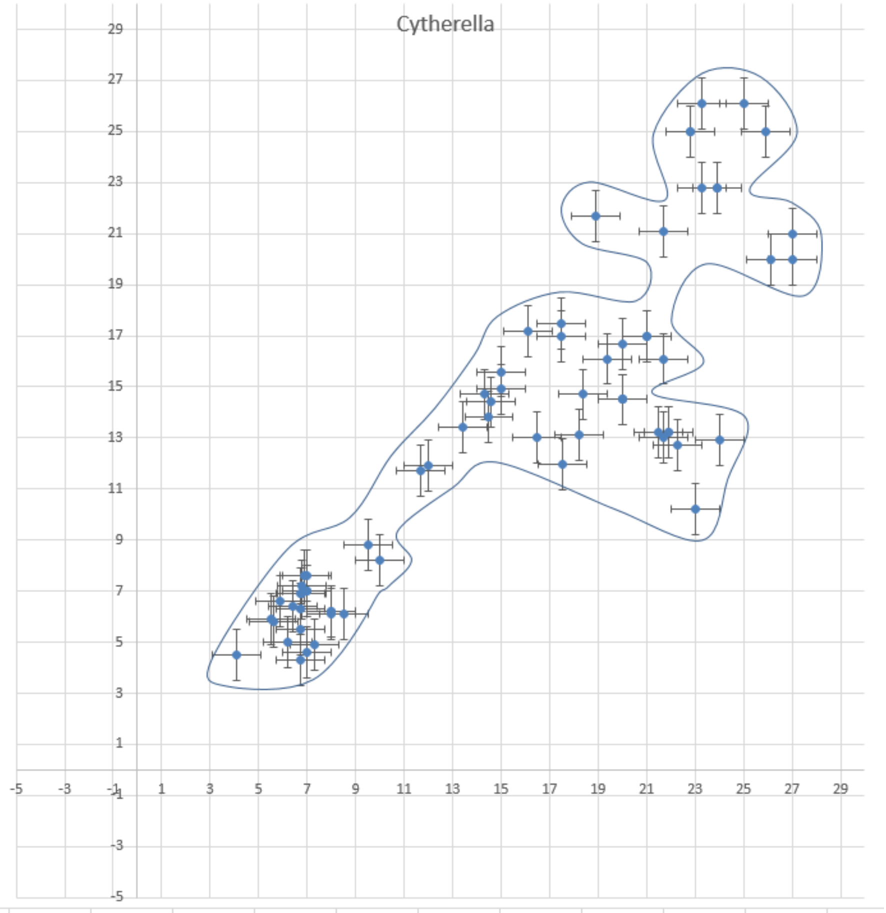
Cytherella
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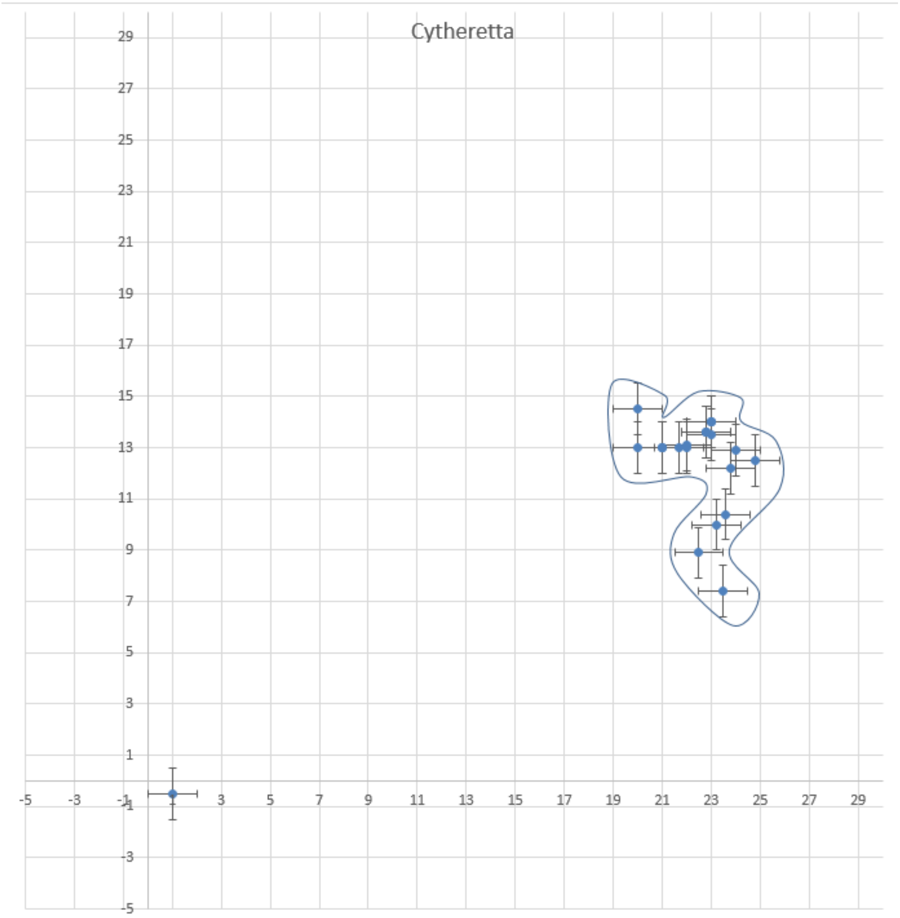
Cytheretta
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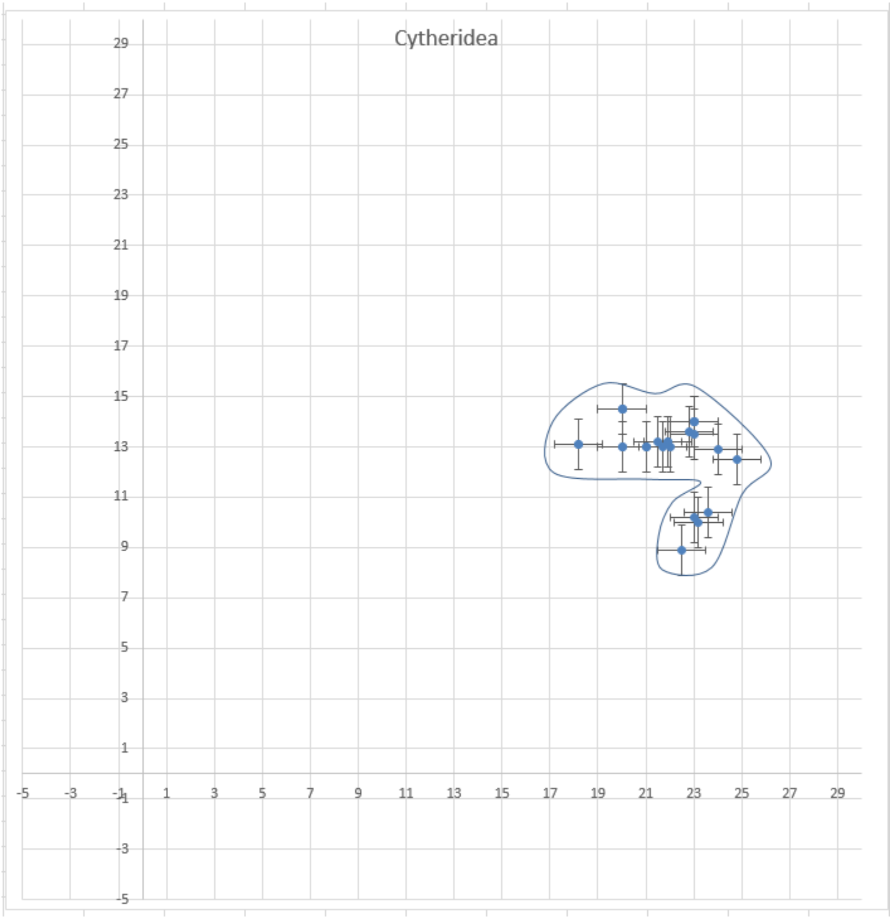
Cytheridea
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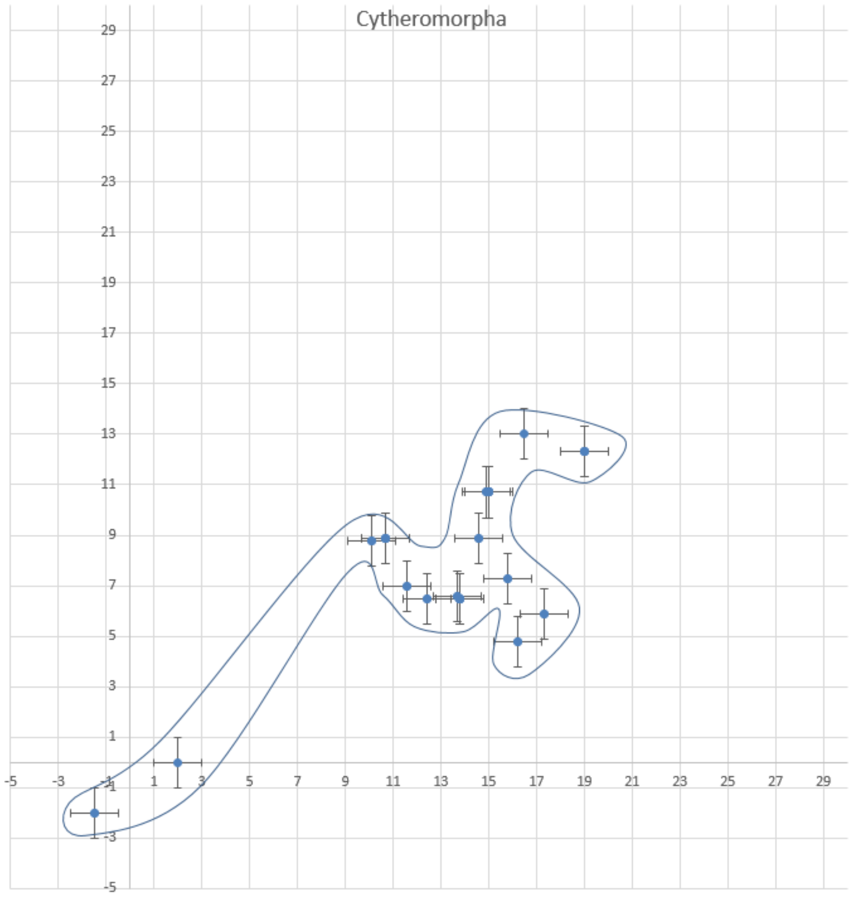
-5 -3 -1 1 3 5 7 9 11 13 15 17 19 21 23 25 27 29


Cytheromorpha
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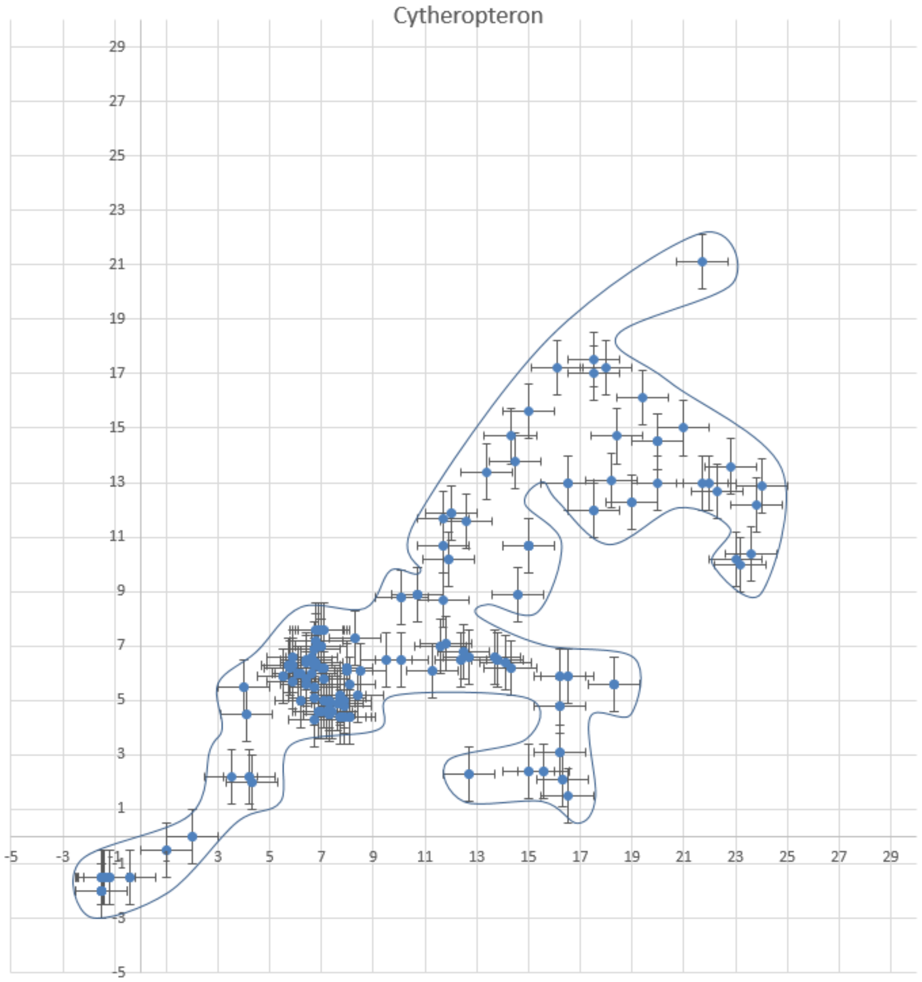
Cytheropteron
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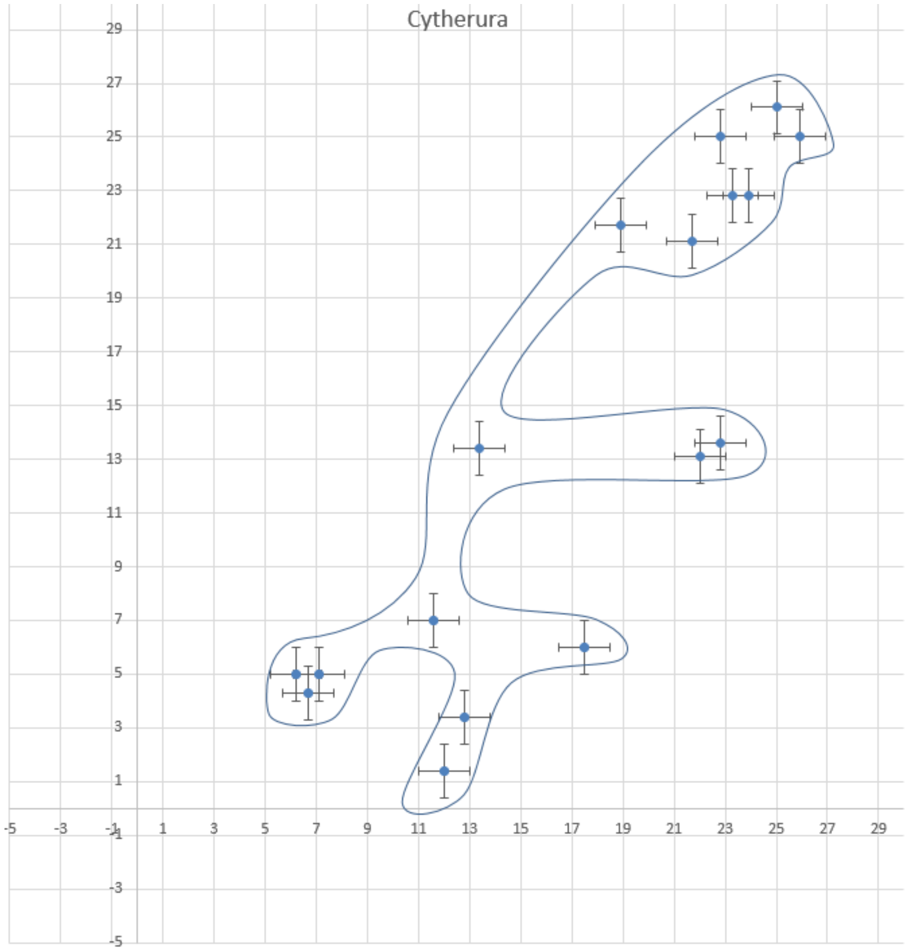
Cytherura
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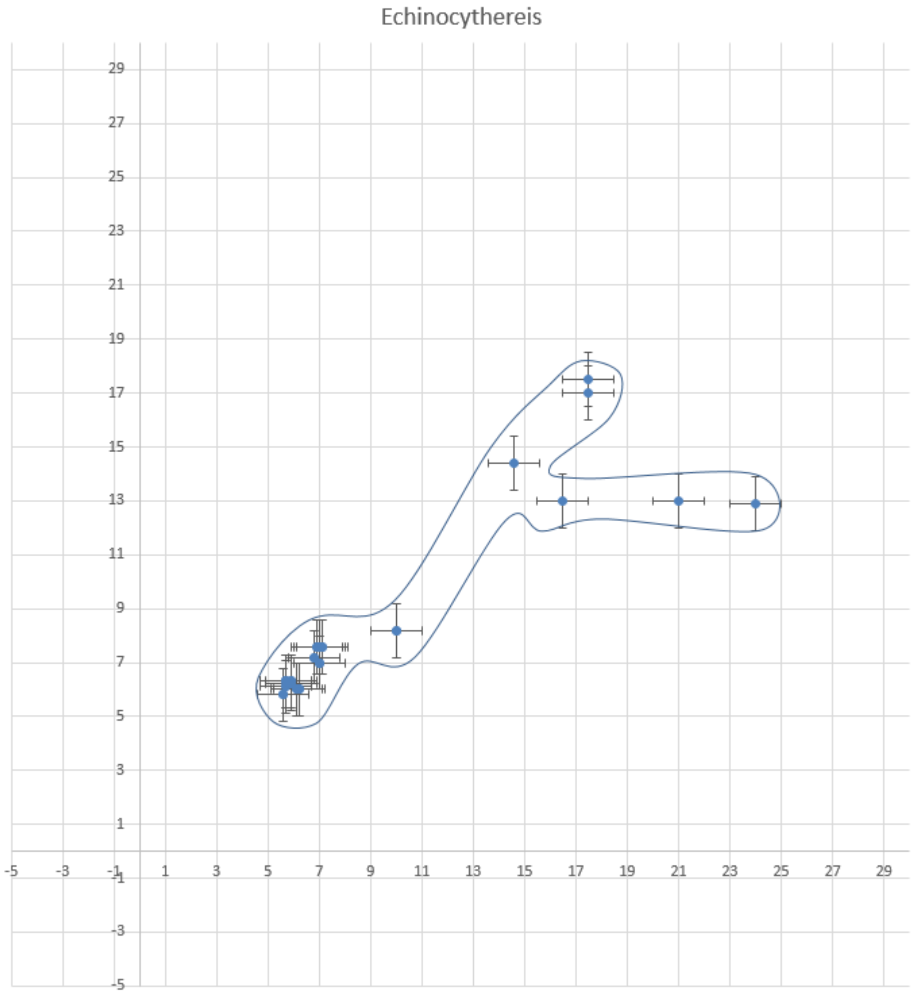
Echinocythereis
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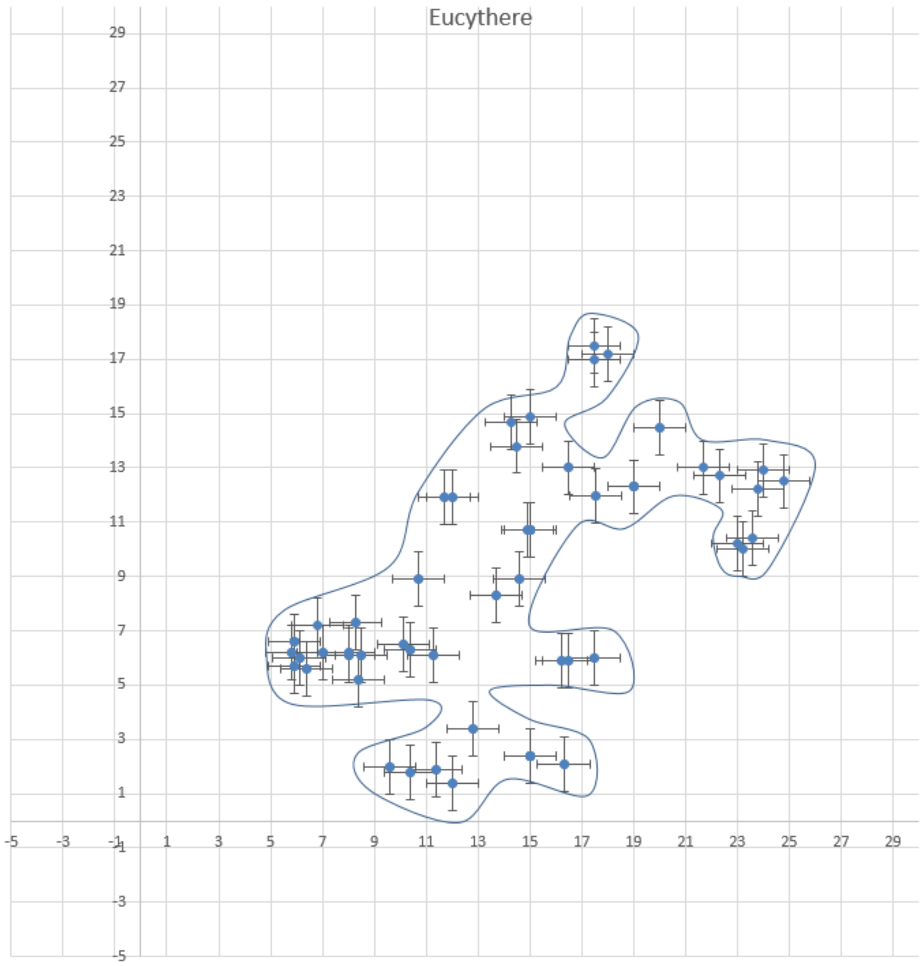
Eucythere
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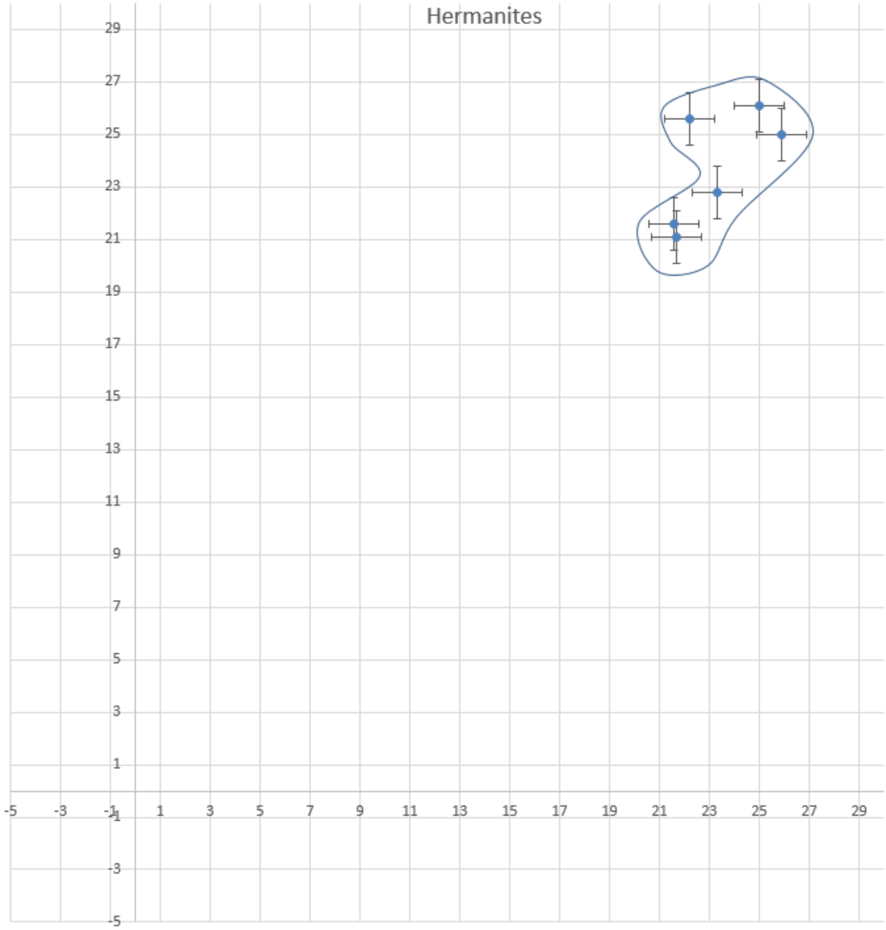
Hermanites
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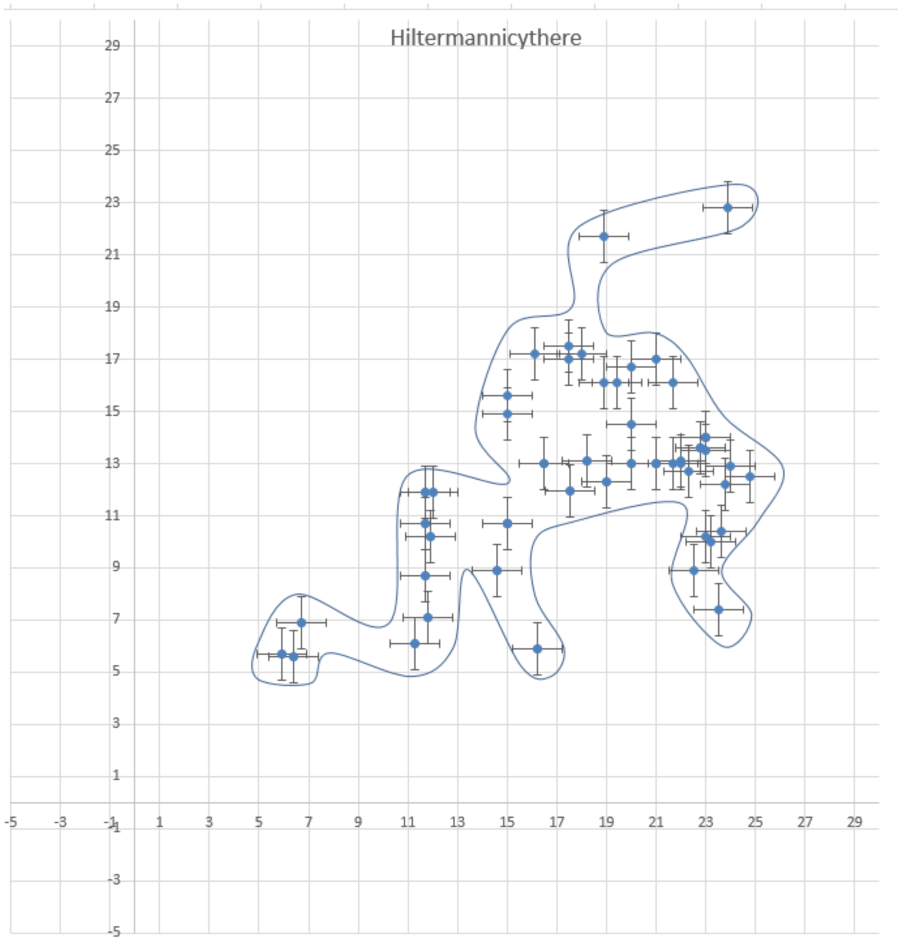
Hiltermannicythere
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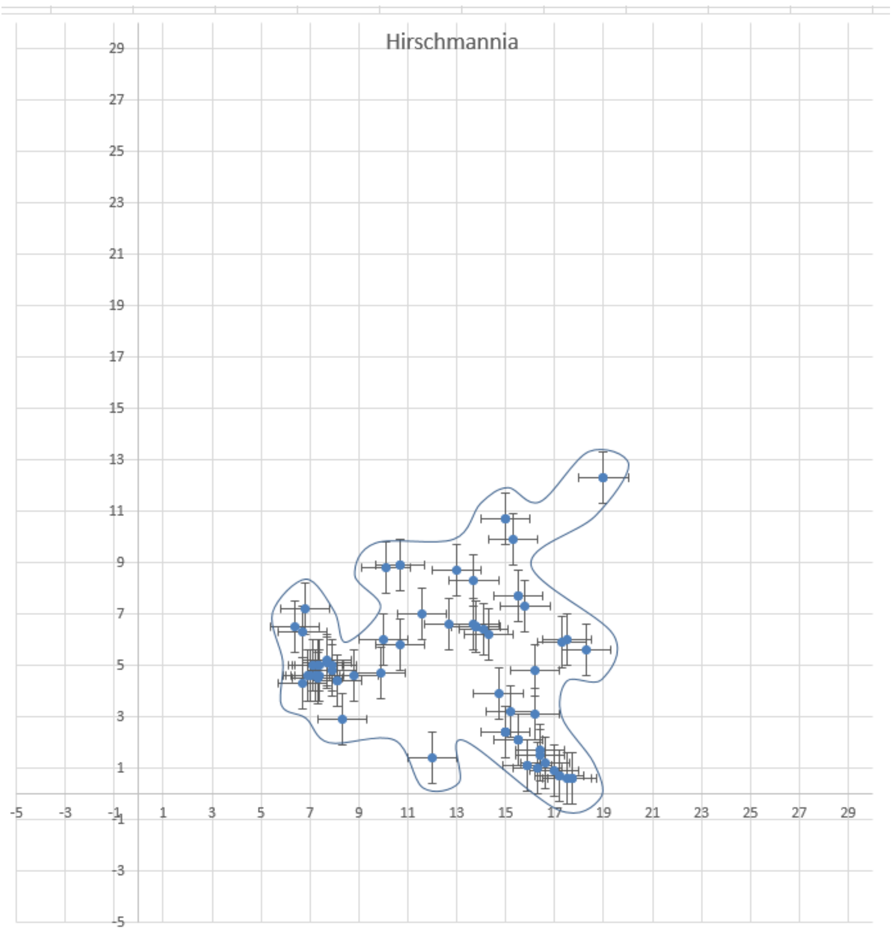
Hirschmannia
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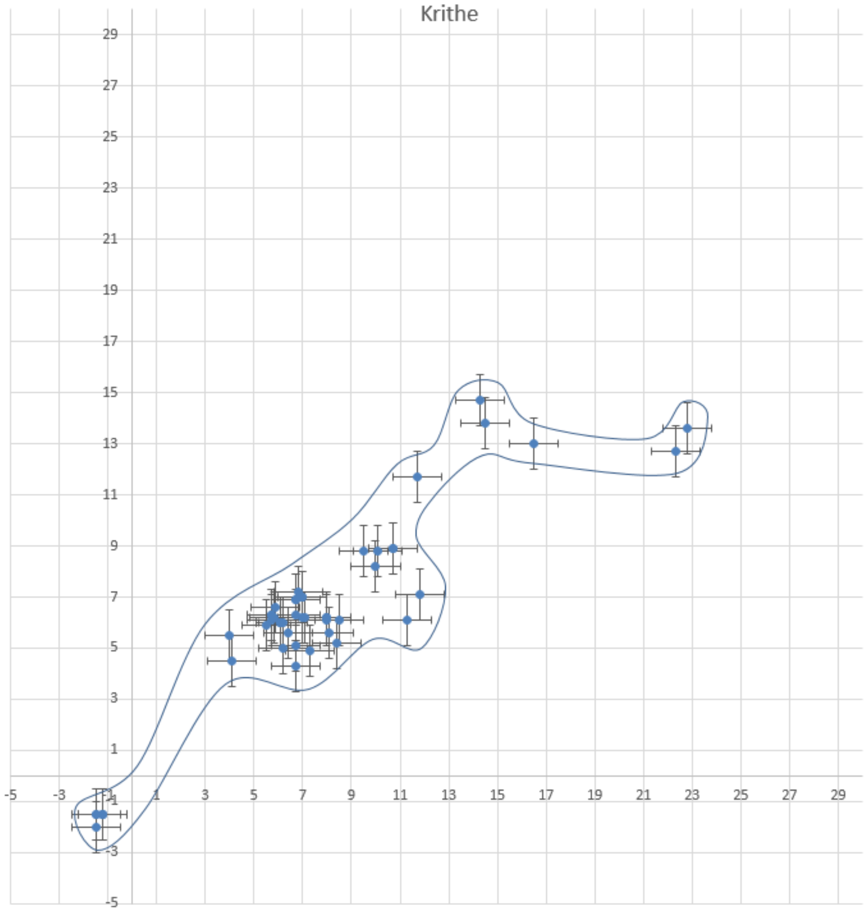
Krithe
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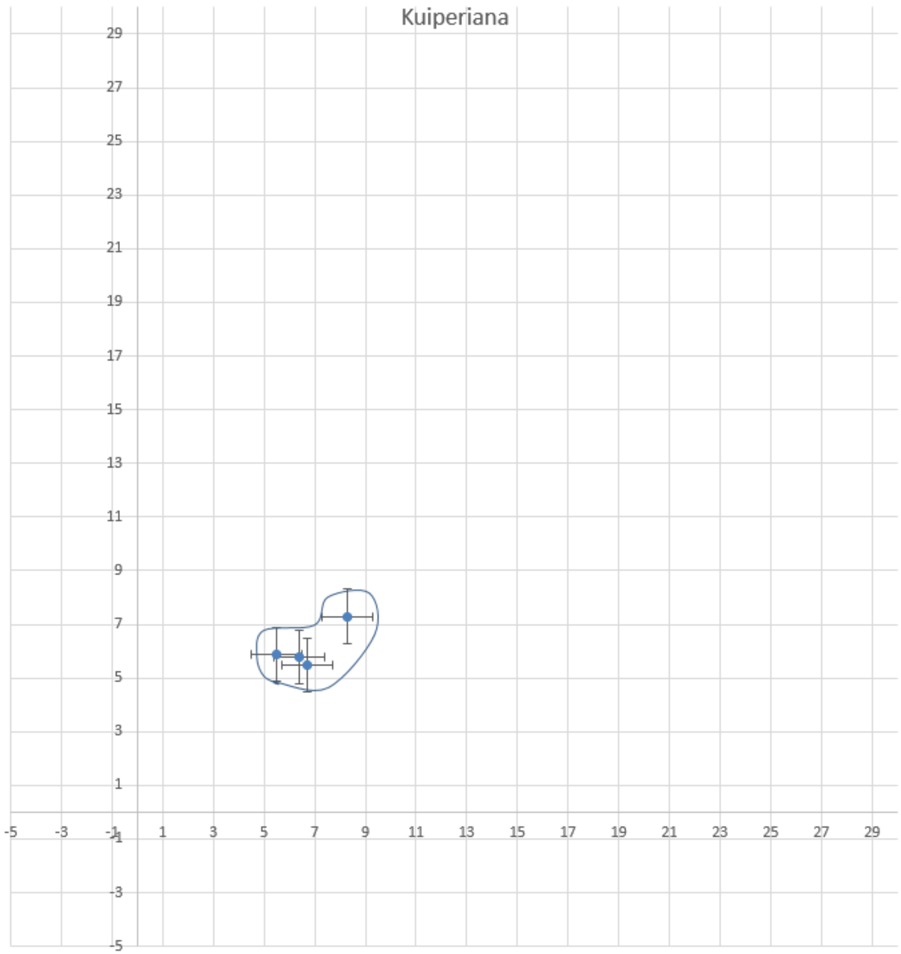
Kuiperiana
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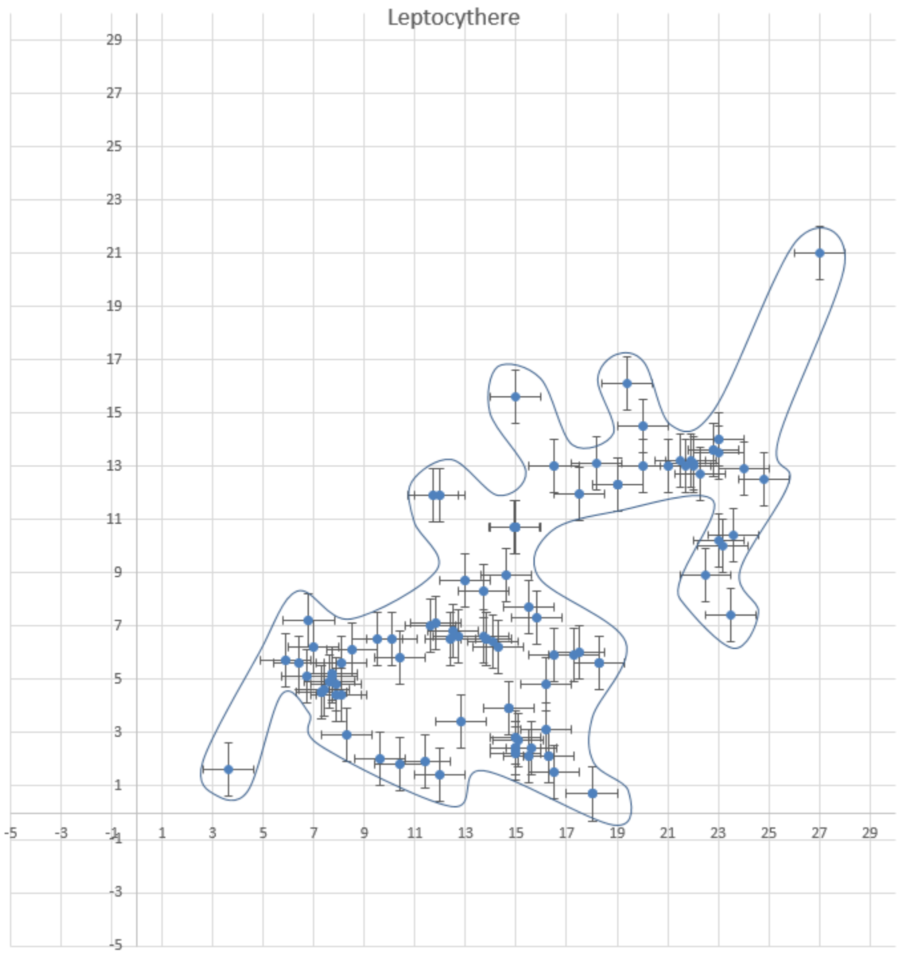
Leptocythere
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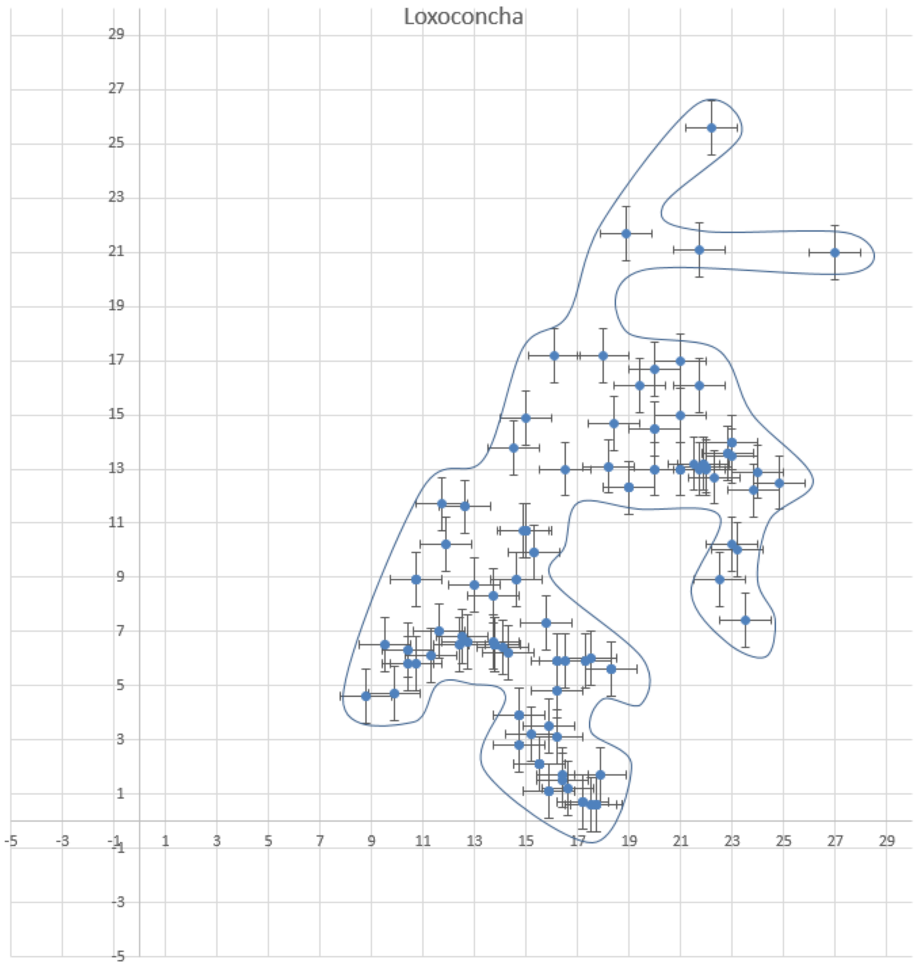
Loxoconcha
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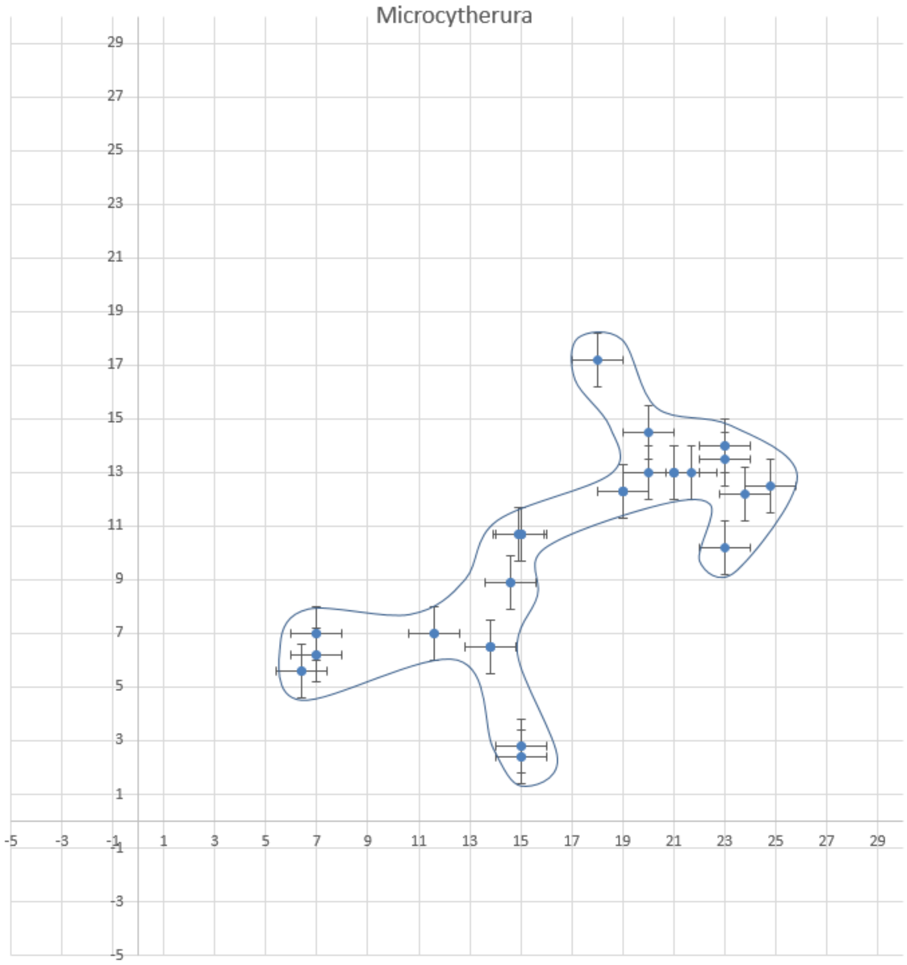
Microcytherura
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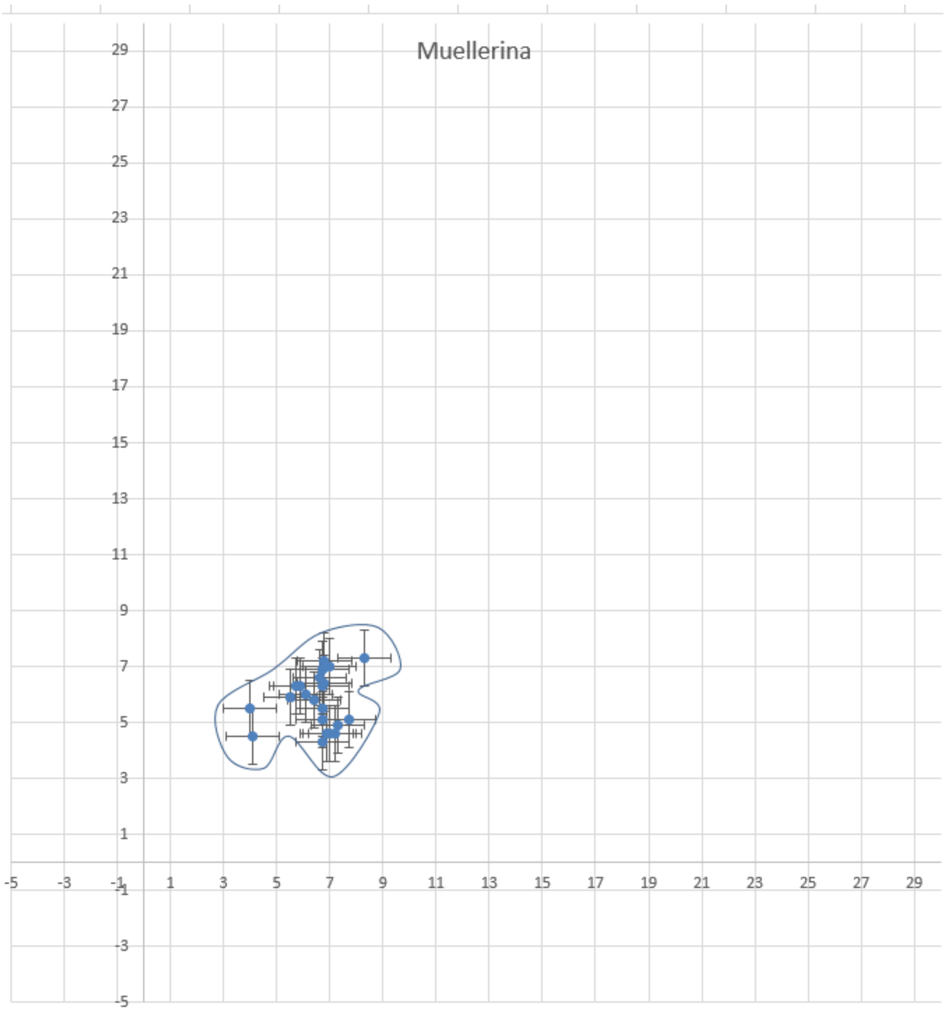
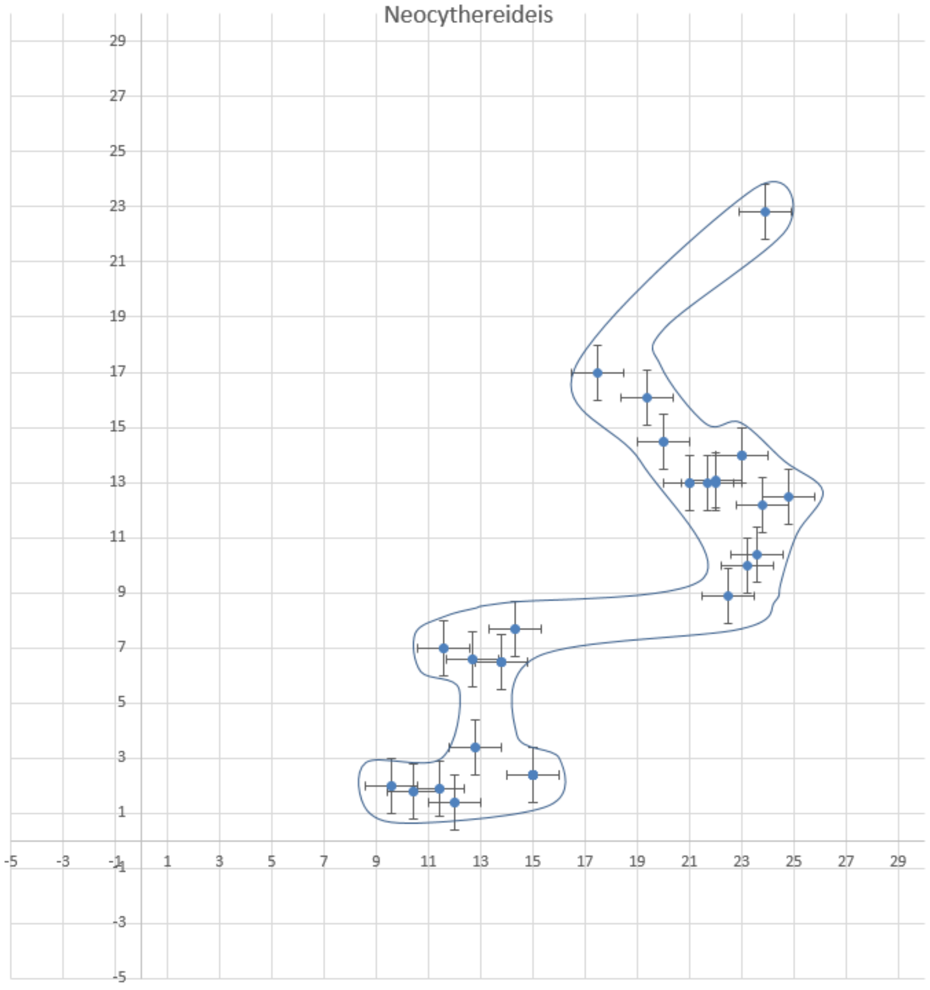
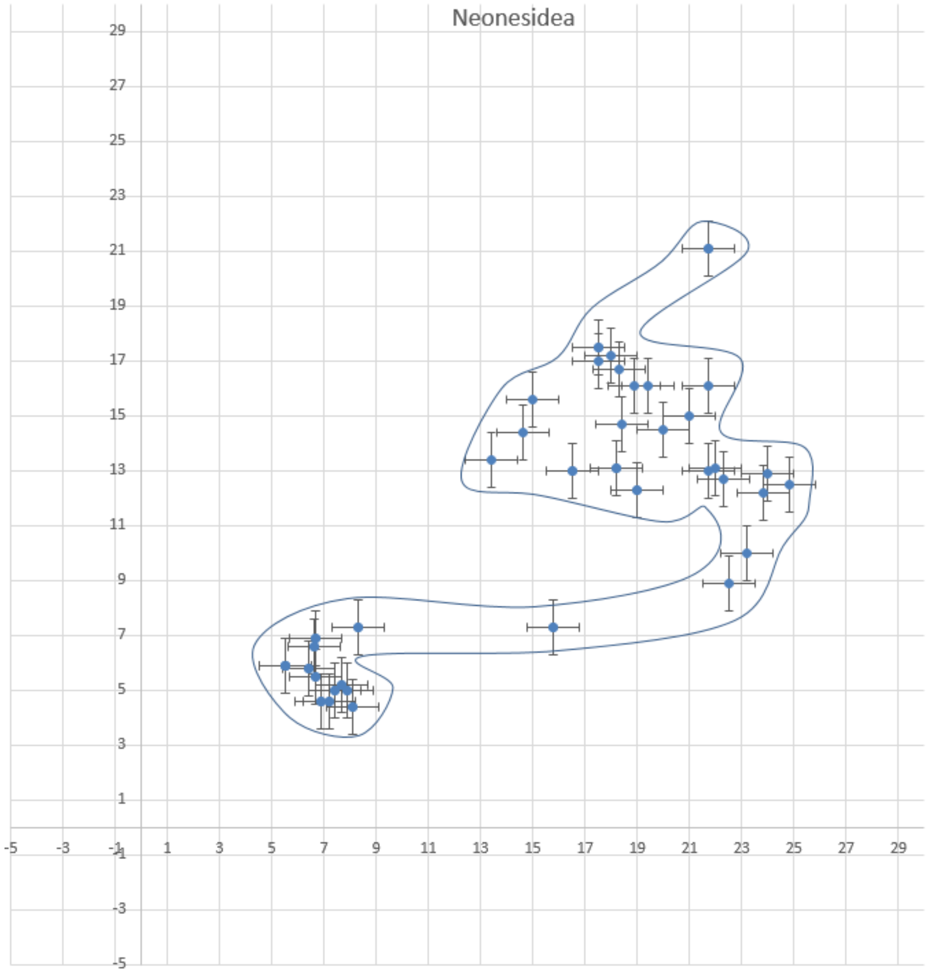


Muellerina



Neocythereideis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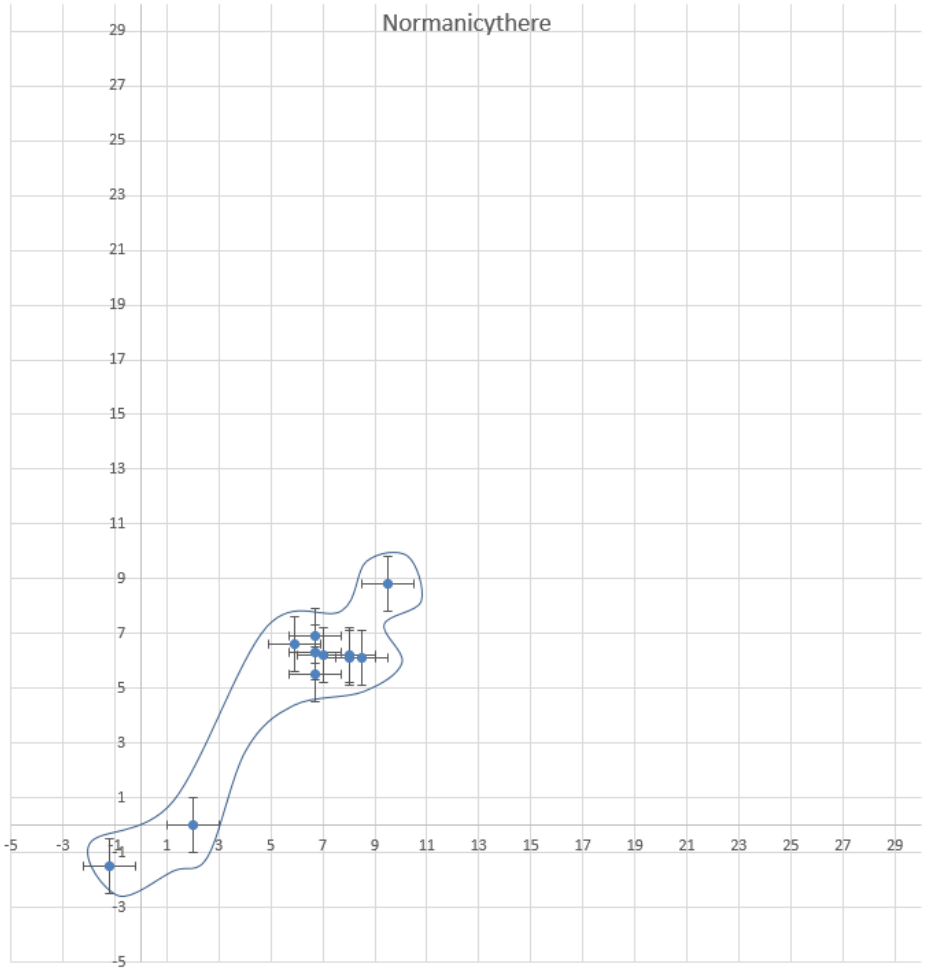
Normanicythere
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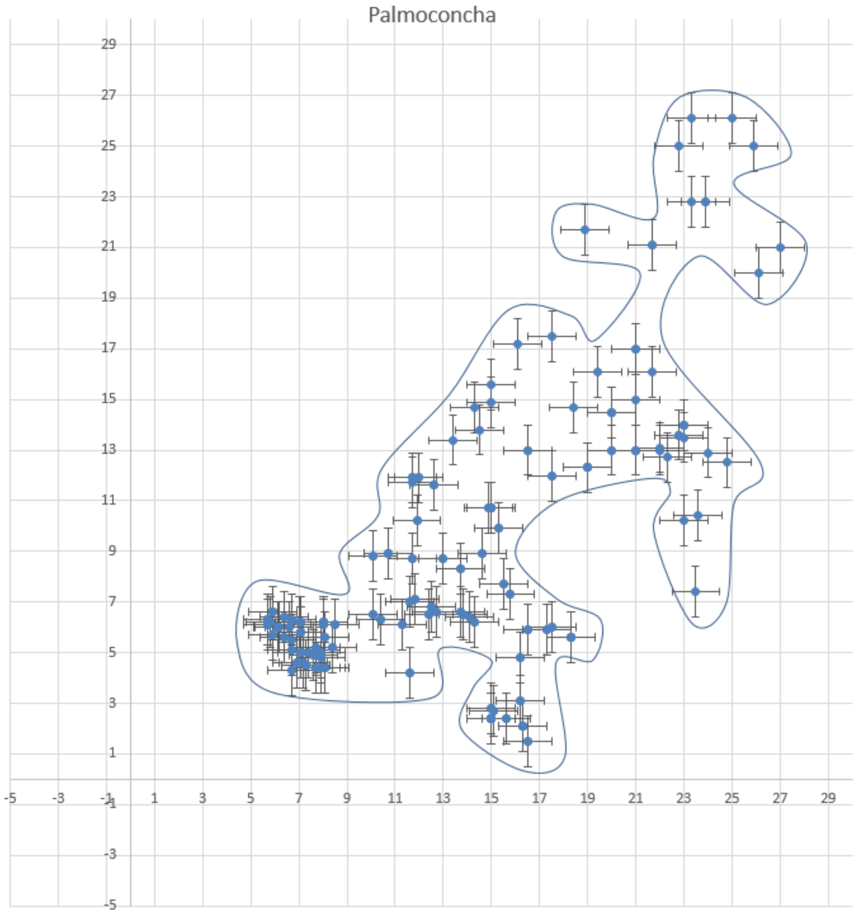
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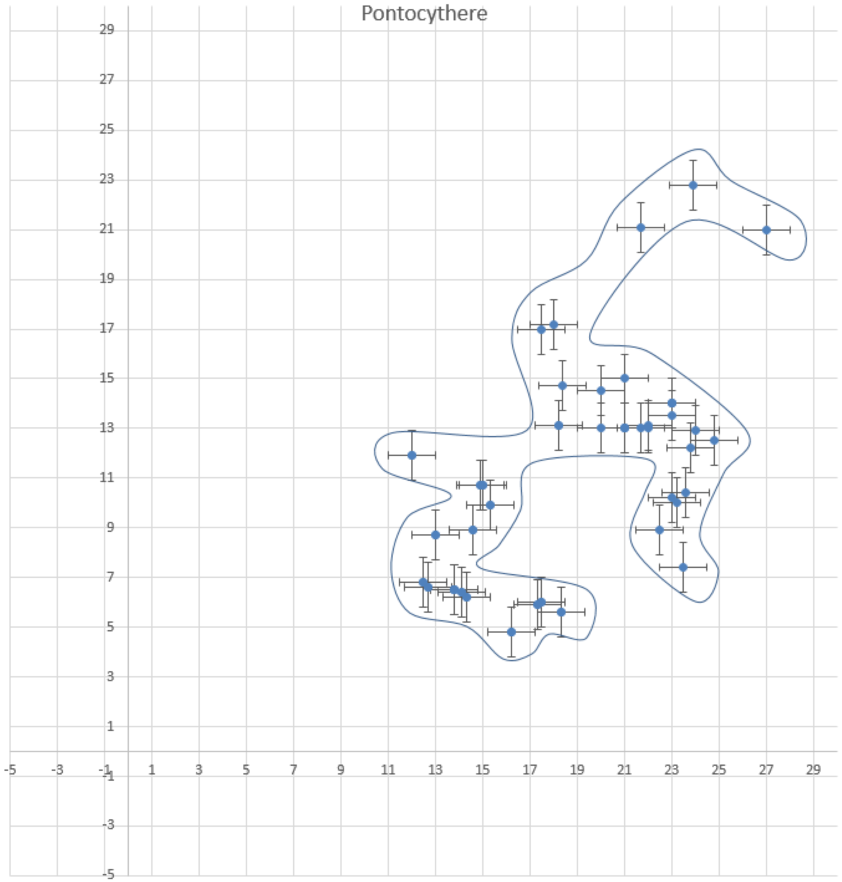
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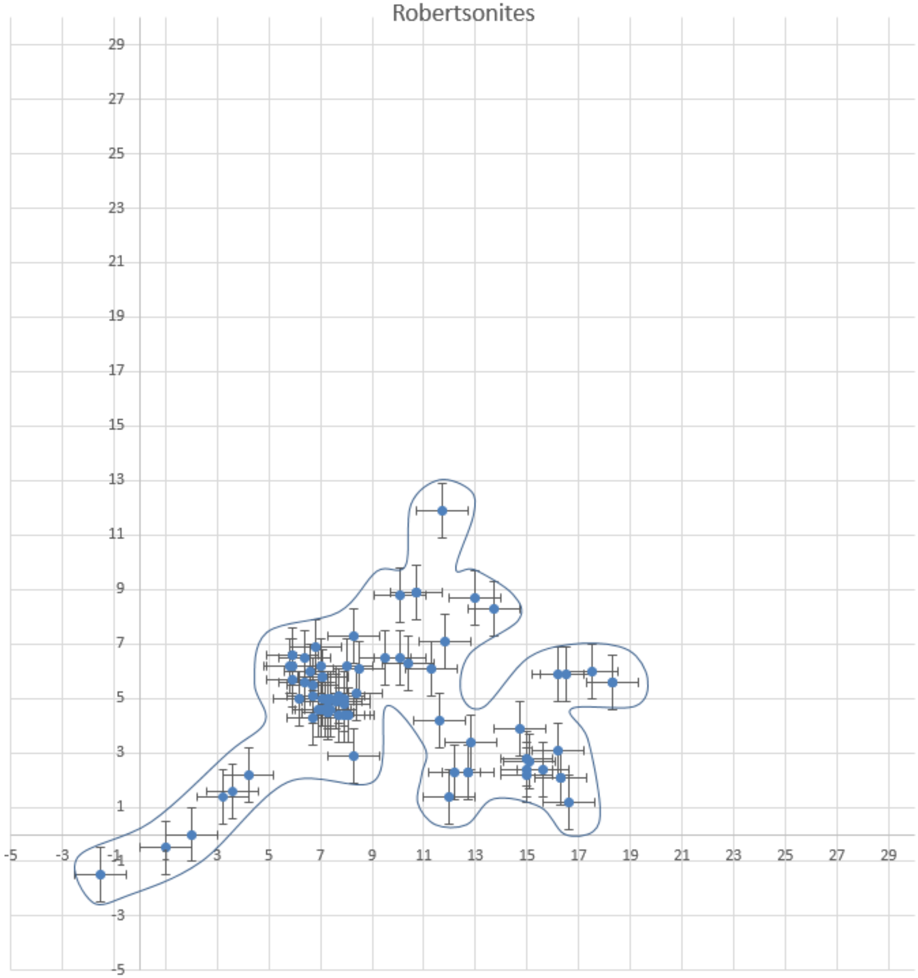
Robertsonites
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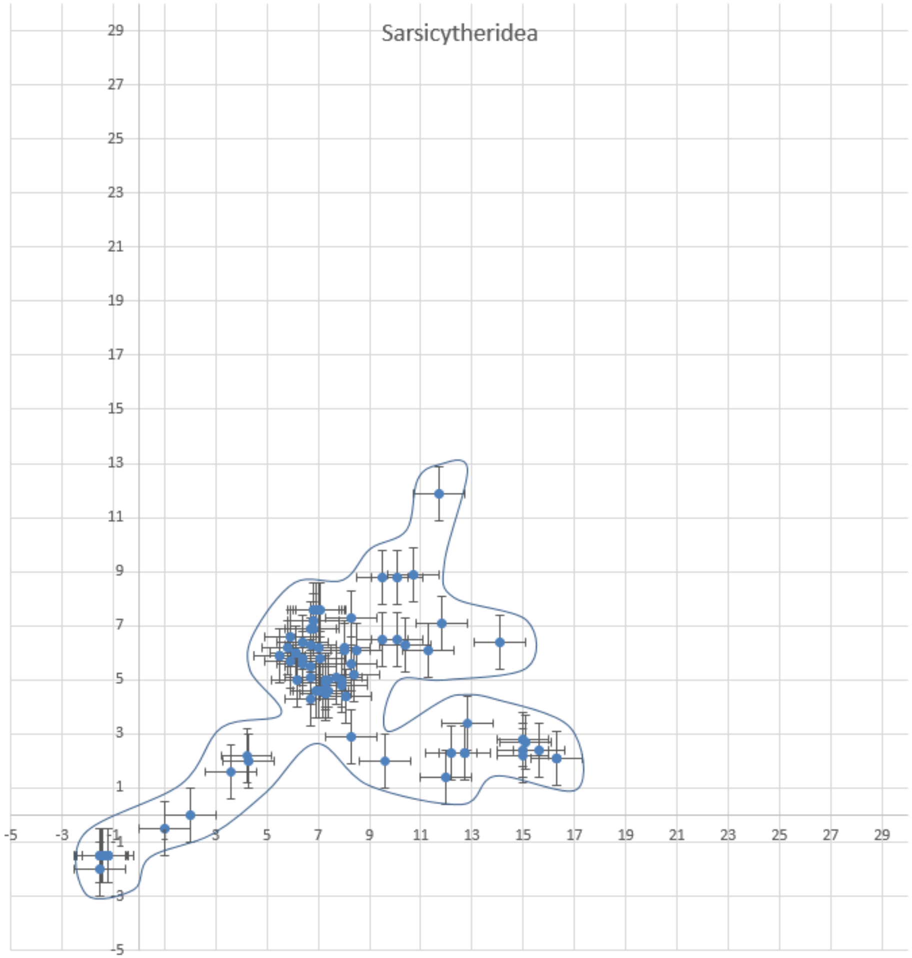
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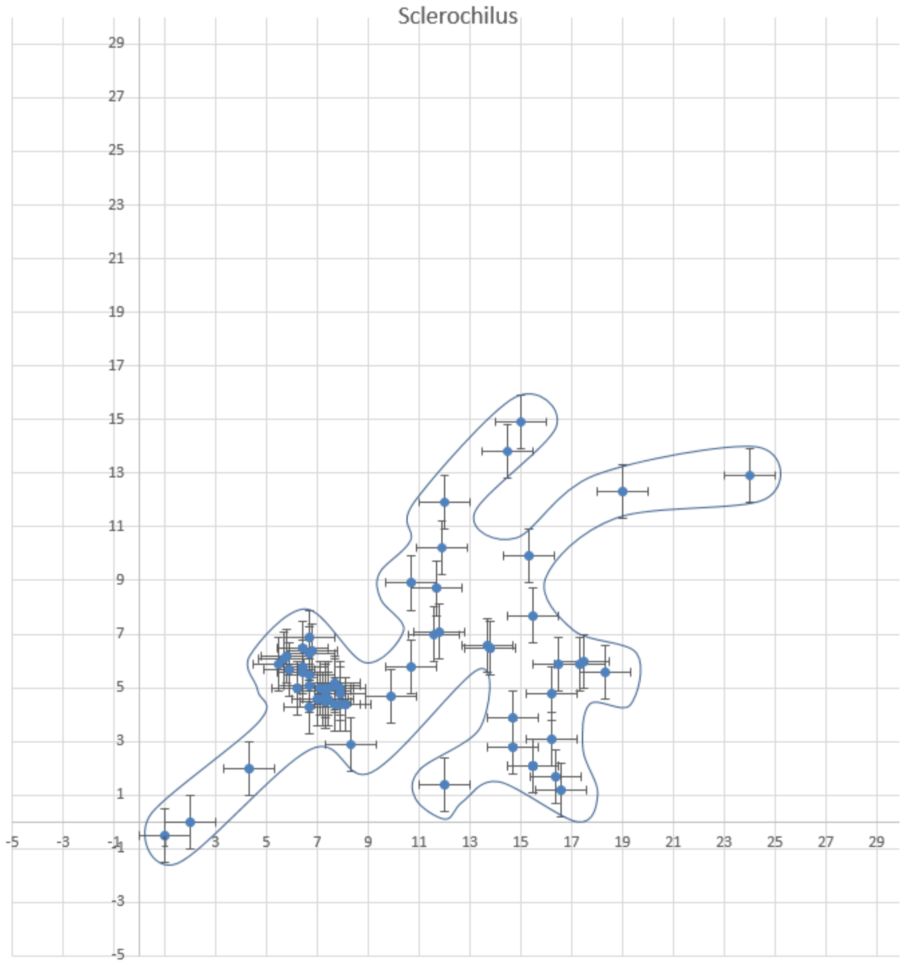
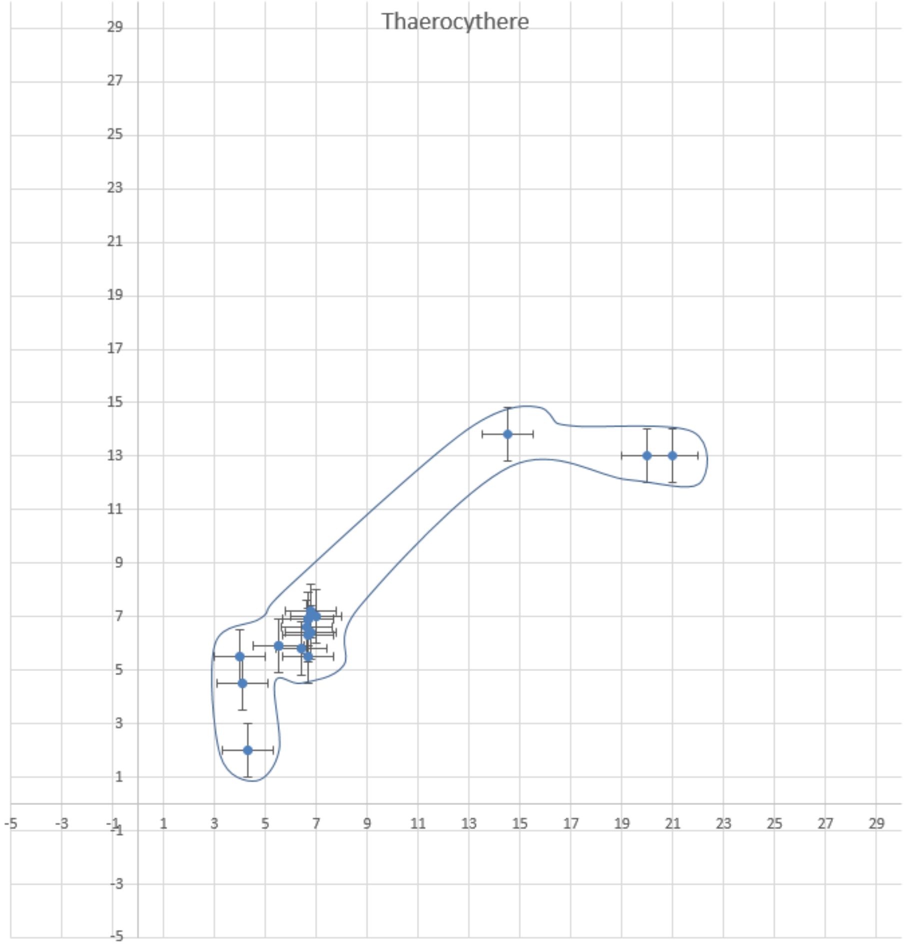
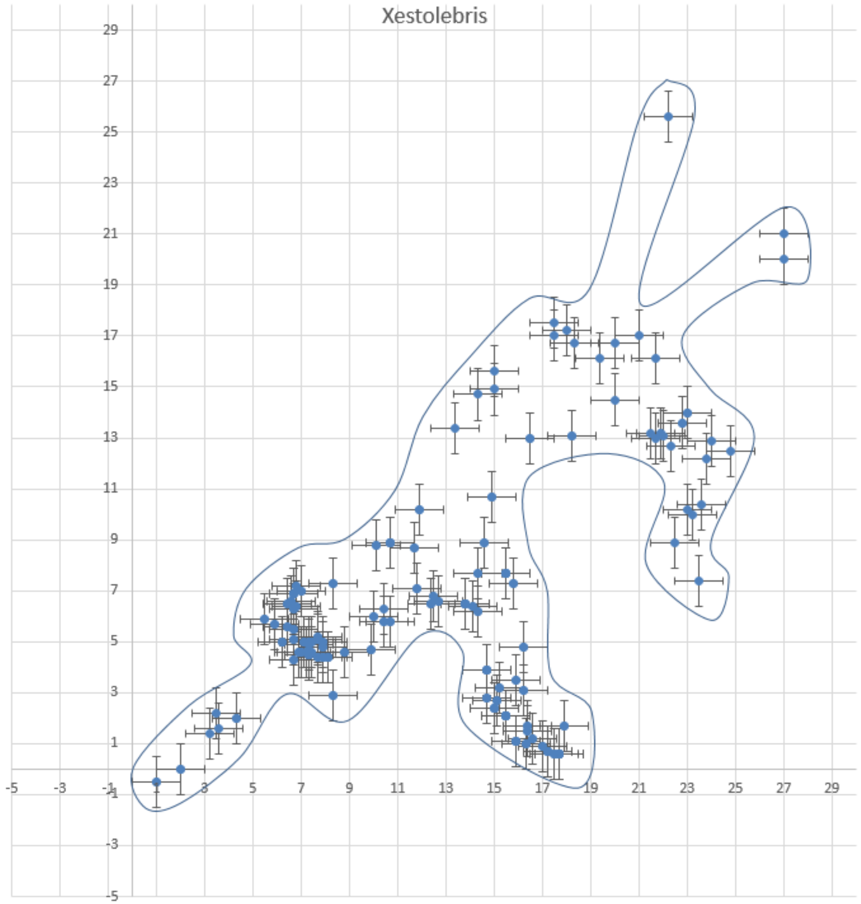

Sclerochilus


Thaerocythere


Xestolebris
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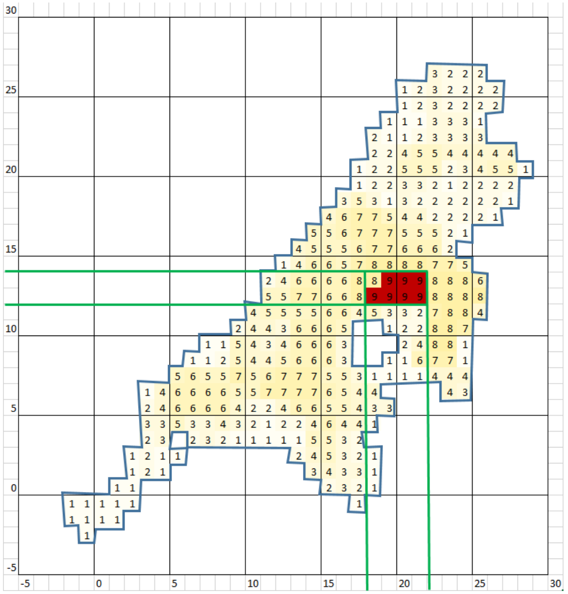
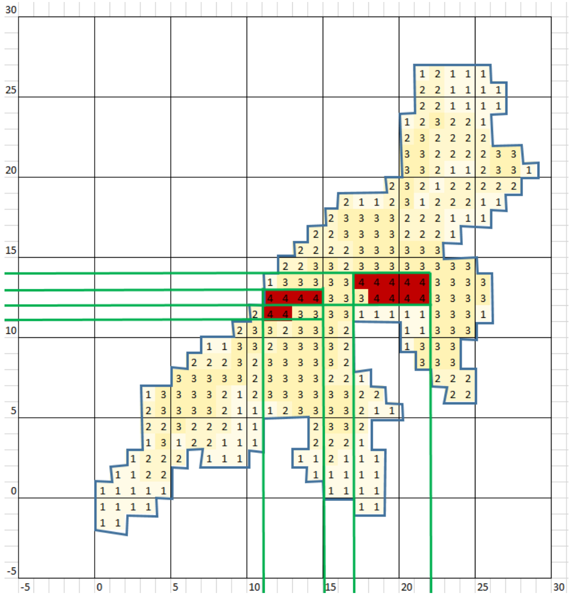
MUTUAL CLIMATIC RANGES FOR SAMPLES

All samples displaying 70-75% and >75% mutuality values, 65-70% values applied only where the mutuality values are no greater than this.

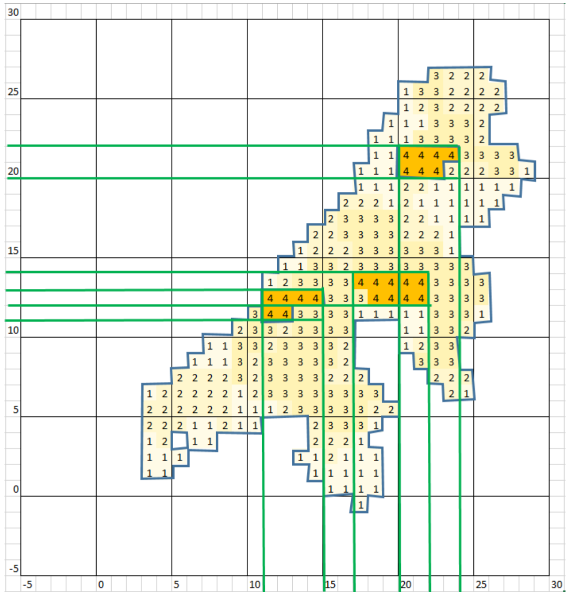
Mutuality Percentage	
🟥	>75%
🟥	70-75%
🟧	65-70%



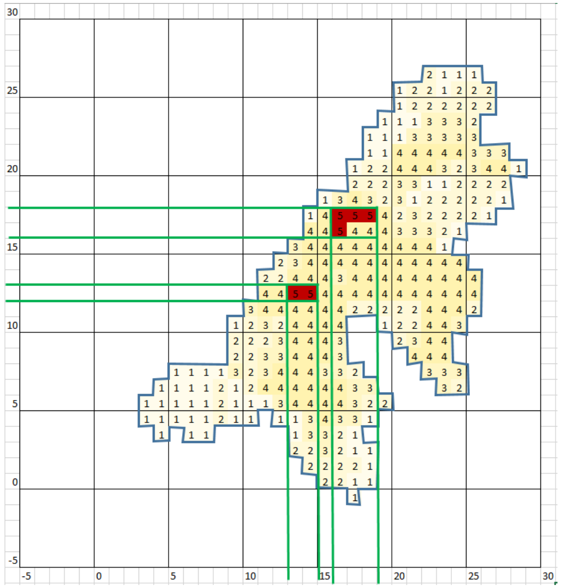
SK1



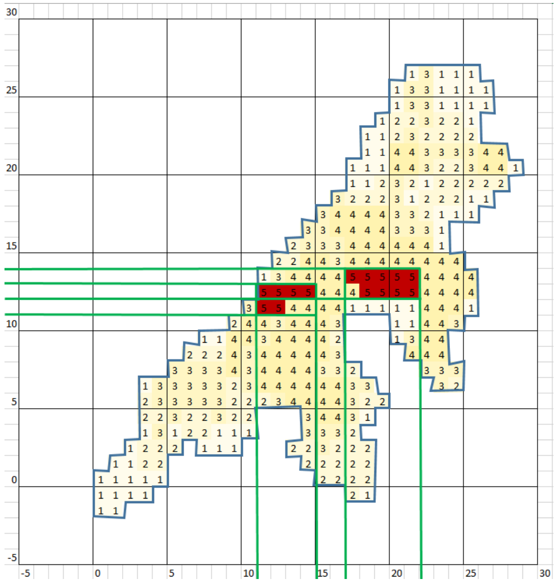
SK2



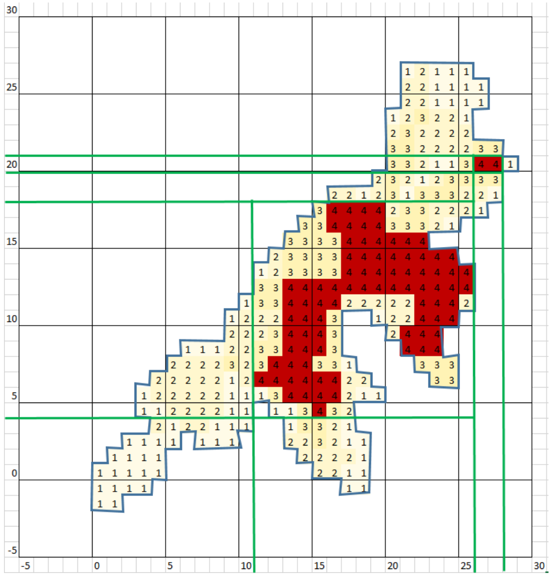
SK3



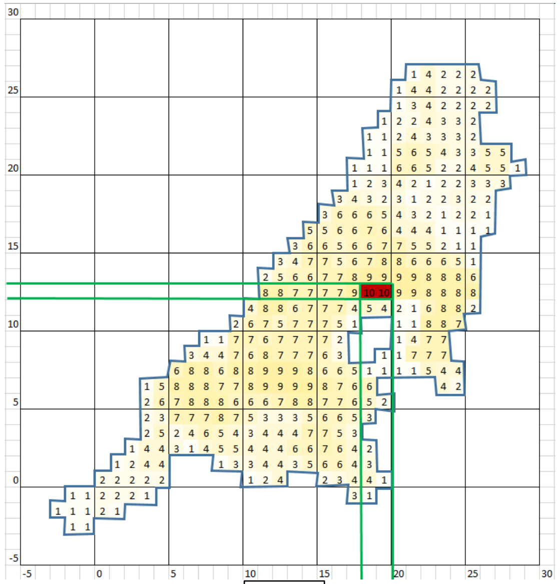
SK4



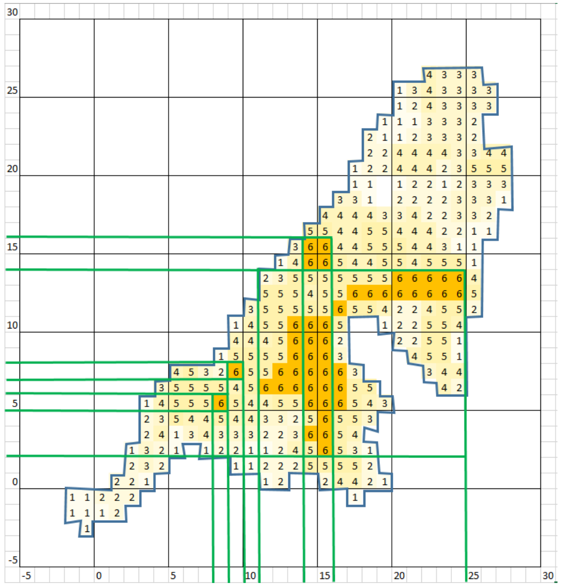
SK5



SK6



SK7



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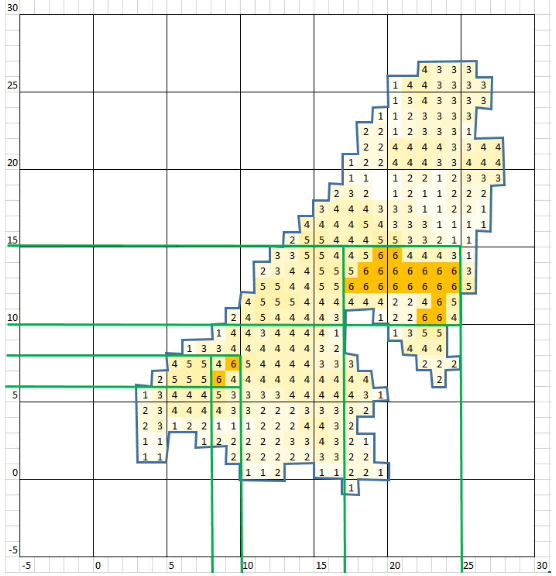
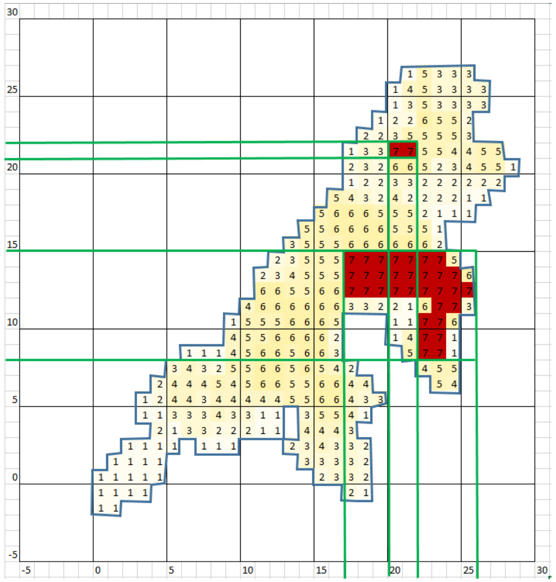


SK9



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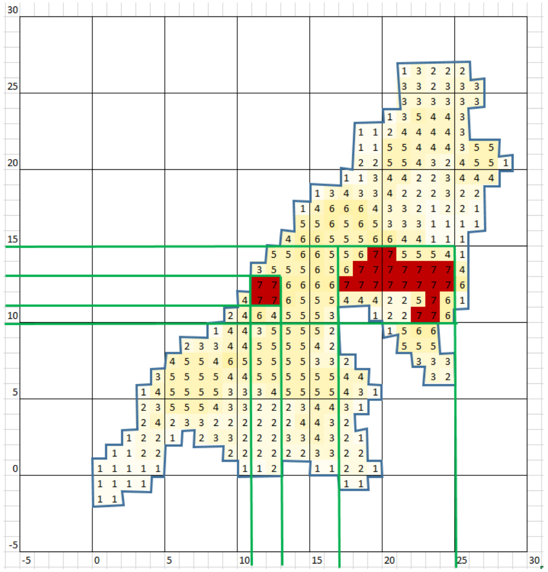

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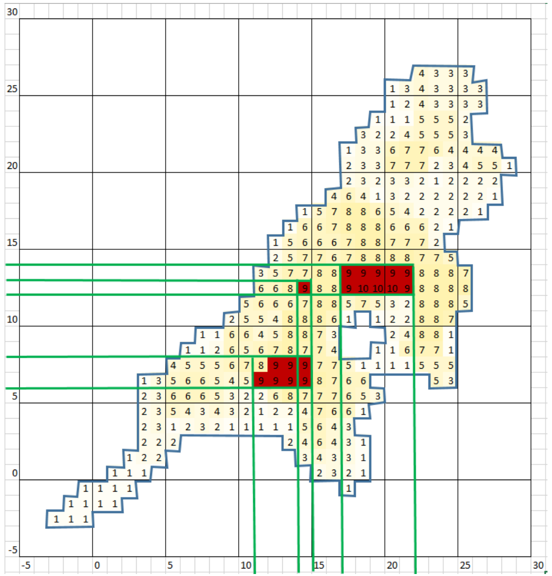

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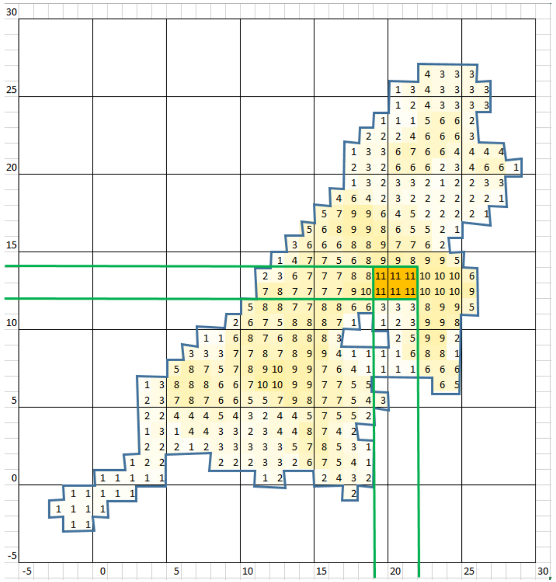
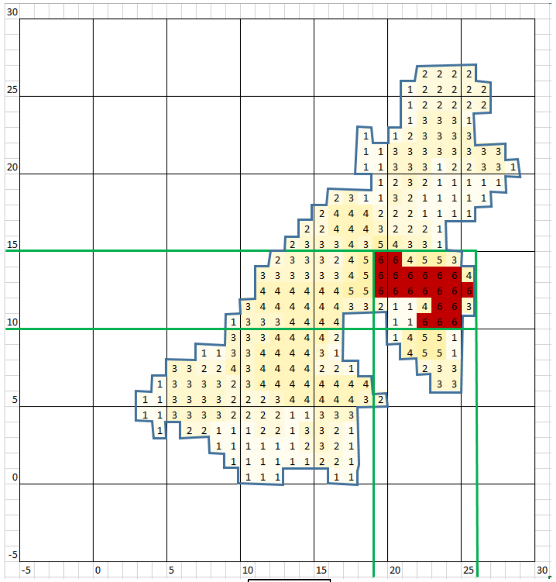
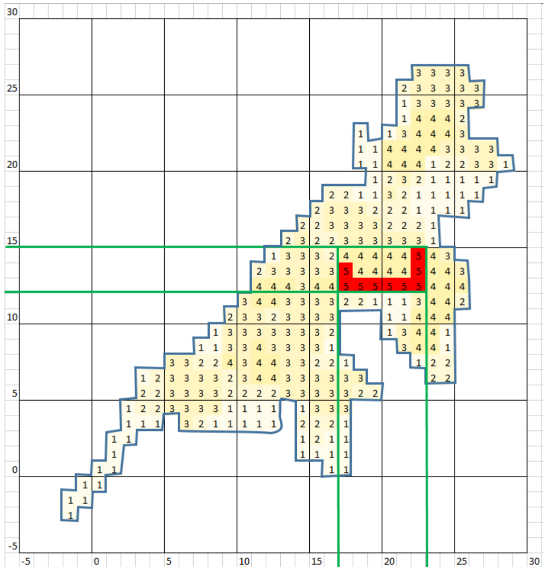


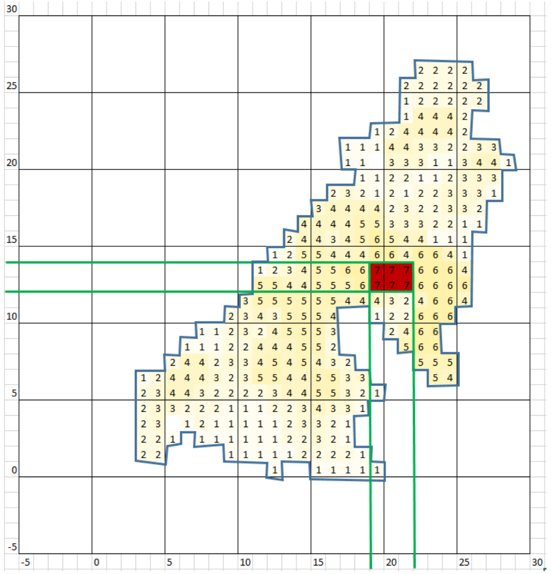
SK – Clay Layer



BP1



BP2



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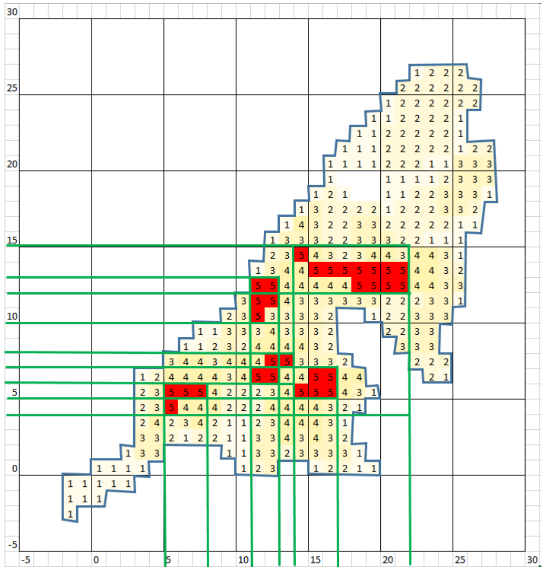
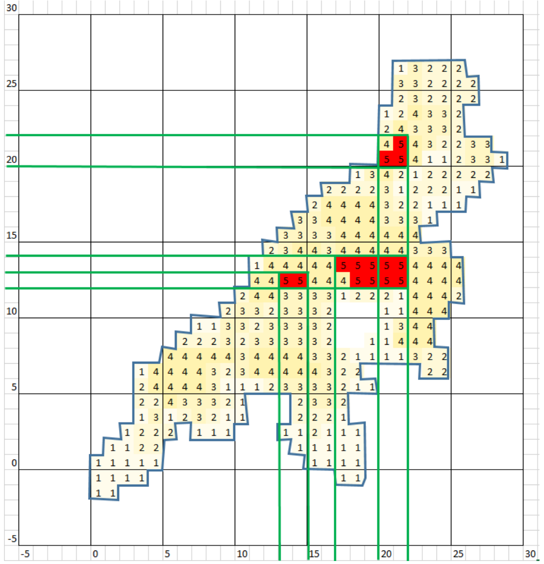
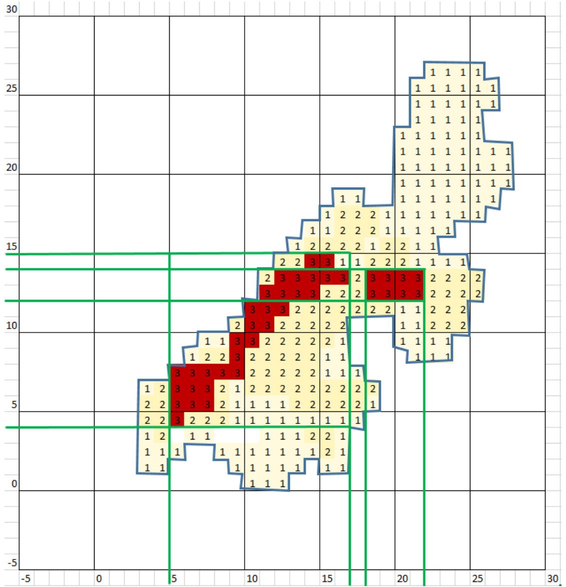


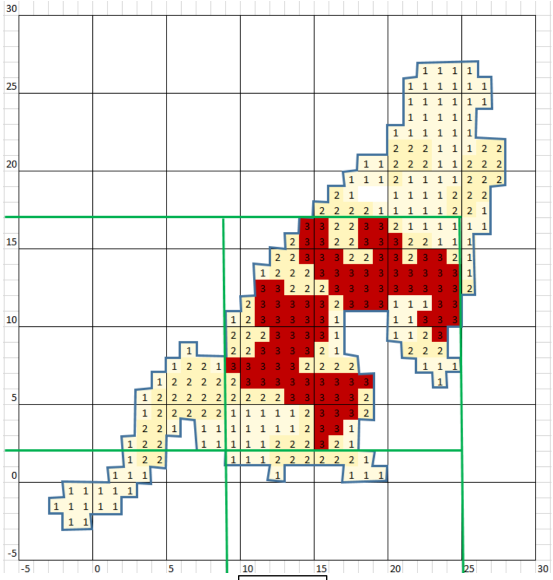
BP4



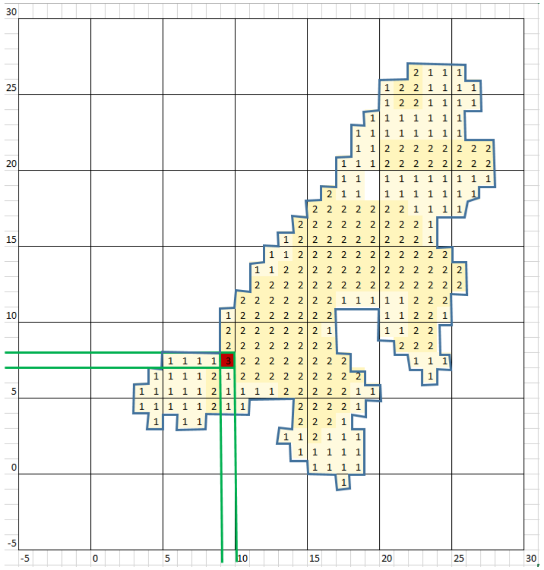
BP5



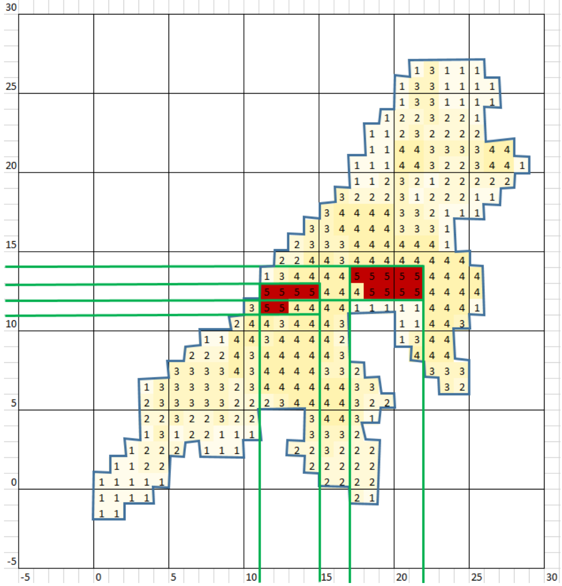
GF1



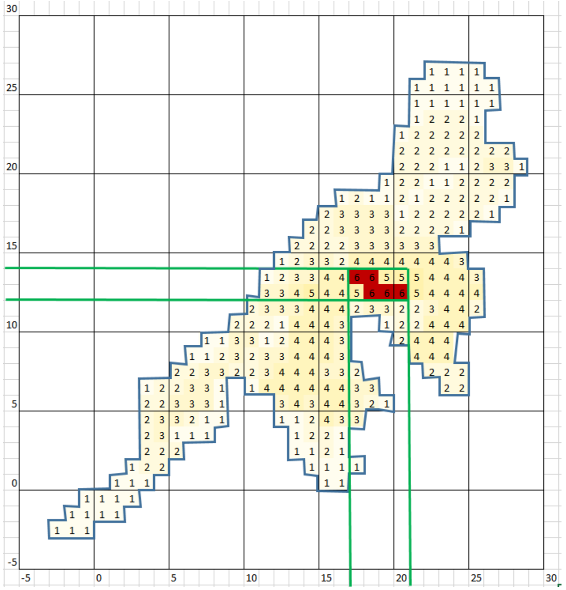
GF2



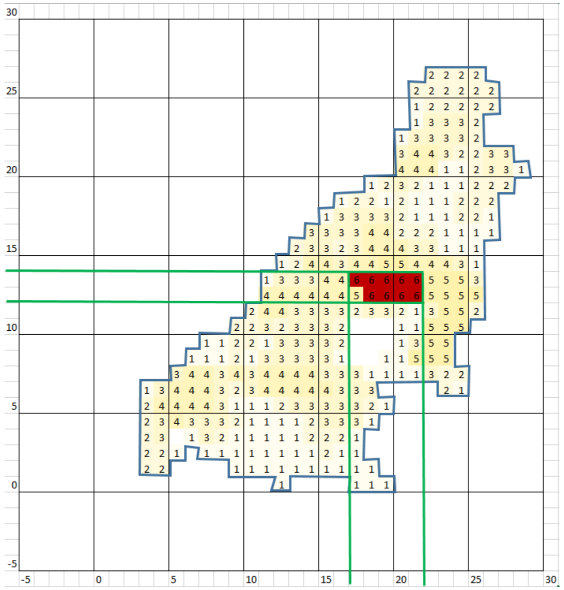
GF3



GF4



OC1



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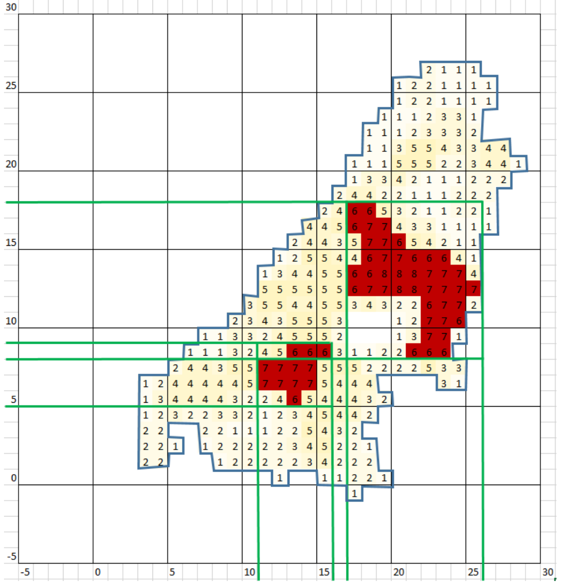

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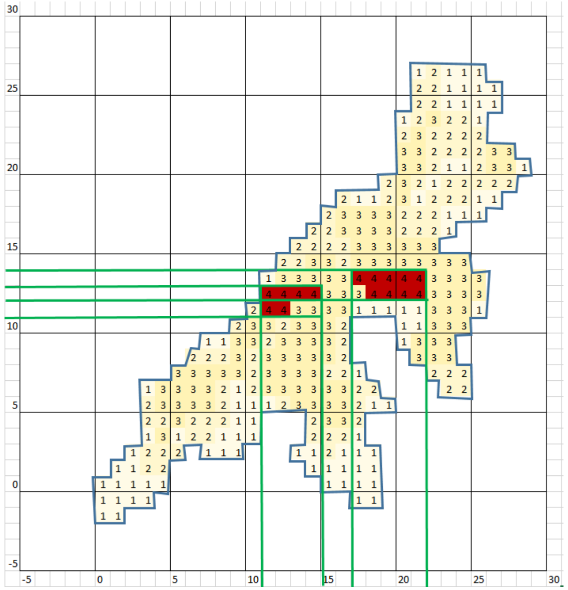
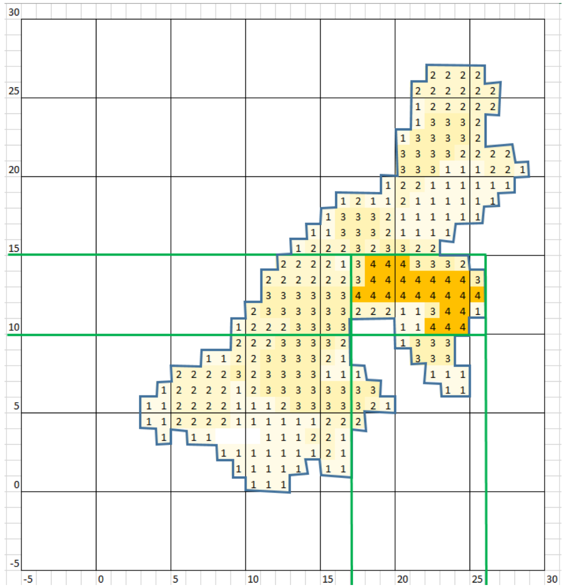
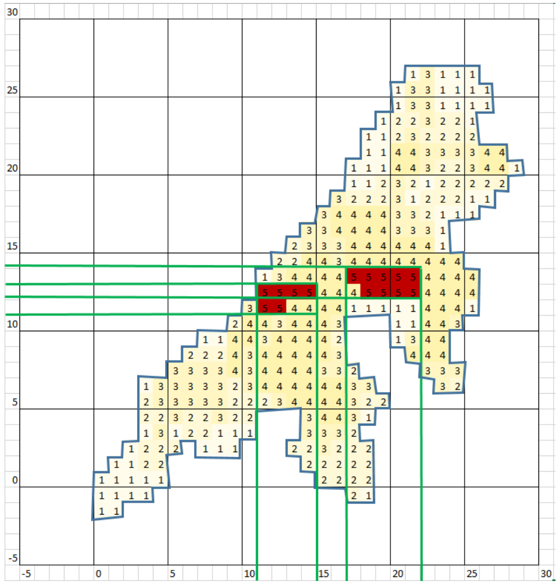


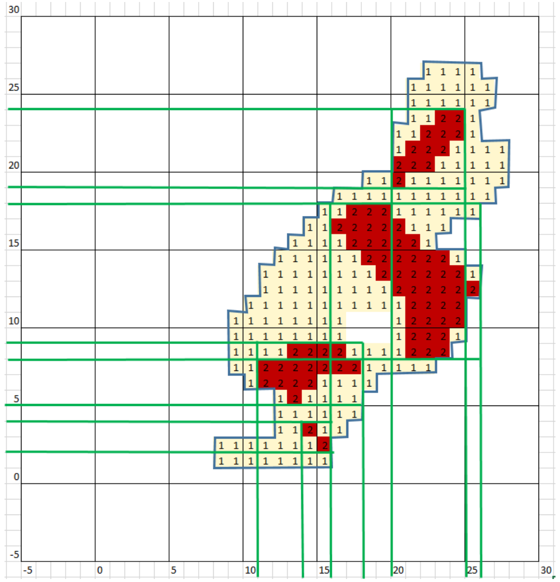
OC4



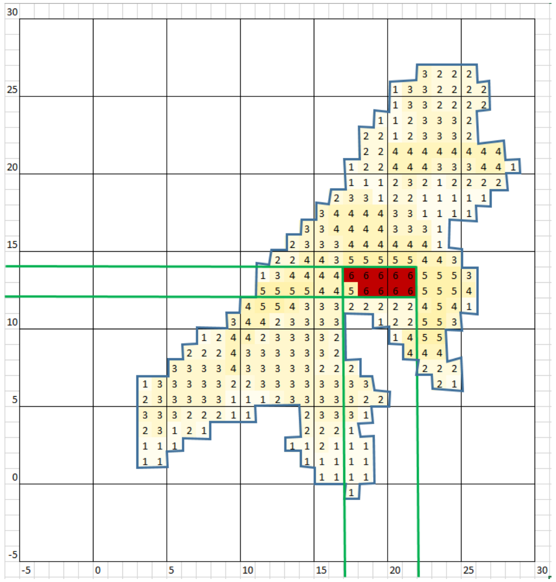
OC5



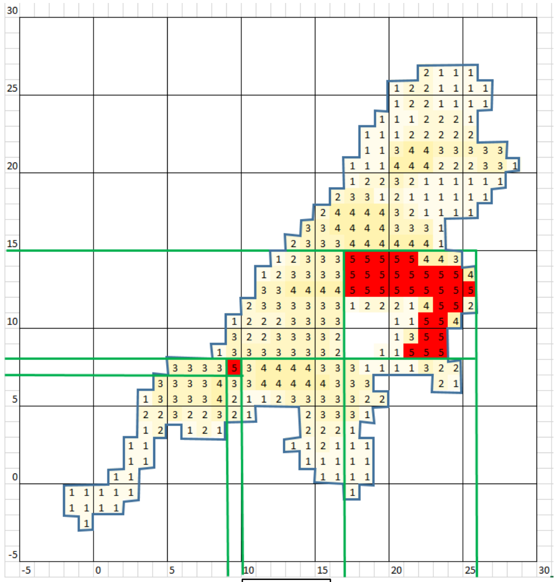
RF1



RF2



RF3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15
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0
-5
-5
0
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10
15
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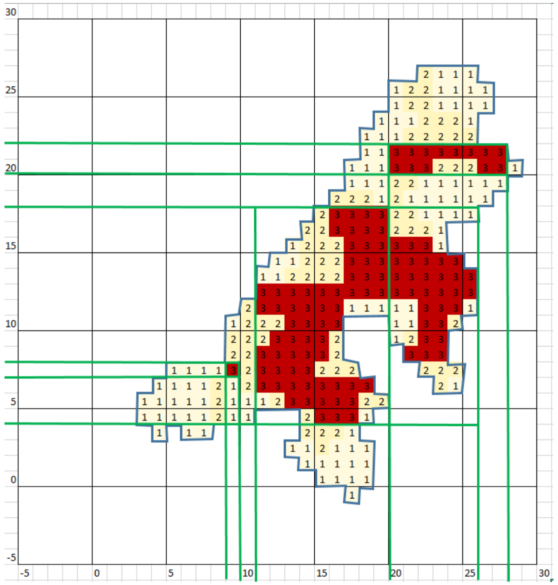
25
30

RF4


30
25
20
15
10
5
0
-5
-5
0
5
10
15
20
25
30

RF5

MUTUALITY PERCENTAGES FOR SAMPLES

SUTTON KNOLL

SK1	SK2	SK3	SK4	SK5	SK6	SK7	SK8	SK9	SK10	SK11	SK12	Clay layer
81.8%	80%	66.6%	83.3%	83.3%	80%	76.9%	66.6%	66.6%	77.7%	77.7%	83.3%	68.7%

BROOM PIT

BP1	BP2	BP3	BP4	BP5
85.7%	71.4%	77.7%	71.4%	71.4%

GEDGRAVE FARM

GF1	GF2	GF3	GF4
75%	100%	100%	83.3%

ORFORD 'THE CLIFF'

OC1	OC2	OC3	OC4	OC5
85.7%	75%	100%	80%	66.6%

RICHMOND FARM

RF1	RF2	RF3	RF4	RF5
83.3%	100%	85.7%	71.4%	75%

MEMBERS MUTUALITY

Ramsholt	Sudbourne
79.3%	83.2%

AVERAGE & UPPER AND LOWER BOUNDS OF MUTUALITY for all sites

Average	Upper Bound	Lower Bound
80.1%	99.6%	60.5%

AVERAGE MUTUALITY AT SITES

Sutton Knoll	Broom Pit	Gedgrave Farm	Orford ‘The Cliff’	Richmond Farm
76.9%	75.5%	89.5%	81.4%	83.1%

SIMPSON AND MARGALEF VALUES FOR SAMPLES

SUTTON KNOLL

	SK1	SK2	SK3	SK4	SK5	SK6	SK7	SK8	SK9	SK10	SK11	SK12
Simpson	8.285714286	3.786885	9.625	5	26.25	14	12.25	5.778523	3.38843	12.23684	7.232877	10.58491
Margalef	4.75158727	2.588124	2.911639078	2.524716322	4.061963104	2.404492	5.652882	4.280742	3.23139	3.785687	4.289995	5.387991

BROOM PIT

	BP1	BP2	BP3	BP4	BP5
Simpson	4.438596	5.516129	4.798387	4.130435	4.0625
Margalef	3.18929	3.056609	4.218996	3.004274	3.376204

GEDGRAVE FARM

	GF1	GF2	GF3	GF4
Simpson	2.472727	3.5	9.428571	5.04
Margalef	2.117737	1.846347	2.817007	3.348664

ORFORD ‘THE CLIFF’

	OC1	OC2	OC3	OC4	OC5
Simpson	7.983871	5.05814	2.697368	5.526316	15.6
Margalef	3.94046	3.528169	3.23139	3.284587	3.11897

RICHMOND FARM

	RF1	RF2	RF3	RF4	RF5
Simpson	4.285714	2	0	10.90909	3.714286
Margalef	3.106675	0.721348	3.640957	3.606738	2.339227

APPENDIX C

OSTRACOD GENERA PHOTOS

Some materials have been removed due to 3rd party copyright. The unabridged version can be viewed in Lancester Library - Coventry University.

Aurila

0.1 mm

Bairdoppilata

Bythocythere

Some materials have been removed due to 3rd party copyright. The unabridged version can be viewed in Lancester Library - Coventry University.

Callistocythere

Carinocythereis

Cletocythereis

Cytherella

Cytheretta

Cytheridea

Cytheromorpha

Cytheropteron

Cytherura

Echinocythereis

Eucythere

Hermanites

Hiltermannicythere

Hirschmannia

Krithe

Kuiperiana

Microcytherura

Leptocythere

Muellerina

Loxoconcha

Neocythereideis

Neonesidea

Normanicythere

Palmoconcha

Pontocythere

Robertsonites

Fragmented Sarsicytheridea

Sclerochilus

Thaerocythere

Xestoleberis

MOST ABUNDANT OSTRACOD SPECIES PHOTOS

Some materials have been removed due to 3rd party copyright. The unabridged version can be viewed in Lancester Library - Coventry University.

Aurila anterocostata

Aurila sherborni

Aurila strongyla

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Some materials have been removed due to 3rd party copyright. The unabridged version can be viewed in Lancester Library - Coventry University.

Aurila trigonula

Cytherideа hoerstgenensis

Hermanites paijenborchiana sensu

Loxoconcha pararhomboidea

Muellerina lacunosa

Muellerina latimarginata

Muellerina metabyssicola

Muellerina orygyma

Muellerina pliocenia

Pontocythere botellina

Thaerocythere biformis