A Holocene sea surface temperature record in mollusc shells from the South African coast

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ABSTRACT

This thesis describes the construction of a Holocene history of sea surface temperatures in coastal regions of the southern Benguela and eastern Agulhas Bank of South Africa, using marine mollusc shells preserved in archaeological middens. Two independent palaeothermometers were employed: the traditional oxygen isotope technique and a new, alternative technique based on temperature-dependent changes in structure and mineralogy of the shell of a South African limpet species, *Patella granularis*. The relationship between the isotopic and structural aspects of shell composition, and habitat temperature was confirmed through examination of living populations.

The oxygen isotope record from the southern Benguela showed three discrete episodes of significant enrichment during the past 12 500 years; at 10 600 yr BP, 2 700 yr BP and 420 yr BP. The timing and duration of these events corresponded with periods of near-global cooling and expansion of glaciers in the high latitudes of both hemispheres. The alternative palaeothermometer was employed to distinguish between the effects of glacial expansion and those of temperature on the oxygen isotope signal. Changes in shell structure and mineralogy which indicated sea surface temperatures between 1°C and 2°C lower than today's average, occurred during periods of isotope enrichment. During each cool episode, approximately one third of the oxygen isotope enrichment was attributed to a drop in sea surface temperature.

The oxygen isotope record in shells from the eastern Agulhas Bank exhibited less millenial-scale variability although this was more likely a function of the low temporal resolution of the archaeological sequence than a true indication of the nature of long-term sea surface temperature changes in the region. The record was related to sea surface temperature by correcting the oxygen isotope values for estimated changes in the isotopic composition of seawater through the Holocene. During the early part of the sequence, sea surface temperatures were cooler than they are today but increased during the mid-Holocene, exceeding the present-day average by more than 2°C around 6 000 years ago. This episode coincided with a climatic (thermal) optimum in some regions of the mid-latitude southern hemisphere.

The variability evident in the Holocene records in both regions was attributed to the same processes which force interannual sea surface temperature anomalies today, namely surface winds and the Agulhas Current. The data challenged current thinking about aspects of the coastal oceanography of South Africa under conditions of global warming. They also failed to confirm a recent model proposed to explain patterns of Late Quaternary climates in southern Africa. The importance of archaeological deposits as unique and valuable sources of information about past climates was emphasised in this study. Future investigations over a wider geographical area are needed to establish the apparent patterns with a greater degree of confidence.

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TABLE OF CONTENTS

page:

LIST AND DESCRIPTION OF FIGURES

LIST OF TABLES

LIST OF APPENDICES

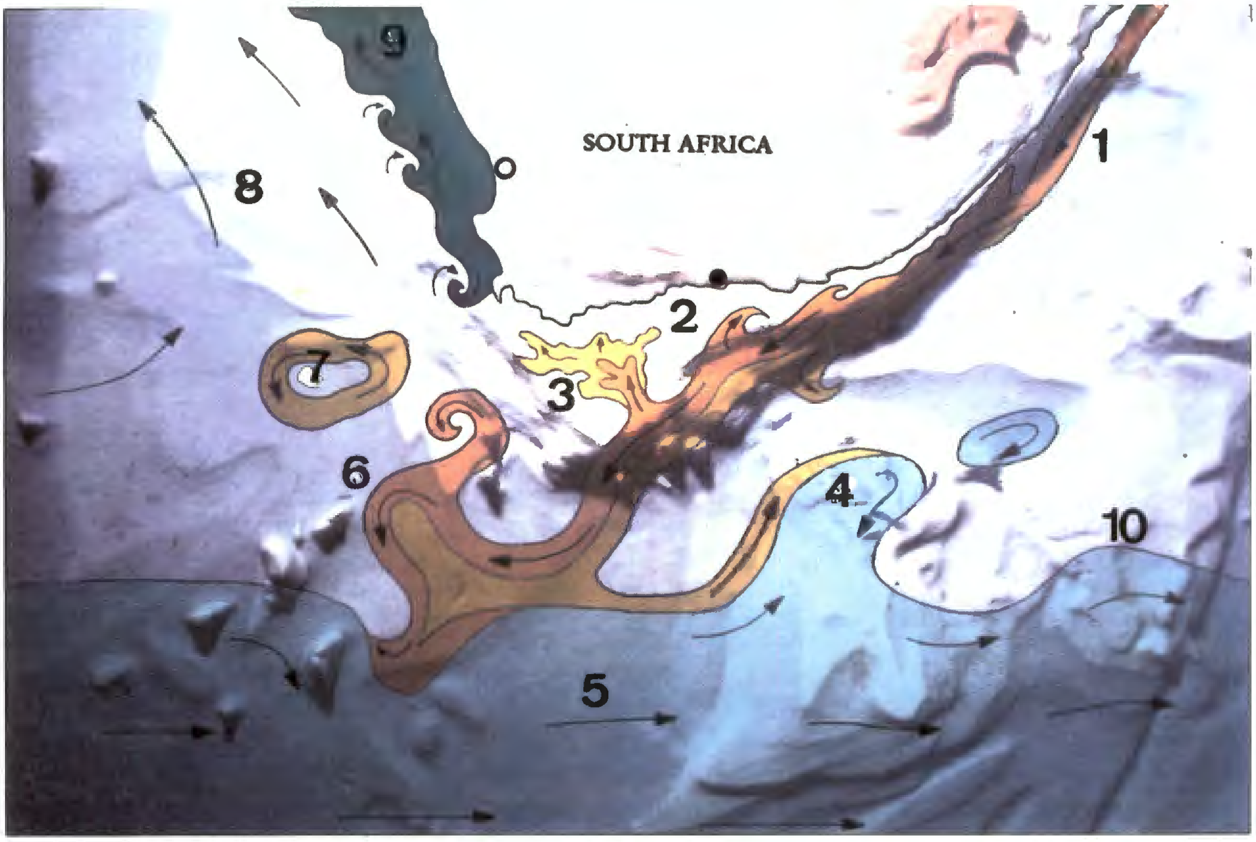


Fig. 1.1. Features of the large-scale oceanic circulation around South Africa shown in relation to the South African coastline and the principal archaeological deposits used in this thesis: Elands Bay Cave (O) and Nelson Bay Cave (●). 1. Agulhas Current; 2. Agulhas Bank; 3. surface plumes from the northern boundary of the current advected across the bank; 4. path of the Agulhas Return Current steered by the Agulhas Plateau; 5. Antarctic Circumpolar Current or west wind drift; 6. the Agulhas retroflection; 7. Agulhas ring shed at the retroflection; 8. south-east Atlantic drift; 9. Benguela Upwelling System; 10. Subtropical Convergence. (reproduced with the kind permission of Johann Lutjeharms).

CHAPTER 1

INTRODUCTION

Holocene climates of southern Africa have, until recently, been of interest mainly to archaeologists studying the relationship between prehistoric people and the changing landscape. As a result, there is compelling evidence that during this period, relatively small-amplitude climatic and environmental changes imposed (as they continue to impose in this region) rather severe constraints on the density and distribution of human populations (Parkington 1986, Deacon and Lancaster 1988). In recent years it has become equally apparent that, with the increased burning of fossil fuels and other forms of atmospheric pollution, human activity may be an important factor influencing the course of future climatic changes (Bell and Walker 1992). Empirical evidence shows that atmospheric temperature, concentrations of carbon dioxide and other greenhouse gases, and global sea level have risen rapidly over the past century (Houghton *et al.* 1990), and suggests that global climate is changing, probably due to unnatural causes. In response to this realisation and to the fact that we have had no direct experience with a climate change of the magnitude expected over the next 100 years, there has been an expanded interest amongst the global scientific community in documenting, understanding and modelling climates of the past (Eddy 1992), an interest which extends beyond that of attempting to understand the history of human social and economic development.

Palaeoclimatology has contributed in large measure to our understanding of the workings of the global climate system especially with regard to the interdependence of the ice, oceanic and atmospheric components (Eddy 1992). Furthermore, there are a number of direct ways in which reconstruction of past climates may assist with the prediction, assessment and rational management of the consequences of future climatic change. First, quantitative palaeoclimate data provide the only real measure against which the results of modelled simulations of current and future climate can be tested. General circulation models are being developed within the constraints of modern and thus short-term observations. To test the degree to which these models are capable of simulating the reality of future climate change, they must be run with a broad range of boundary conditions derived from quantitative reconstructions of actual, past states of the earth (Shackleton *et al.* 1989). Second, the reconstruction of past climates and environments provides some indication of the potential response of the atmospheric, oceanic and terrestrial systems to raised temperature and carbon dioxide levels. The predictions of modelled simulations suggest that responses will be geographically variable (Crowley and North 1991), thus emphasising the importance of studies on a regional and local scale. Furthermore, as knowledge of the history of climate increases, the frequency, magnitude and duration of natural oscillations become apparent. Thus, by providing a long term perspective of climatic changes on all-time scales, the palaeoclimate record does enable us, to some extent, to distinguish natural variability from change caused by recent human activity.

The intention of this thesis is to provide a record of sea surface temperature variability in the coastal oceans around South Africa during the Holocene period. The coastal and oceanic setting of the study area is illustrated in Fig. 1.1. Palaeotemperature information was contained in the isotopic and structural composition of marine mollusc shells, collected from the rocky intertidal zone by prehistoric hunter-gatherer communities who discarded the remains in caves and open middens along the western and southern Cape coasts of South Africa. In the following discussion, I explain why this particular approach to palaeoclimatic reconstruction was taken.

Why the Holocene ?

Evidence accumulated to date shows that climate of the present Interglacial period, which includes the last 10 000 years, has been relatively stable and average global temperature fluctuations have not exceeded 2°C (Folland *et al.* 1990, Dansgaard *et al.* 1993) (Fig. 1.2A). In contrast, high-resolution ice-core records of the last glaciation and deglaciation indicate that irregular, abrupt temperature switches of up to 7°C were accomplished within a few decades (Dansgaard *et al.* 1989, Johnsen *et al.* 1992, Alley *et al.* 1993). Temperature and CO_2 fluctuations of large amplitude also occurred during the previous Interglacial (GRIP members 1993) suggesting that the period once considered an appropriate analogue for future global warming was indeed one of unstable and rapidly changing climate (Fig. 1.2B).

Holocene climate has also been characterised by oscillations between warmer and cooler periods (Fig. 1.3). However, the most extreme warm event, the Holocene Climatic Optimum (hypsithermal) and the most extreme cool event, the Little Ice Age of the late Holocene, involved mean global temperature shifts of less than 2°C (Grove 1988, Folland *et al.* 1990), an exceptionally stable period compared with the

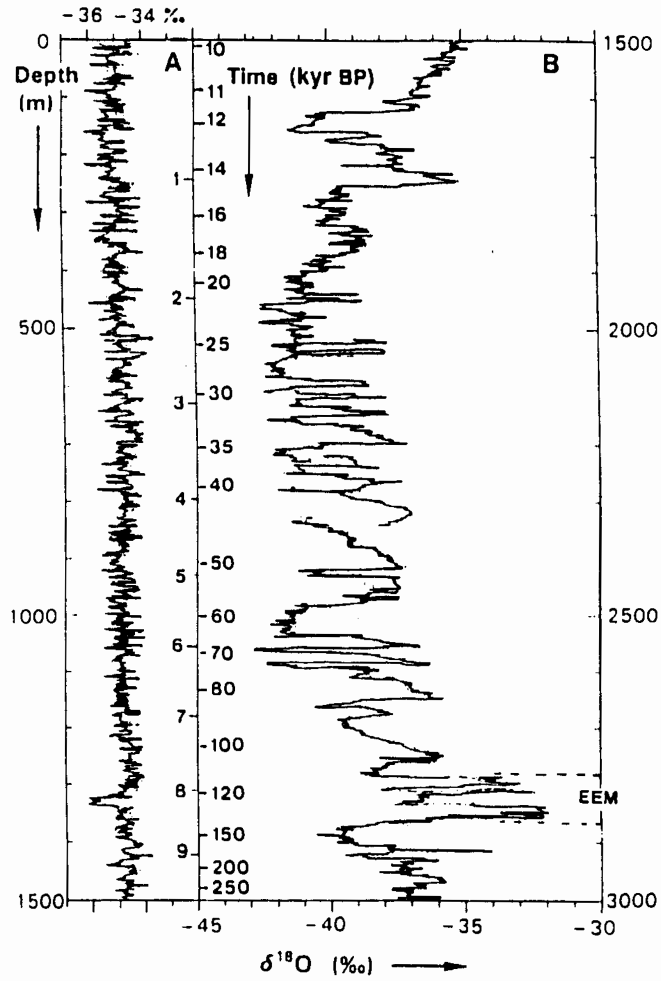


Fig. 1.2. The oxygen isotope record in the GRIP Summit ice-core, central Greenland, 0 to 10 000 years ago (A) and 10 000 and 250 000 years ago (B). Oxygen isotope changes of 1‰ indicate air temperature changes of 1.5°C. Holocene temperature fluctuations at this site did not exceed ±1.5°C. In contrast, climate for 230 000 years preceeding the Holocene, including that of the Last Interglacial (Eem), was characterised by abrupt temperature shifts of large amplitude (adapted from Dansgaard *et al.* 1993).

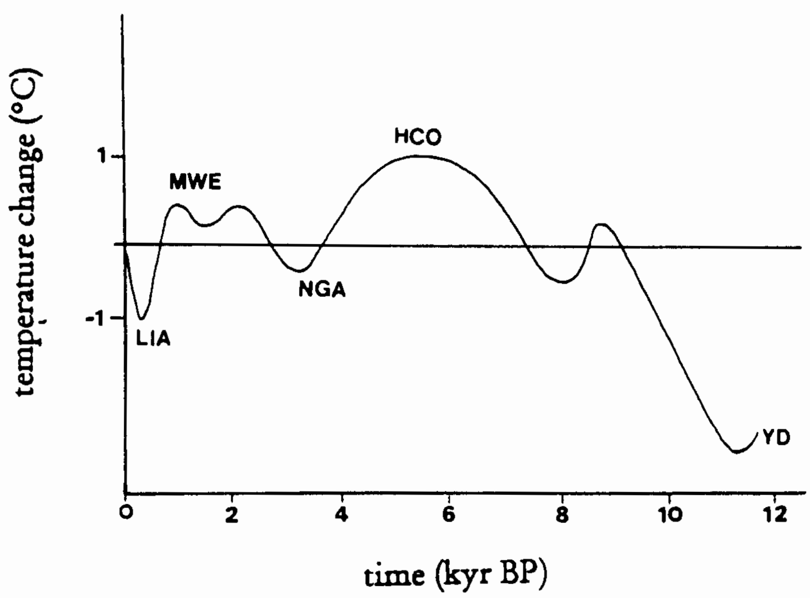


Fig. 1.3. Global average temperature variations since 12 000 yr BP. The Holocene appears to be a period of unusual climatic stability; the biggest climatic shifts involved temperature departures of not more than 2°C. YD = Younger Dryas; HCO = Holocene Climatic Optimum; NGA = Neoglacial Advance; MWE = Medieval Warm Epoch; LIA = Little Ice Age (adapted from Folland *et al.* 1990).

characteristic pattern of the past 230 000 years (Dansgaard *et al.* 1993). Thus, the nature and direction of current changes can only be recognised and measured against a record of the natural variability in the present system. Furthermore, the palaeorecord shows that seemingly innocuous temperature fluctuations during the Holocene were often accompanied by severe regional changes in precipitation, the incidence and severity of floods and droughts and the distribution and abundance of plant and animal species (Bell and Walker 1992). Archaeological evidence and historical accounts indicate that the impact of such "small-scale" climatic change on human populations was often quite considerable (Lamb 1982).

Certain periods during the Holocene e.g. the Climatic Optimum and Medieval Warm Epoch may have value as analogues of human-induced warming, particularly in providing information about regional and local consequences of global changes. It has been argued that past warm events cannot be used as analogues of future climate because the mechanisms involved i.e. changes in solar radiation, were then quite different and resulted in changes in the seasonal distribution of warmth rather than an absolute increase (Kutzbach 1986). However, considering that the geographical distribution of future positive anomalies is not well established, this argument is not strictly valid (Shackleton *et al.* 1989). The Holocene is also considered to be an attractive time period for palaeoclimatic studies because it falls well within the time range in which radiocarbon dating is reliable.

Why sea surface temperatures ?

A major gap in our knowledge of Holocene climate lies within the ocean, specifically in the direction and magnitude of changes at the sea surface. Tracking long-term changes in sea surface temperatures and understanding the processes which drive them are particularly important to the study of global change as much of the residual heat which drives atmospheric anomalies is stored in the upper ocean (consider El Niño for example). Sea surface temperature variability in the coastal oceans around South Africa is linked to intra- and interannual patterns of climate and rainfall over the adjacent sub-continent. The association is particularly direct on the west and south coasts of South Africa where sea surface temperatures are strongly influenced by wind speed and direction. Seasonal and interannual changes in the strength and position of the dominant atmospheric circulation systems and anomalous conditions associated with decadal-scale cycles of wet and dry periods, can be identified in the record of sea surface temperatures at the coast. Furthermore, positive feedback between the oceanic and atmospheric systems has been identified in recent studies (Walker and Shillington 1990) which show that sea surface temperature anomalies in both the south-east Atlantic and Indian Oceans impact rainfall patterns on land, most likely by influencing the potential of certain synoptic weather systems.

South of Africa, interocean exchange of thermocline waters occurs via the intrusion of Agulhas Current water into the south-east Atlantic, a process considered to be climatically important on a global scale. The passage of warm surface water into the cool Benguela system is a regular, if not continuous, occurrence today and is considered an important link in the surface route of the global thermohaline circulation system which transports and redistributes heat between the equator and the poles. This "conveyor belt" may have played a major role in abrupt and short-lived climatic events, such as the Younger Dryas, which cannot be explained by Milankovitch forcing (Broecker *et al.* 1985, Broecker and Denton 1989).

Why archaeological deposits ?

There are two main reasons why we know so little about Holocene sea temperatures which have to do with the nature of the material traditionally used to reconstruct ocean climate, i.e. deep-sea sediments. In many areas, low sedimentation rate prevents reliable time discrimination and methods used to extract sediment cores often do so at the expense of the top 20-30 cm which includes most of the Holocene sediment (Crowley and North 1991). In South Africa, these problems are compounded by the aerobic nature and therefore bioturbation of sediments beneath the southern Benguela (Rogers and Bremner 1991), and by the scouring action of the Agulhas Current (Dingle *et al.* 1987).

Archaeological deposits present an alternative source of material for the reconstruction of a detailed recent history of coastal conditions. In South Africa, archaeological deposits have been used as the primary source of information about terrestrial environments of the Late Quaternary (Deacon and Lancaster 1988) in the absence of traditional indicators such as lake sediments and glacial moraines. The nature and variety of materials preserved in archaeological accumulations lend themselves particularly to the reconstruction of many aspects of the coastal environment. Studies of Holocene sea level fluctuations, rainfall patterns, terrestrial temperatures and changes in the distribution of animal and plant species have been

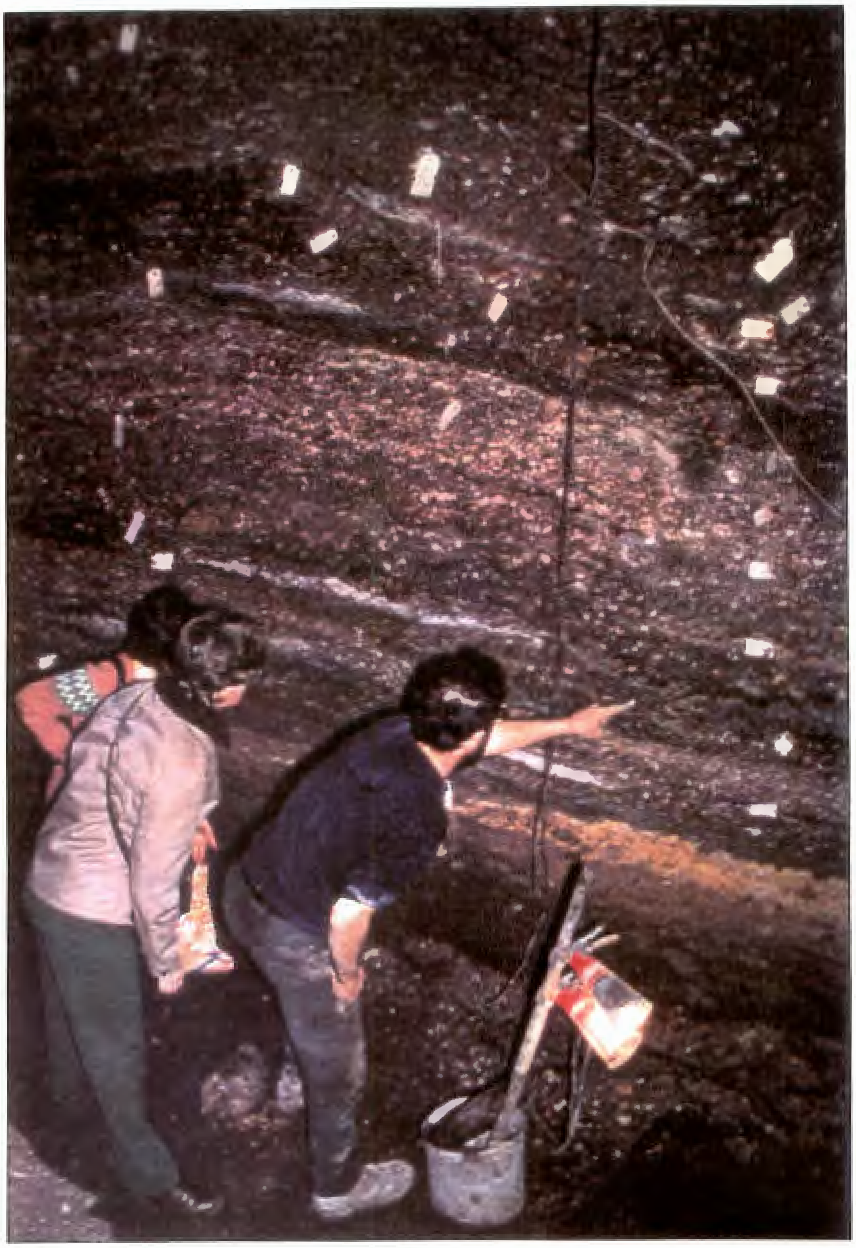


Fig. 1.4. An excavated section through the archaeological deposit in Nelson Bay Cave. Dr Richard Klein points to layers, approximately 10 000 years old, in which marine shells first became abundant. The depth of deposit from the surface to this layer is over 2.5 m (from Klein 1972).

conducted in South Africa using archaeological material. These studies have contributed in large measure to our present understanding of local climate and ecosystem changes during this period. Archaeological remains are also particularly useful for studies of this kind because in most cases, large quantities of material were concentrated in one place over a short space of time resulting in sequences of high chronological resolution. The availability of carbonaceous material such as charcoal for radiocarbon dating further increases the attractiveness of archaeological deposits for palaeoclimatic studies.

At the same time, it should be remembered that these deposits were the result of human activity and therefore pose a number of unique problems for the reconstruction of environmental history. Firstly, the materials present in the deposit are not necessarily representative of everything that was present in the surrounding environment. Humans selected the materials and species they preferred from what was available and there is some evidence that local gathering practises impacted on the natural environment (Parkington 1976). Therefore, environmental determinations based on the relative abundance of species or the size-frequencies of populations remain problematic because any visible changes may be the result of human action rather than natural processes. Secondly, human occupation of specific sites was rarely continuous; it would appear that prehistoric hunter-gatherer groups moved from place to place depending largely on the availability of food and water. Temporal gaps, where no deposition has occurred, in the archaeological sequence of a given site are normal and thus make it impossible to reconstruct a continuous record of the environment. A third problem may arise from the nature of archaeological investigations. The questions posed by archaeologists are frequently quite different from those posed by palaeoclimatologists, the former often do not require large quantities of material to be sampled at high-resolution intervals and in many instances, material invaluable to the climatologists have been discarded. To date, the full potential of South African archaeological sites for palaeoclimatic studies has rarely been realised.

Why molluscs ?

The oxygen isotope ratio of the $CaCO_3$ shells of many marine mollusc species have been shown to correspond to the temperature of the seawater in which they live (Wefer and Berger 1991). They are therefore a potentially useful tool for the reconstruction of regional marine palaeotemperatures. Mollusc shells are abundant in all Holocene archaeological deposits along the coast of South Africa. The material is usually well-preserved, especially in cave sites and the longer sequences contain shell in all layers dating back at least 12 000 years. Most of these these shell middens contain massive amounts of material which is fairly easily accessible and because all species have representative populations on the present coastline, they are amenable to modern observation and monitoring.

In this thesis, two independent techniques were employed to reconstruct palaeotemperatures. The first was the oxygen isotope technique which is well-established and widely used in palaeoceanography. In this study, the isotopic composition of both whole-shell powders and serially extracted sub-samples were measured. A second thermometer, based on the temperature-dependence of shell structure and mineralogy, was developed on living mollusc populations grown under conditions of known temperature and employed as a means to distinguish between temperature and ice-volume effects in the oxygen isotope record.

Palaeotemperature records were constructed from two major archaeological sites located adjacent to the western and southern Cape coasts of South Africa (Fig. 1.1). These particular sites were chosen for their extensive Holocene deposits which had been previously excavated (Parkington 1977, Klein 1972, Inskeep 1985) (Fig. 1.4). Shells in the Eland's Bay Cave deposit were used to construct sea surface temperatures in the southern Benguela upwelling regime for the past 12 500 years, excluding the period 7900 to 4300 yr B.P. when the cave was not occupied by humans (Parkington 1977, 1986). Samples from open middens and other cave sites in the vicinity of Elands Bay Cave were included for data after 4000 yr B.P. A Holocene record of surface temperatures on the eastern Agulhas Bank was constructed using shells from the Nelson Bay Cave deposit (Klein 1972, Inskeep 1985). The mollusc species used for isotope analyses was present in the deposit between 8660 and about 650 yr B.P. The timing and timespan of events in each record are known from radiocarbon dates either on layers from which the samples were excavated or on individual shells used in the analyses. Accurate dating is an important and neccessary requisite in palaeoclimatic reconstructions not often recognised by workers in related fields. In order to identify local responses to outside forcing, to compare local signals with changes recorded elsewhere or to link ocean and terrestrial climates, the timing and longevity of the discrete episodes must be determined as precisely as possible.

The thesis is divided into eight chapters, the first comprising this introduction. A brief description of the remaining chapters is given below.

Chapter 2: Aspects of present-day sea surface temperature variability on the western and southern coasts of South Africa

Interpretation of sea surface temperature changes in the palaeorecord is based on knowledge of present-day fluctuations and the processes which drive them. In Chapter 2, aspects of the present-day coastal oceanography of the southern Benguela and eastern Agulhas Bank are reviewed with emphasis on the nature and mechanisms of intra- and interannual variability. The nature of the intra-annual signals in each region are quite different although inter-annual changes appear to be forced by similar factors. A number of studies indicate that interannual variability in the southern Benguela is related to events in the equatorial Pacific, notably phase changes of the El Niño-Southern Oscillation (Walker *et al.* 1984). In this chapter, unpublished data are presented which illustrate that at similar relationship exists between interannual variability on the eastern Agulhas Bank, and phase changes of the Southern Oscillation.

There is a strong link between oceanic and atmospheric conditions over southern Africa which means that information about sea surface temperatures provides insight into wind and rainfall patterns on land. In Chapter 2, the relationship between atmospheric conditions and coastal sea surface temperatures is discussed and in Chapter 7, this information is used to interpret the Holocene sea surface temperature record in terms of terrestrial palaeoclimate.

Little information was available on intra- and interannual sea temperature variability on the eastern Agulhas Bank at the time of this study. Thus, time series of sea surface temperature, wind, the southern oscillation index (SOI) and regional wind field maps were compared in order to identify the mechanisms forcing interannual sea surface temperature variability in this region. The study was a collaborative effort and resulted in a paper submitted for publication (Cohen *et al. in prep.*). Dr Mark Jury, Department of Oceanography, University of Cape Town (UCT), and Dr Eckart Schumann, Department of Coastal Oceanography, University of Port Elizabeth, both made a significant contribution to the study by providing datasets of wind and SOI, in the statistical analysis of the data and also in the interpretation thereof.

Chapter 3: Oxygen isotope palaeothermometry

In Chapter 3, the theory and technique of oxygen isotope thermometry is reviewed, with particular reference to its application to marine mollusc shells. I discuss the theory of temperature-dependent oxygen isotope fractionation between water and calcium carbonate and traces the historical development of the technique and the palaeotemperature equation. Oxygen isotope analyses have been conducted on a wide range of contemporary molluscan taxa from different environments. In general, the evidence now available indicates that the shell carbonate of marine species is accreted at or near equilibrium with sea water. However, the quality of the palaeotemperature record in mollusc shells is not dependent solely on equilibrium precipitation but also on a number of species-specific characteristics. Of special interest is the influence of shell mineralogy on the isotopic composition and post-depositional preservation of shell material.

Chapter 4: The isotopic temperature record in recent *Patella spp.* from the coast of South Africa

In Chapter 4, a study of the isotopic temperature record in three South African mollusc species is described. The aim of this study was to test the potential of three different limpet species, *Patella granatina, Patella granularis* and *Patella tabularis*, as palaeothermometers. Two different analytical techniques were employed. First, the whole-shell mineral composition of *P. granatina* and *P. granularis* was quantified by X-ray diffractometry. As oxygen isotope analyses of *P. tabularis* shells involved only the calcite layer, it was not necessary to quantify the relative proprtions of aragonite and calcite in the shell. Second, the oxygen isotope composition of all three species was measured and compared with actual records of sea surface temperature at each collection site.

Shackleton (1973) showed that the isotopic composition of the calcite layer of *P. tabularis* shells reflected the temperature of seawater in which they accumulated but he adjusted the palaeotemperature equation according to temperature records from a site approximately 100km east of where the shells were collected. Thus, the purpose of reanalysing this species was to compare isotope values and temperature records from the same site.

A fair amount of the isotopic data on whole shells of west coast species were reported in my honours thesis and a subsequent publication (Cohen 1988). The database has since been expanded and new temperature records have become available, thus allowing for a more reliable interpretation of the data.

Chapter 5: Temperature-dependent changes in the shell microstructure of *Patella granularis*: an alternative palaeothermometer

In Chapter 5, the development of an alternative palaeothermometer based on temperature-dependent structural changes in the shell of *Patella granularis* is described. The palaeothermometer was developed in order to distinguish the effect of changing isotopic composition of sea water from the effect of temperature on the oxygen isotope record constructed from midden shells. Both whole shell mineral composition and shell microstructure in different populations were examined and quantified, and compared with sea surface temperature records. A new, simple way to quantify these changes is presented, one which is not affected by erosion or partial dissolution of the aragonite layers. This study was a collaborative effort between myself and my supervisor in the Department of Zoology, UCT, Professor George Branch, who first noticed that the relative widths of the outer shell layers of *P. granularis* were different between different populations on the west and east coasts of South Africa. The results of this study have been published (Cohen and Branch 1992).

Chapter 6: A Holocene sea surface temperature record in mollusc shells from the southwest African coast

Chapter 6 is a description and interpretation of the palaeotemperature record constructed using shell material from cave sites and open middens in the vicinity of Elands Bay on the west coast of South Africa. Two records were constructed using each of the palaeothermometers described in Chapters 3 and 5. Sea surface temperature changes evident in these records were interpreted in terms of the processes described in Chapter 2 and their apparent relationship to global climatic events of the Holocene. This results of this study have been published (Cohen *et al.* 1992). My co-authors were Professor John Parkington, Archaeology Department, UCT who excavated the Eland's Bay Cave and Dunefield Midden sites and provided valuable insights into the relationship between stratigraphic layers in the sequences, Professor Geoff Brundrit, Department of Oceanography, UCT who drew my attention to the importance of the Agulhas-Benguela interocean exchange in the global thermohaline circulation cell and Professor Nick van der Merwe, Archaeology Department, UCT and Archaeometry Laboratories, Harvard University who acted in a supervisory capacity and provided both laboratory facilities and financial support for this study.

Chapter 7: Holocene sea surface temperatures on the south coast of Africa: implications for terrestrial climate and rainfall

The construction of a Holocene sea surface temperature record for the eastern Agulhas Bank coastal region is described in this chapter. Oxygen isotope measurements were made on shells from the Nelson Bay Cave archaeological deposit and the results were interpreted in terms of present-day processes which force sea surface temperature variability on the eastern Agulhas Bank. The aragonite:calcite palaeothermometer described in Chapter 5 could not be used as *Patella granularis* shells were not present in the deposit. Consequently, Fairbanks' (1989) global ocean isotope curve was used to estimate changes in the isotopic composition of seawater through time.

Interpretation of the sea surface temperature records from the southern Benguela and eastern Agulhas Bank was extended to include the terrestrial climate of the adjacent subcontinent. A link between atmospheric circulation anomalies producing lengthy wet and dry spells over southern Africa, and sea surface temperature anomalies in the coastal oceans was made with an "ocean-atmosphere conceptual model". The conceptual model is speculative but is based on reported observations of present-day processes and the predictions of mathematical models.

The study of the Nelson Bay Cave material received financial support from the Climate Research Group, University of the Witwatersrand, under the directorship of Professor Peter Tyson. Professor Tyson also contributed to a manuscript resulting from this study which has been submitted for publication (Cohen and Tyson, *in prep.*).

Chapter 8: Summary

The final chapter summarises the thesis.

CHAPTER 2

ASPECTS OF SEA SURFACE TEMPERATURE VARIABILITY ON THE WESTERN AND SOUTHERN COASTS OF SOUTH AFRICA

2.1 Introduction

The aim of this thesis is to examine the Holocene history of sea surface temperature variability on the western and southern coasts of South Africa. The palaeoceanographic data are interpreted in terms of our understanding of processes which force sea surface temperature variability in these regions today whilst taking into account the possible effects of different boundary conditions such as changes in seasonal insolation during the early Holocene. In this chapter, a description is given of aspects of the oceanography and meteorology of the southern Benguela and eastern Agulhas Bank which are relevant to the interpretation of the palaeoceanography of these regions. The link between coastal sea surface temperatures, wind and rainfall patterns over the subcontinent is noted and these inter-relationships are later used to infer Holocene patterns of terrestrial climate from the palaeotemperature data presented in this thesis.

Apart from the publications resulting from this study, there is to date, no published information regarding the Holocene history of sea surface temperatures in the coastal oceans around South Africa. Nevertheless, information retrieved from studies of sediment cores from the northern Benguela (Oberhansli 1991), at the Subtropical Convergence Front (Morley and Hays 1979, Prell *et al.* 1979, Prell *et al.* 1980) and from beneath the Agulhas Current (Hutson 1980, Winter 1990) have shed some light on the behaviour of adjacent systems during periods when global climate was different from that of today.

In contrast, there *is* a great deal of information about intra- and interannual variability in the present-day southern Benguela largely as a result of the establishment, in 1981, of the Benguela Ecology Programme which was designed to study the relationship between the physical oceanography of this productive region and its important commercial fisheries. In this chapter, the nature and mechanisms of surface temperature variability in the southern Benguela are described using information previously published by independent authors. The oceanography of the Agulhas Bank is rather less well-known although it is now receiving renewed attention as a focal point of fisheries input into the southern Benguela (Proceedings of the Benguela Ecology Program Workshop, Agulhas Bank Synthesis *in press*). Much of the information regarding interannual variability on the eastern Agulhas Bank which is described in this chapter is drawn from Cohen *et al.* (*in prep.*).

In the literature, the southern Benguela and eastern Agulhas Bank have for convenience, been treated as two distinct oceanographic systems. However, common mechanisms forcing interannual and longer-term sea surface temperature variability in both regions are apparent. Both are influenced by changes in the strength and positions of the dominant atmospheric circulation systems over the south Atlantic and southern oceans. The Agulhas Current, the western boundary current in the south-Indian Ocean, also contributes to interannual variability in the southern Benguela and eastern Agulhas Bank. The passage of warm, Agulhas water over the Agulhas Bank and also into the southern Benguela is sensitive to changes in the volume transport of the current which therefore, may affect both coastal regions in the same manner.

2.2 The Benguela Upwelling System

The Benguela Upwelling System, rather than the Benguela Current per se, is the dominant oceanographic feature on the west coast of Africa between 15°S and 34°S (see Fig. 1.3). It refers to that region of the coast characterised by a "pronounced negative surface temperature anomaly" i.e. surface temperatures significantly lower than the adjacent ocean, for part or most of the year (Shannon 1985), caused by primarily wind-driven, coastal upwelling of cold (8°-10°C), nutrient-rich South Atlantic Central Water (SACW) from between 200m and 300m depth (Taunton-Clark 1985). Upwelling originates close to the coast and results in a well-developed thermal front which separates warm, saline South Atlantic surface water on the seaward side from comparatively fresh, cool SACW on the shelf. The front is generally considered to lie within 185 km of the coastline although Lutjeharms *et al.* (1991) have shown that long filaments of upwelled water may on occasion penetrate far to the west of this boundary into the central ocean basin. The Benguela region can be divided into northern and southern parts on the basis of differences in the seasonal wind regime

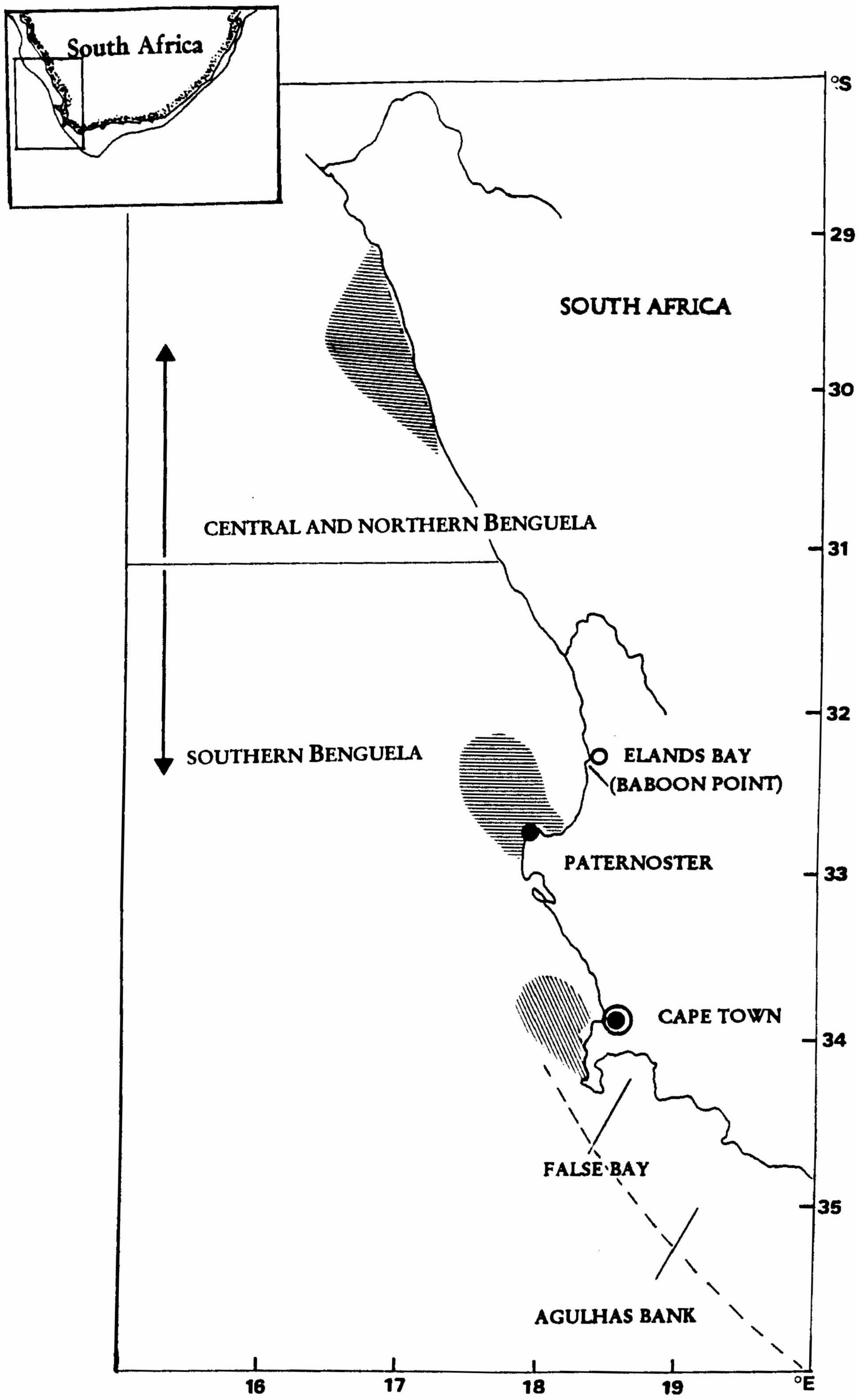


Fig 2.1. Map of the west coast of South Africa indicating the northern boundary of the southern Benguela at about 31°S. Upwelling events are more pronounced in the shaded regions because of local topographic effects on wind and steep bathymetry. The location of study sites mentioned in the text are indicated. Note that Paternoster, on the Cape Columbine headland, is a region of intense upwelling. Elands Bay receives cold, newly-upwelled water from this upwelling tongue.

wind regime (Shannon 1985) (Fig. 2.1). In this thesis, only the southern Benguela i.e. south of 31°S is considered. Here, wind-induced coastal upwelling is highly seasonal and reaches a maximum during spring and summer (between September and March) (Shannon 1966, Andrews and Hutchings 1980). North of 31°S, the macroscale wind field is less seasonally variable and upwelling is perennial (Shannon 1985).

The general meteorology of the southern Benguela has been described by Jury (1980), Shannon *et al.* (1981), Nelson and Hutchings (1983) and Kamstra (1985). The entire region is dominated by the South Atlantic Anticyclone (SAA) which is associated with dry, summer conditions on land (Fig. 2.2A). The SAA is centred on 30°S but shifts through approximately 6° of latitude between summer and winter reaching its southermost position in summer. As a result, coastal regions in the southern Benguela experience predominantly southerly and south-easterly winds during the summer season. These winds are upwelling-favourable as they result in a net movement of surface water offshore, to the west and cool (8-10°C), subsurface, SACW wells up at the coast. In summer, a steep temperature and pressure gradient arises between the interior land mass and the coastal regions, and the strong land-sea breezes which result enhance the south-easterly winds (Shannon 1985), an effect which is especially pronounced in the northern Benguela adjacent to the Namib desert (Shannon 1985). The response of sea surface temperatures to upwelling-favourable conditions varies regionally. Lowest temperatures, associated with newly-upwelled water, are recorded at coastal sites where steep bathymetry aids the uplift of cold water to the surface (Taunton-Clark 1985) and local orographic effects concentrate or steer the wind (Taunton-Clark and Jury 1986) (Fig. 2.1). Where bathymetry is shallow and in sheltered bays along the west coast, upwelled water seldom reaches the coast unchanged and temperatures below 10°C are rare.

The south-easterly wind regime is modulated by eastward-moving low pressure cells which originate south of the continent. They have periods of between three and six days (Preston-Whyte and Tyson 1973) and are usually accompanied by cold fronts. During summer, these systems are often steered south of the continent by the SAA (Fig. 2.2A). In winter the SAA moves north and the low pressure cells penetrate the southern tip of Africa as far north as 31.5°S, producing westerly to north-westerly winds, often accompanied by rain (Fig. 2.2B). Thus, the coastal region adjacent to the southern Benguela receives most of its rainfall during the winter months. Westerly and north-westerly winds also affect sea surface temperatures in the coastal southern

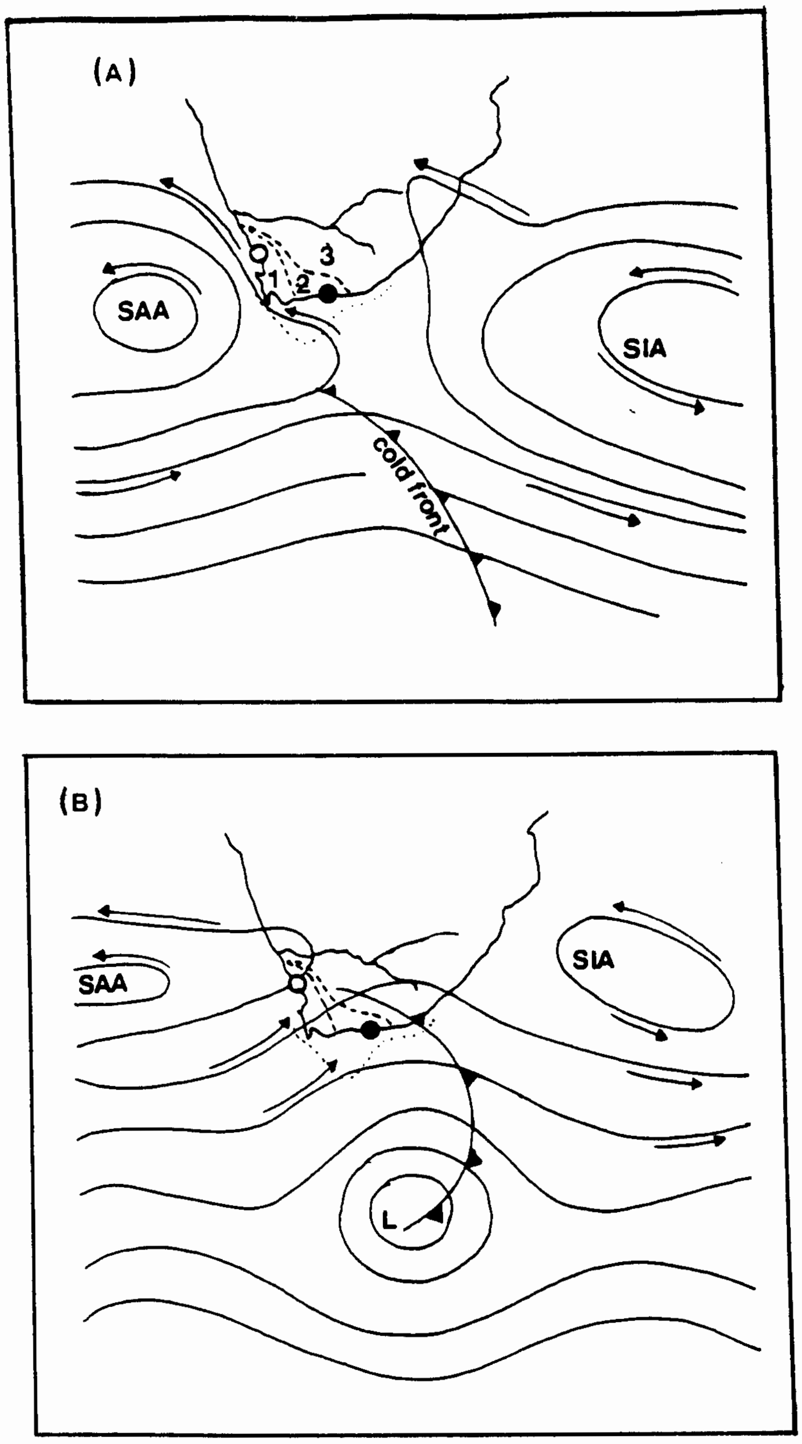


Fig. 2.2. Basic elements in the seasonal pattern of air pressure distribution and wind direction (↖) over South Africa in summer (A) and winter (B). SAA and SIA = South Atlantic and South Indian Anticyclones. In (A), southerly and south-easterly winds blow along the west coast (where Elands Bay Cave is situated) and cold water upwells inshore. Intermittent upwelling events along the south coast (where Nelson Bay Cave is situated), are forced by easterly winds associated with anticyclonic ridging. The low pressure systems, associated cold fronts and westerly winds are displaced southward so the winter rainfall region (1) is dry. In contrast, moist air in circulation about the South Indian high brings rainfall to the summer rainfall region (3). In (B), the high pressure systems move north and westerly winds blow along the west and south coasts. Upwelling is suppressed and warm, oceanic water moves inshore. Cold fronts invade the winter rainfall region bringing rain whilst the summer rainfall region is dry. Rainfall in region (2) is not strongly seasonal.

○Elands Bay Cave; ●Nelson Bay Cave

(adapted from Van Heerden and Hurry 1992)

Benguela by aiding the movement of warm oceanic water inshore. As a result, daily-scale sea surface temperatures in the southern Benguela are often higher in winter than they are during intense periods of upwelling in summer (see Fig. 2.4). Whereas there is little seasonal difference between average winter and summer temperatures, pulsed upwelling results in high day-to-day variability in summer.

The influence of the Agulhas Current on sea surface temperatures in the southern Benguela

Sea surface temperatures in the southern Benguela are also influenced by the east coast Agulhas Current. This warm, fast current flows southwestward close to the edge of the continental shelf executing an often abrupt, anticyclonic turn near 16°-20°E, 40°-42°S (the Agulhas retroflection), before flowing back as the Agulhas Return Current into the south-west Indian Ocean, along the northern edge of the Subtropical Convergence (Lutjeharms 1981) (see Fig. 1.3). The Agulhas retroflection is unstable and may coalesce and spawn large rings (average diameter: 320 km) of warm, salty water, which drift off into the south-east Atlantic (Lutjeharms 1981) (see Fig. 1.3). Agulhas water may also enter the south Atlantic via direct, intermittent leakage from the main body of the current (Shannon *et al.* 1990) or as eddies, formed on the northern border of the current, advect across the Agulhas Bank and enter the Benguela system (Shannon 1985, Duncombe-Ray 1991, Duncombe-Rae *et al.* 1992). Ring-shedding is associated with increasing westward penetration of the retroflection, which may extend far into the South Atlantic. The westernmost extent of the retroflection is unclear, although warm water of Agulhas origin has been identified in satellite images as far west as 8°W (Lutjeharms 1988). On the contrary, anomalous reversals of the current have also been observed far upstream of its characteristic location (Lutjeharms and van Ballegooyen 1988). The effect of such anomalous retroflections on decreasing the volume of Indian Ocean water transported into the south-east Atlantic, on ring-shedding and on the sea surface temperatures of downstream coastal regions, has not been quantified although it is recognised that such events may have large-scale climatic implications (Lutjeharms and van Ballegooyen 1988).

The volume transport of the Agulhas Current strongly influences the latitudinal position of the retroflection. An inertial jet model used by Lutjeharms and van Ballengoyen (1984) predicted further westward penetration of the current for low volume transports and further east and southward penetration for higher transports. This observation is particularly interesting in the light of earlier palaeoceanographic studies in the Agulhas Current region. Data collected by Hutson (1980) and Prell *et al.* (1980) indicated that the Agulhas Current was weaker and shallower during the Last Glacial Maximum. Both authors suggested that, as a result, the Agulhas retroflection was located to the east of its present position.

Volume transport of the Agulhas Current, the position of the retroflection and influx of Indian Ocean water into the southern Benguela are probably modulated by wind intensity over the south-west Indian Ocean (Brundrit and Shannon 1989, Shannon *et al.* 1990, Shannon and Lutjeharms 1990). However, despite strong seasonality in the surface wind field over the south-west Indian Ocean, there is to date no evidence to suggest corresponding variability in the surface speed of the Agulhas Current (Grundlingh 1980, Pearce and Grundlingh 1982). Nevertheless, it is important to note that the conclusions of these authors were based on very small sets of data possibly inappropriate for the study of seasonal variability and there is in fact, no study yet designed to address the question of seasonal volume flux in the Agulhas Current.

On the other hand, it is well-established that there is a flow of water in the upper 1000 m from the Indian Ocean into the south-east Atlantic. Bang (1973) noted that the presence of Agulhas water, albeit modified (Shannon 1990) is normal west of the Cape Peninsula and Lutjeharms and Valentine (1988) suggested that Agulhas rings are present just off the Cape Peninsula (35°S 15°E) about 30% of the time. The significant transfer of Indian Ocean Central Water into the South Atlantic is revealed by wind-driven ocean circulation models as well as field observations (Boudra and Chassignet 1988, Semtner and Chervin 1988, Fujio *et al.* 1991, Gordon and Haxby 1990, Lutjeharms and Gordon 1987) Gordon *et al.* (1992) suggested that as much as two-thirds of Benguela thermocline water is drawn from the Indian Ocean via eddy-shedding from the retroflection, intermittent streams, or surface Agulhas Bank water passing into the Benguela Current.

The extent of the influence of Agulhas Current water on sea surface temperatures in the coastal southern Benguela has not been quantified and to date, only recent, rather extreme events have been recorded and their effects analysed. However, reasonable speculation about the possible impact of warm water leakage into the southern Benguela can be made. Surface temperatures in the nearshore southern Benguela may

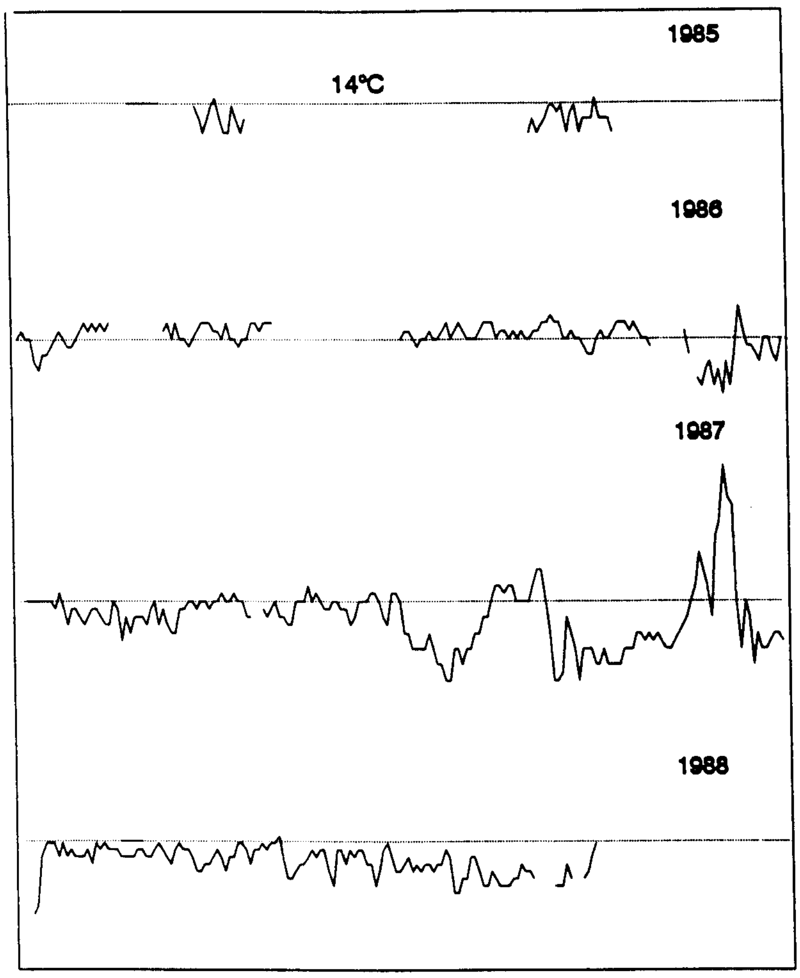


Fig. 2.3. Sea surface temperatures at Paternoster[1], a coastal upwelling zone in the southern Benguela, between July and December from 1985 to 1988. The dotted line indicates the 14°C isotherm. Water temperatures during 1986 were between 1°C and 2°C higher than they were in other years and the anomaly was most likely associated with the major intrusion of Agulhas Current water into the southern Benguela reported by Shannon *et al.* (1990)

[1] Sea temperature data provided by the Sea Fisheries Research Institute in Cape Town

rise due to the advection of warm water northwards or as warm Agulhas water, rather than cool, SACW, is upwelled at the coast. Agulhas water is also thought to contribute to the surface heating of warm, offshore water to the west of the upwelling zone. During 1986, a major intrusion of the Agulhas Current caused sea surface temperature anomalies of up to 3°C in the south-east Atlantic to the west of the upwelling system (Shannon *et al.* 1990). Sea surface temperature records from the coastal zone at Paternoster, just south of Elands Bay show that this intrusion also impacted on sea surface temperatures close inshore, which were between 1° and 2°C higher than average for the duration of the intrusion (Fig. 2.3).

This interocean exchange of water south of Africa also has important implications for local weather and rainfall on the Cape west coast and in the interior (Brundrit and Shannon 1989, Duncombe-Ray 1991) as there is evidence to suggest that storm depressions which move over these large bodies of warm water intensify due to the ocean-to-atmosphere transfer of sensible and latent heat. Furthermore, the passage of heat and salt into the south-east Atlantic has been recognised in recent years as a possible link in a global thermohaline circulation cell which transports excess surface heat from the equatorial Pacific to the northern North Atlantic, where it is released to the atmosphere as a by-product of North Atlantic Deep Water (NADW) production (Gordon 1985, 1986, 1988). The passage of warm water from the Indian into the south-east Atlantic Oceans occurs via the Agulhas-Benguela exchange which is considered a potential choke point in the surface route (Gordon 1992). Broecker (1985) and Broecker and Denton (1989) proposed that abrupt climatic cooling during the last deglaciation was caused by an interruption of this "heat conveyor" which, through the process of NADW production serves as an important heat source to the adjacent European continent. If this was indeed the cause of major events such as the Younger Dryas, then the passage of Indian Ocean water into the south-east Atlantic may well have ceased or been significantly reduced. On the other hand, Rintoul (1991) argues that waters entering the Drake Passage provide the dominant feedwater for NADW production, in which case Agulhas-Benguela interocean exchange may have been unaffected by any reorganisation of the global ocean circulation. The possible impact of reduced NADW production on Holocene sea surface temperatures in the southern Benguela, is considered further in Chapter 6.

In a study of intra-annual sea surface temperature variability at a site near Cape Town in the southernmost southern Benguela, Taunton-Clark and Kamstra (1988) showed that, as a consequence of coincident peaks in summer upwelling and solar radiation, there was no strong, seasonal temperature signal in the inshore region. Sea surface temperatures at Baboon Point, an exposed rocky outcrop below Elands Bay Cave (Fig. 2.1), were available for the period January 1990 to December 1992. A plot of the average monthly temperatures during this time indicate that these effects are also evident at sites to the north of Cape Town (Fig. 2.4). Average monthly summer temperatures are difficult to tell apart from average monthly winter temperatures as upwelling events decrease the overall temperatures in warm months and the onshore movement of warm, oceanic water offsets the effects of cool air during winter months. However, on a daily or weekly scale, sea temperatures are more variable in summer than in winter indicating the modulation of upwelling-favourable winds by the relatively free zonal passage of eastward-moving cyclones (Taunton-Clark and Kamstra 1988). The influence of the Agulhas Current on surface temperatures in the southern Benguela may also be a factor contributing to the high degree of short-term variability in this region (Shannon 1985).

Interannual sea surface temperature variability in the southern Benguela are correlated with El Niño events in the Pacific (Walker *et al.* 1984, Taunton-Clark and Kamstra 1988). During the low phase of the Southern Oscillation, in which southward currents advect warm water along the Peruvian and Equadorian coasts, sea surface temperatures in the southern Benguela are often anomalously high, although the mechanism by which these anomalies occur appears to be different from those forcing the Pacific events. Taunton-Clark and Kamstra (1988) suggested that Benguela cold events evident in the temperature record between 1960 and 1978, were analogous to an extended summer situation in which the SAA was located further south, blocking the activity of the east-travelling cyclones. Thus, extended periods of low sea surface temperatures in the southern Benguela would have been associated with anomalously dry conditions along the west coast of South Africa. Benguela warm events were considered analogous to an extended winter situation during which the SAA was located further north of its mean summer position allowing cyclonic activity to excercise its full effect with increases in rainfall over the west coast winter rainfall region associated with anomalously high inshore sea temperatures. Walker *et al.*

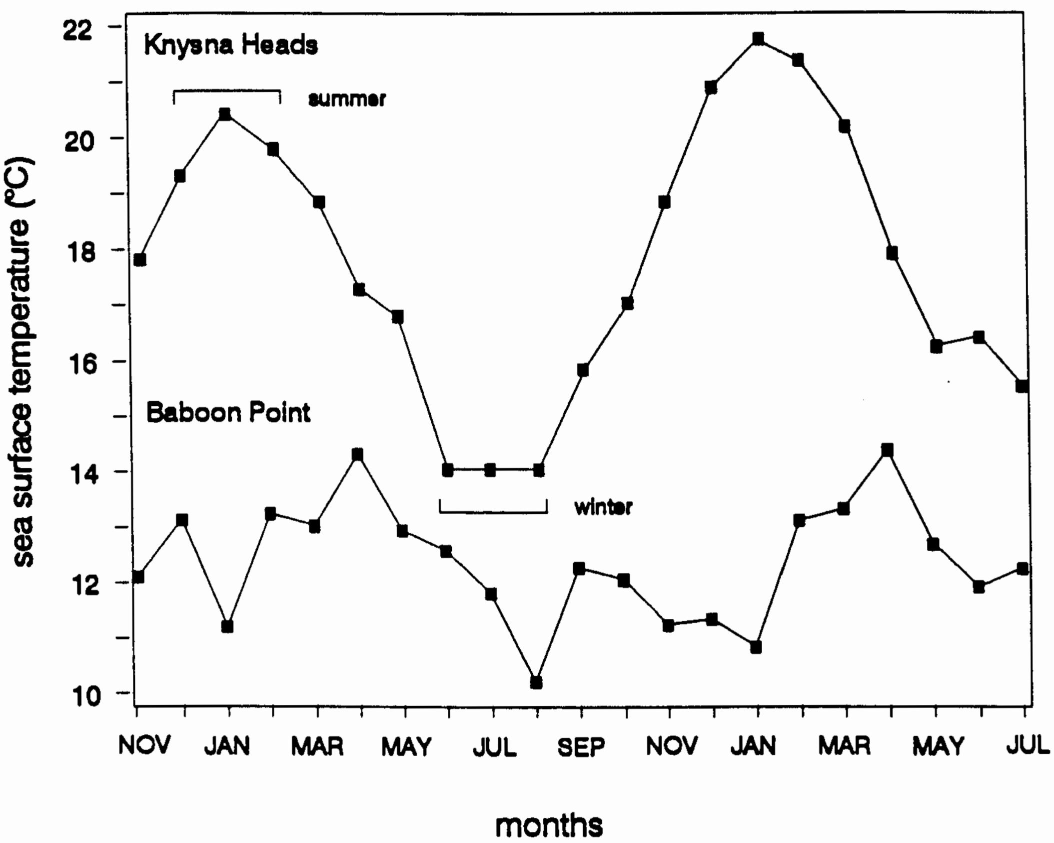


Fig. 2.4. Mean monthly sea surface temperatures on the western and southern coasts of South Africa, from November 1990 to July 1992, are compared. At the Knysna Heads[1], south coast, a strong seasonal signal was evident and summer temperatures were much higher than, and easily distinguishable from, winter temperatures. At Baboon Point[2], west coast, there was no obvious seasonal signal as cool, upwelling events occurred during summer when insolation was highest. Between 1990 and 1992, sea temperatures at Baboon Point during winter were often warmer than they were during the summer months.

[1] Sea temperature data supplied by the DF Malan Airport Meteorological Office in Cape Town
[2] Sea temperature data provided by the Sea Fisheries Research Institute in Cape Town

(1984) showed that the major Benguela warm event of 1982/83 was coincident with a more northerly penetration of the westerly wind belt in summer and a northward shift of the SAA and the Subtropical Convergence Front. This scenario supports the findings of Lindesay *et al.* (1986) who reported that rainfall in the south-western Cape increased during summers in which the southern oscillation index was low (i.e. El Niño summers). In contrast, low index summers often mean severe and potentially crippling droughts for the summer rainfall region of southern Africa (Lindesay 1986).

2.3 The Agulhas Bank

The coastal oceanography of the Agulhas Bank differs from that of the southern Benguela in that upwelling, rather than being a dominant feature, is intermittent, solar radiation has a greater effect on seasonality and the influence of the Agulhas Current, especially in the eastern parts, is greater. The influence of the Agulhas Current is, however, greatest on the east coast of South Africa from north of Durban (30°S) to Algoa Bay (34°S), where the shelf is narrow and the current flows close inshore (Schumann 1987). Indeed, sea surface temperatures off Durban vary between 22°C in winter and 27°C in summer (Shannon *et al.* 1989), and are amongst the highest along the country's coastline. The Agulhas Bank begins south of Port Elizabeth where the shelf widens to form a relatively shallow topographical feature (Fig. 2.5). The bank is widest south of Cape Infanta where it extends more than 200km offshore (Shannon *et al.* 1989). Evidence from archaeological deposits on the south coast suggests that the entire bank was exposed at the Last Glacial Maximum 18 000 years ago, when sea level was 120m lower than it is today. Then, the Agulhas Bank supported a productive grassland community of vegetation and large bovids (Klein 1972).

The Agulhas Bank is divisible into western, central and eastern sectors, based on different hydrological conditions related primarily to forcing by the Agulhas Current and wind-driven coastal upwelling (Probyn *et al. in press*) (Fig. 2.5). The coastal topography is characterised by a series of large, crenulated, half-heart shaped bays with prominent capes, which face the south-west Indian Ocean (Schumann *et al.* 1982). One of these is Cape Seal (Fig. 2.5) at the head of the Robberg Peninsula which protrudes four kilometers into the Indian Ocean and forms the southern margin of Plettenberg Bay (Rogers 1966). Nelson Bay Cave is located on the seaward side (south face) of the Peninsula. It is the largest of a number of caves occupied by hunter-

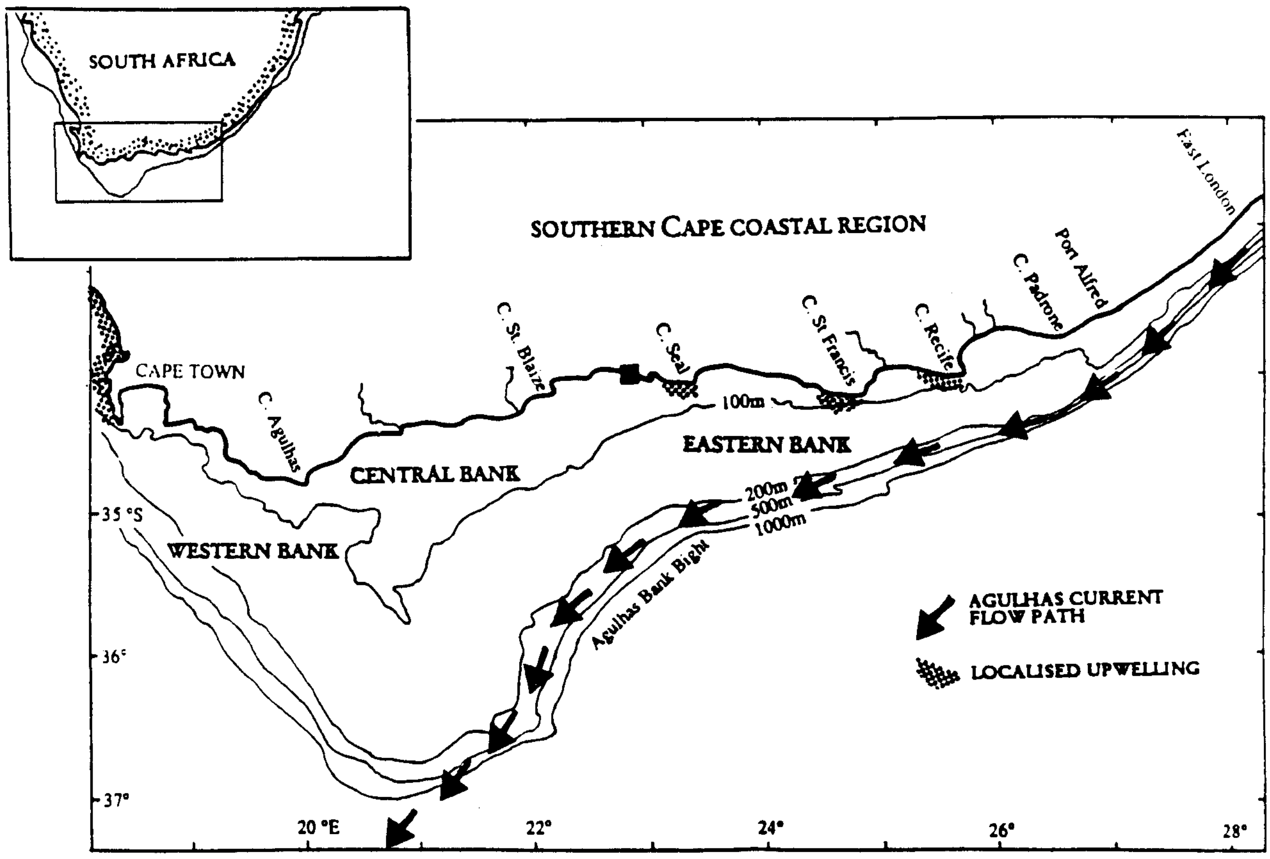


Fig. 2.5. Features of the Agulhas Bank region showing relative positions of Knysna (■), Cape Seal and the Robberg Peninsula at the coast in the eastern sector, and the southern edge of the Benguela upwelling system to the west. Areas which most often experience summer upwelling are shaded. The characteristic flow path of the Agulhas Current is shown, along the 200 m contour (adapted from Probyn *et al. in press*)

gathering people through the Pleistocene and Holocene. Nelson Bay Cave is today approximately 18 m above present mean sea level (Klein 1972) and may have formed during the early part of the Last Interglacial when sea level was between 15 m and 18 m higher than it is today (Butzer and Helgren, in Klein 1972). The presence and nature of the Agulhas Bank, and the bathymetry around Cape Seal, have important consequences for the local oceanography.

The oceanography of the Agulhas Bank was studied briefly in the early 1980's but is now receiving renewed attention as a focal point of fisheries input into the southern Benguela (Proceedings of the BEP workshop, Agulhas Bank synthesis, *in press*). The results of earlier studies show that insolation, wind, and the Agulhas Current play an important role in daily and seasonal fluctuations of sea surface temperature at the coast (Schumann *et al.* 1982, Beckley 1983, Walker 1986, Largier and Swart 1987). The coastal orientation and steep bottom topography characteristic of the capes of the eastern Agulhas Bank assist the uplift of sub-surface waters especially at the coast (Schumann *et al.* 1982).

The general meteorology of the southern Cape has been described in a number of reports including Schumann *et al.* (1991), Schumann and Martin (1991) and Schumann (1992). Whereas the dominant zonal component of surface winds at Elands Bay in summer is easterly due to the southward position of the SAA, zonal winds along the coast of the eastern Agulhas Bank are predominantly from the west throughout the year (Schumann and Martin 1991) due to its close proximity to the circumpolar wind belt. However, in spring and late summer when the SAA is midway between its maximum summer and maximum winter latitudinal positions, upper-level Rossby waves in the circumpolar jetstream force the anticyclone to ridge eastward (see Fig. 2.2) and as a result, easterly, upwelling-favourable winds may blow at the coast (Schumann *et al.* 1982). Anticyclonic ridging produces a pulsed wind regime so upwelling events are intermittent and short-lived (Jury *et al.* 1990). Nevertheless, the impact of upwelling events can be dramatic and Schumann *et al.* (1982) and Beckley (1983) reported sea surface temperature anomalies of up to 8°C following spells of strong easterly winds.

The influence of the Agulhas Current on
sea surface temperatures of the eastern Agulhas Bank

The inshore waters of the Cape south coast are not influenced directly by the Agulhas Current, the main flow of which lies far out to sea beyond the shelf break (Schumann *et al.* 1982). However, Swart and Largier (1987) showed that the presence and nature of the Agulhas Current along the south-eastern edge of the Agulhas Bank promotes the establishment of an intensive and spatially extensive vertical thermocline over this region in summer. A basal layer of cold, Indian Ocean Central Water (< 10°C) is forcibly upwelled over the shelf edge whilst the surface layer of warm, subtropical surface water (> 18°C) is maintained and continually replenished by Agulhas Current water penetrating onto the shelf in the form of plumes associated with meanders of the current. Shelf-edge (as opposed to coastal) upwelling and continual inflow of warm, sub-tropical surface water occur predominantly over the eastern sector of the Agulhas Bank and together with solar heating of the surface waters, determine the strong (5°C/10 m), shallow (20-40 m) thermocline present in this region in summer (Probyn *et al.* in press). The significance of the impact of the Agulhas Current on the thermal structure of eastern bank water is emphasised by the contrasting situation on the western bank, where the Agulhas Current turns away from the shelf edge. Here, shelf-edge upwelling is not a marked feature, intrusions of warm surface plumes and eddies are not as prevalent, and as a result, the thermocline is weaker and deeper than it is on the eastern bank (McMurray 1990).

The winter situation on the Agulhas Bank is less well documented. However, the available evidence shows that decreased insolation causes surface water cooling, and in the absence of a strong thermocline, deep mixing of the water column occurs in the presence of predominantly westerly wind conditions (Probyn *et al. in press*). Furthermore, shelf-edge upwelling of South Indian Central Water decreases during winter and originates from shallower depths. As a result, the bottom water on the eastern Agulhas Bank is warmer during winter than during summer (Swart and Largier (1987). This means that, in the absence of a thermocline, even if upwelling-favourable winds should blow during the winter months, a characteristic cool signal would not be registered in the coastal surface water temperature. Lutjeharms and van Ballegooyen (1988) and Goschen and Schumann (1990) noted that shear-edge eddies and their related warm-water plumes of Agulhas Current water (see Fig. 1.1) may be forced inshore during a south-westerly wind and thus increase the sea surface temperature of the coastal regions. The magnitude of sea surface temperature change under these conditions has not been quantified.

Intra- and interannual sea surface temperature variability on the eastern Agulhas Bank

Cohen *et al.* (*in prep.*) analysed time series of coastal sea surface temperature and local winds on the eastern Agulhas Bank, regional winds and the global southern oscillation index in order to examine the forcing mechanisms responsible for intra- and interannual sea surface temperatures in this region (Appendix 2.1). A plot of the averaged monthly sea surface temperatures from November 1990 to July 1992 illustrates the strong seasonal signal in the data, with highest sea temperatures attaining in mid-summer and lowest temperatures in mid-winter (Fig. 2.4). The amplitude of the seasonal signal over this period reached 7°C suggesting that solar insolation plays a dominant role in seasonal changes whereas advective processes such as intermittent summer upwelling, which may dampen the signal, warming due to winter mixing of surface and sub-surface layers and intrusions of Agulhas Current surface water, are of secondary importance. The situation on the eastern Agulhas Bank is quite different from that in the southern Benguela where summer upwelling offsets insolation (Fig. 2.4). On the other hand, standard deviations of sea surface temperature on the eastern bank in summer are about double those of winter suggesting that intermittent upwelling events do contribute to the variability of coastal temperatures on a monthly time scale (Cohen *et al. in prep.*).

Interannual sea surface temperature variability on the eastern Agulhas Bank from January 1972 to December 1992 was strongly correlated with both the frequency of easterly winds in the region and with phase changes of the Southern Oscillation (Cohen *et al. in prep.*). The correlations were more significant if only the summer months were considered (Fig. 2.6A,B). Negative sea surface temperatures anomalies occurred in summer when the frequency of easterly wind anomalies was high and this is to be expected considering that it is the easterlies which force upwelling of cold, South Indian Central Water at the coast (Fig. 2.6A). Similarly, when the frequency of easterly winds was low or negative, sea surface temperatures were higher than average suggesting that apart from there being a reduction in the incidence of upwelling, westerly winds probably contribute to the warming of coastal waters by advecting warm offshore water into the coastal region. These observations therefore support suggestions by previous authors (Schumann *et al.* 1982, Swart and Largier 1987) of a relationship between wind strength and direction and sea surface temperatures on the eastern Agulhas Bank.

In the light of these observations and those of Walker *et al.* (1984) and Taunton-Clark and Kamstra (1988) for the southern Benguela, it is not suprising that a strong correlation was found between sea surface temperature anonalies and phase changes of the Southern Oscillation (Fig. 2.6B) (Cohen *et al. in prep.*). When the southern oscillation index (SOI) was high i.e. during La Nina or anti-El Niño, sea surface temperatures on the eastern Agulhas Bank were anomalously low. During low-index phases, coastal temperatures were anomalously high. The link between El Niño-Southern Oscillation events in the Pacific and interannual coastal temperatures in the southern Benguela was suggested by these authors to be via the circumpolar westerlies in the southern hemisphere which shift north of their mean summer position during low phases of the Southern Oscillation. This northward shift is accompanied by an equatorward displacement of the SAA and thus the upwelling-favourable winds. Coastal sea surface temperatures on the eastern Agulhas Bank respond to these atmospheric circulation systems in the same way; therefore the link between interannual coastal temperature variability in this region and phase changes of the Southern Oscillation is most likely to be also through the circumpolar wind belt.

2.4 Summary

The available information indicates that, on interannual time scales, sea surface temperatures in the southern Benguela upwelling system and the eastern Agulhas Bank coastal region respond to changes in the position of the major atmospheric circulation systems over the south-east Atlantic and southern oceans and to changes in the volume flux of the Agulhas Current, which is responsive to the surface wind field over the south-west Indian Ocean. There is strong evidence to suggest that phase changes of the Southern Oscillation, associated with the Pacific El Niño, force interannual sea surface temperature variability on the west and south coasts of South Africa via these atmospheric circulation systems. Seasonal shifts in the latitudinal positions of the anticyclonic and cyclonic circulations bring both seasonality of rainfall and coastal upwelling events to the west coast. Anomalous rainfall patterns analogous to extended summer or extended winter seasons, which affect both the winter and

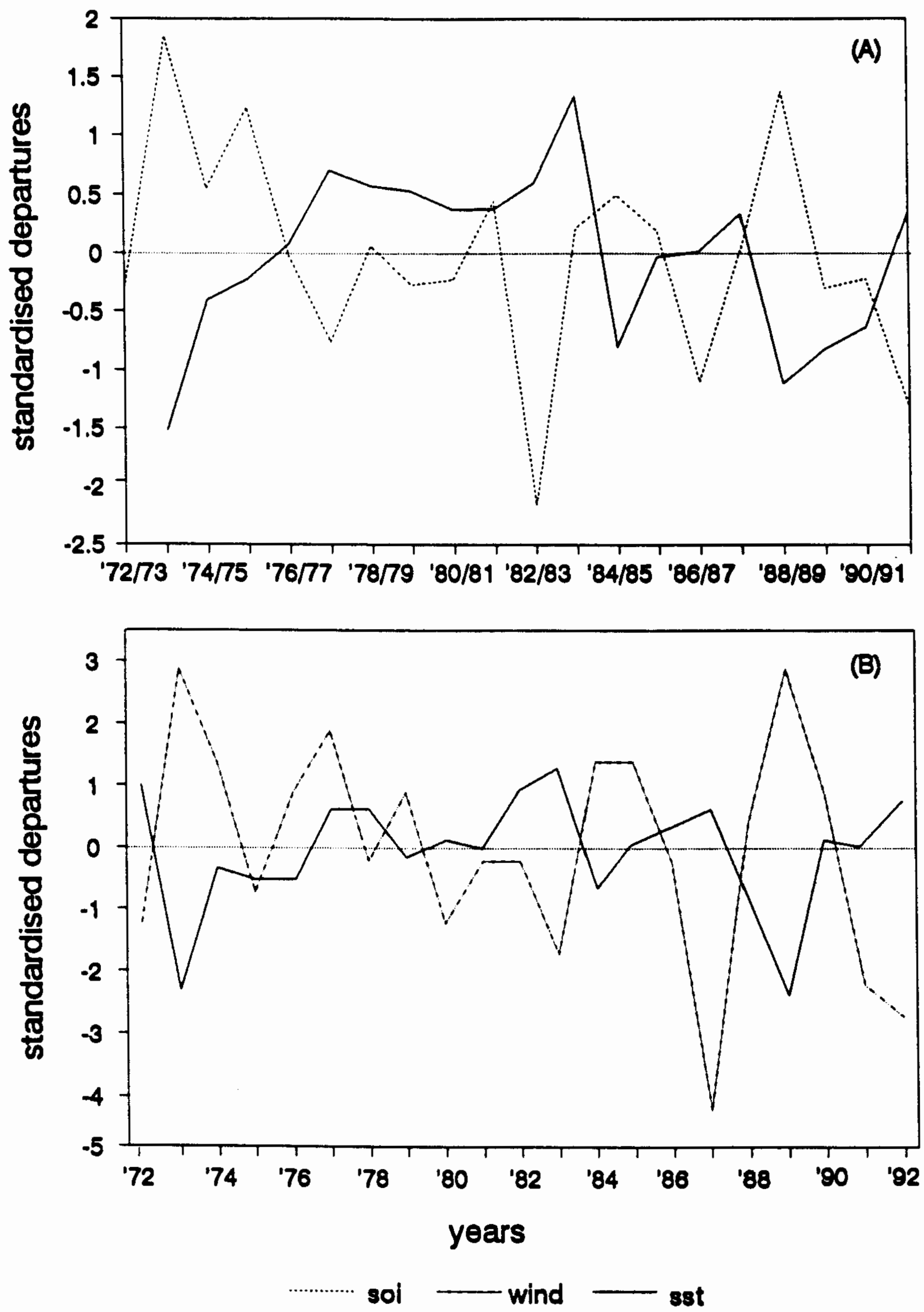


Fig. 2.6. Standardised departures of the southern oscillation index[1] (SOI) and Knysna sea surface temperature[2] (SST) for months November to April each year from 1972-1992 (A), and of Knysna SST and easterly wind frequency[3] at Port Elizabeth airport for January and February only from 1972-1992 (B). At +1 year lag, SST anomalies are well-correlated with anomalies in the SOI ($r=-0.55$, $p<0.05$), and also with the frequency of easterly winds $>1ms^{-1}$, at zero lag ($r=0.66$, $p<0.05$). (after Cohen *et al.* in prep.).

[1] SOI data supplied by the Climate Analysis Center, NOAA (CAC 1992)
[2] Temperature data supplied by the DF Malan Airport
[3] Wind data for Port Elizabeth made available by the Weather Bureau.

summer rainfall regions in South Africa, have been linked to El Niño events in the equatorial Pacific. In this chapter, the response of sea surface temperatures in the coastal southern Benguela and eastern Agulhas Bank to seasonal and interannual changes in regional atmospheric and oceanic circulation, has been illustrated.

Whereas the oceanography of these coastal systems are quite different, their responses to atmospheric and oceanic forcing on interannual time scales are similar. Sea surface temperatures in both regions decrease significantly when the southerly position of the SAA is maintained for unusually long periods, associated with Pacific La Niña, and when alongshore winds intensify. In contrast, sea surface temperatures in both regions increase when the circumpolar westerlies move northward for unusually long periods, often during Pacific El Niño, and the Subtropical Convergence Front shifts north. Sea surface temperature in both regions are also affected by volume transport in the Agulhas Current, thought to be driven by surface winds over the south-west Indian Ocean.

CHAPTER 3

OXYGEN ISOTOPE PALAEOTHERMOMETRY

3.1 Introduction

Oxygen isotope thermometry, when applied to aquatic environments, is based on the temperature-dependent distribution of oxygen isotopes (^{18}O:^{16}O) between carbonate skeletons and the water in which they are accreted or precipitated. The technique was developed in the 1940's and 1950's and rapidly developed into one of the most widely used tools in the reconstruction of past environments. Its application has been successful in many branches of marine geology and biostratigraphy, in particular the discovery of the nature of glacial-interglacial cycles (Shackleton and Opdyke 1973, Mix and Ruddiman 1985), sea level history (Chappell and Shackleton 1986), the circulation of the palaeoceans (Labeyrie *et al.* 1987) and the rates at which these processes have changed in the past (Lehman and Keigwin 1987). The technique is not restricted to the reconstruction of marine palaeotemperatures. Oxygen isotope records obtained from deep ice-cores (Dansgaard *et al.* 1989, Lorius *et al.* 1985, Jouzel *et al.* 1987), speleotherms (Hendy and Wilson 1968, Talma *et al.* 1992), land snails (Margaritz *et al.* 1980, 1981), tree rings (Burke and Stuiver 1981), peat bogs (Brenninkmeijer *et al.* 1981) and fresh water lake sediments (Eicher and Siegenthaler 1976) have contributed to the reconstruction of terrestrial palaeoclimates.

Aspects of the oxygen isotope technique, including the history of its development, the theory of isotope fractionation and the procedure of oxygen isotope analyses have been reviewed by a number of authors (Hecht 1976, Faure 1986, Duplessy 1979, Rye and Sommer 1980, Hayes 1982, Hoefs 1987). By and large, the procedures employed by laboratories around the world are similar and isotope data are made comparable with the use of accepted reference standards. In some laboratories, the employment of fully-automated light isotope mass spectrometers obviates the need for manual preparation of the carbon dioxide gas from a cleaned carbonate sample and therefore reduces the risk of human error and contamination of the sample during analysis. In this study the majority of measurements were made on an off-line Micromass 602E spectrometer and samples were prepared manually according to the methods prescribed by McCrea (1950) and Shackleton (1974). This chapter includes a description of the methods employed in this study as well as the theory on which the oxygen isotope technique is based. Inability to measure directly the oxygen isotope composition of palaeowaters poses a major problem to workers attempting to read palaeotemperatures from the oxygen isotope composition of fossil carbonates. Indirect estimates of the changing isotopic composition of seawater through time are available but sufficient data for the Holocene period are lacking. Difficulties inherent in the application of this technique as a thermometer when biologically-precipitated carbonates are used have also become apparent and are discussed in this chapter with reference to the application of oxygen isotope thermometry to marine molluscs.

3.2 The Oxygen Isotope Technique and Development of the Palaeotemperature Scale

The relationship between isotope composition and temperature

Harold Urey (1947) suggested that accurate measurement of the ^{18}O content in carbonate rocks and calcareous skeletons could be used to determine the temperature at which they were formed. His suggestion was based on knowledge of the thermodynamic properties of isotopes. In equilibrium chemical reactions, the various isotopes present in the system are preferentially distributed between different compounds so as to reduce the free energy of the system. The heavy isotope (with higher dissociation energy) is attracted to the chemical compound to which it is bound most strongly. Under equilibrium conditions and for the purposes of palaeothermometry, temperature is the most important factor determining the distribution of isotopes. With increasing temperature, the energy differences between heavy and light isotopes decreases so the preferential distribution or fractionation of isotopes between the two compounds becomes less pronounced (O'Neil 1986).

Mollusc shells are composed of thousands of discrete calcium carbonate ($CaCO_3$) crystals (Gregoire 1972, Wilbur 1972). The shell of most molluscs, excluding the majority of cephalopods and some ophisthobranchs, is external and secreted by a single epithelial layer of the mantle (Crenshaw 1982). Shell carbonate derived from three sources of marine bicarbonate, (sea water, metabolic carbon dioxide and tissue carbonate) and calcium obtained from sea water and food are concentrated in the extra-pallial space between the mantle and the shell and combined intracellularly to form $CaCO_3$ (Wilbur 1972). With input from various sources, including metabolised CO_2, it is difficult to imagine how the oxygen isotope ratio of shell carbonate remains representative of that of sea water, offset only by an amount dictated by water temperature. Aspects of the life history including variable growth rate, anaerobic respiration during valve closure, shell dissolution and disruptive activities such as reproduction should, theoretically, alter the original oxygen isotope value of incoming HCO_2 either directly, as in shell dissolution, or indirectly by influencing metabolic rate. However, "kinetic" and "metabolic" processes (McConnaughey 1989) which cause isotopic disequilibria in calcareous skeletons have been reported mainly for carbon isotopes (Tanaka 1986, Wefer and Berger 1991). Urey *et al.* (1951) predicted that oxygen isotope equilibrium should be achieved by most shelled organisms because the growing surface is constantly bathed in sea water so that free exchange of oxygen isotopes between sea water and extra-pallial CO_2 occurs. When shell formation occurs under equilibrium conditions, the heavy oxygen isotope (^{18}O) concentrates preferentially in the calcium carbonate crystals relative to seawater. The magnitude of isotopic fractionation between the shell carbonate and surrounding sea water is described by the fractionation factor, α, where:

$$\alpha_{carbonate\text{-}water} = \frac{(CaC^{18}O_3/CaC^{16}O_3)}{(H_2{}^{18}O/H_2{}^{16}O)}$$

For the temperature range which concerns us, i.e. 0°C to 25°C, α is related to temperature by the following equation (O'Neil *et al.* 1969):

$$10^3 \ln\alpha = (3.78 * 10^6/T^2)-3.89$$

Between 0°C and 25°C, the relationship is approximately linear.

Measurement and expression of the isotope ratio

Measurements of the carbonate sample isotope ratio and of the water sample isotope ratio are made independently on a light stable isotope ratio mass spectrometer. Most stable isotope abundances and variations are reported in terms of a relative difference function, the δ value, which is defined as follows:

$$\delta^{18}O = \frac{(R_{sample}-R_{standard})}{(R_{standard})} * 1000 \qquad (1)$$

δ values are usually only significant at the third decimal place and are therefore expressed in parts per thousand ($^o/oo$).

The palaeotemperature equation

The relationship between temperature and the isotopic fractionation between calcium carbonate and water is described by the palaeotemperature equation. The original form of the palaeotemperature equation (2) was derived experimentally using living molluscs grown under controlled conditions in a range of temperatures between 7°C and 29°C (Epstein *et al.* 1951, 1953):

$$t°C = A - B\,(\delta_{sample}) + C\,(\delta_{sample})^2 \qquad (2)$$

where A, B and C are constants. Epstein and Mayeda (1953) reported a large variation in the $\delta^{18}O$ composition of natural waters and modified the original Epstein equation by introducing a term, δ_{water}, so as to be able to correct for changes in the isotopic composition of seawater between glacial and interglacial times. Thus:

$$t°C = A\text{-}B(\delta_{sample}\text{-}\delta_{water}) + C(\delta_{sample}\text{-}\delta_{water})^2 \qquad (3)$$

This form of the palaeotemperature equation remains unchanged although subsequent experiments by various workers in the field (Craig 1965, O'Neil *et al.* 1969, Shackleton 1974) yielded slightly different values for A,B and C. Craig (1965) added corrections for instrumental (mass spectrometric) effects and for isotope fractionation during acidification, which leaves the evolved CO_2 about 10% more enriched than the original carbonate. Shackleton (1974) demonstrated that the palaeotemperature equation derived from O'Neil (1969) was a better representative of isotopic equilibrium in the calcitic foraminifera *Uvigerina* over a wider temperature range and especially for temperatures below 7°C. Shackleton's equation (2) differs from that of Craig (1965) in the values of B and C such that:

$$t°C = 16.9\text{-}4.38(\delta_s\text{-}\delta_w) + 0.10(\delta_s\text{-}\delta_w)^2 \qquad (4)$$

δ_S-δ_W is the Craig (1965)-corrected difference between $\delta^{18}O$ of CO_2 extracted from the shell carbonate and the $\delta^{18}O$ of CO_2 isotopically equilibrated with the water in which the shell was precipitated (Shackleton 1974), both expressed relative to the same standard.

The original standard used in the development of the classic "Epstein" palaeotemperature scale was the rostrum of a Cretaceous belemnite from the PeeDee Formation of South Carolina (PDB-1, Chicago) (Craig 1957) and its value refers to the solid carbonate, not that of the acid-liberated CO_2. That supply has long been exhausted and secondary reference standards including those prepared by the International Atomic Energy Agency (I.A.E.A.) and the National Bureau of Standards (NBS) are presently in use. Oxygen isotope values of carbonates for ocean palaeotemperature studies are reported relative to the original PDB value. Another internationally accepted reference standard is SMOW (Standard Mean Ocean Water) which was originally a hypothetical water sample with an isotope ratio similar to that of an average sample of ocean water. The oxygen isotope composition of sea water samples are most often reported relative to SMOW (Craig 1961). Conversion between $\delta^{18}O_{V\text{-}SMOW}$ and $\delta^{18}O_{PDB}$ can be made using the equations of Coplen *et al.* 1983:

$$\delta^{18}O_{V\text{-}SMOW} = 1.03091\delta^{18}O_{PDB} + 30.91 \qquad (5)$$

and

$$\delta^{18}O_{PDB} = 0.97002\delta^{18}O_{V\text{-}SMOW} - 29.98 \qquad (6)$$

3.3 Changes in the oxygen isotope composition of seawater (δw)

Geographical variability

It is evident from equations (3) and (4) that the oxygen isotope value of two variables, δ_S and δ_W, must be known before t can be derived using the palaeotemperature scale. For the modern ocean, δ_W can be measured or is often assumed a value of $0°/oo$. However, in most cases, the oxygen isotope composition of palaeowaters cannot be measured directly and must be independently estimated. The oxygen isotope composition of seawater during the present day is strongly positively correlated with salinity (excepting in the vicinity of sea ice formation). This is because the same processes which affect salinity, i.e. evaporation and precipitation, also affect the oxygen isotope value. When water evaporates from the surface of the ocean under equilibrium conditions, the water vapour is isotopically depleted (fewer ^{18}O molecules) because $H_2{}^{16}O$ has a higher vapour pressure than $H_2{}^{18}O$. The condensate (rain) is enriched in ^{18}O relative to water vapour and the isotope composition of the *first* raindrops is similar to that of the ocean water. However, rain becomes progressively depleted toward higher latitudes and inland toward the centre of continents (Dansgaard 1964, Faure 1986) so in most cases fresh water, snow and ice are isotopically depleted relative to open ocean water. Ocean water with a salinity of 35°/oo has an $\delta^{18}O$ range of less than 1°/oo (Rye and Sommer 1980). However variations in salinity are accompanied by variations in δ_w in the same direction i.e., as salinity increases, $\delta^{18}O$ also increases. In the northern North Atlantic, a 10°/oo increase in salinity may be accompanied by as much as 5°/oo isotope enrichment (Epstein and Mayeda 1953, Craig and Gordon 1965).

Amongst the water masses of concern in this thesis ie., South Atlantic and South Indian Ocean Central waters, tropical and subtropical surface waters and Agulhas Current surface water, salinity variation is relatively small (34.5°/oo to 35.5°/oo) (Shannon 1985). The $\delta^{18}O$ value of coastal water samples at four sites of interest between Namibia and Mocambique have been measured. These sites are representative of the range of water types which influence the areas under study. The data show no significant difference between sites (Talma pers comm.) and the average value of δ_w is 0.3°/oo ± 0.3°/oo. These data are not, however, representative of variability between the microhabitats. Marine molluscs growing at or near to river mouths may yield oxygen isotope values which are depleted relative to that expected for equilibrium precipitation. Also, a few authors have expressed concern over the hourly-scale oxygen isotope variability of rock-pool water which may provide a refuge for intertidal molluscs (Chinzei *et al.* 1987). No time-series of oxygen isotope variability in these micro-environments is yet available. However, large diurnal fluctuations in oxygen concentration (up to 20 ppm) and water temperature (greater than 10°C) have been recorded in inter-tidal rock pools on the South African coast (Huggett and Griffiths 1986).

Chronological variability

Given that evaporation and precipitation are processes which significantly affect the oxygen isotope ratio of sea water, it follows that the growth and decay of terrestrial glaciers and polar ice sheets seasonally or over millenia as a result of these processes, will contribute to the per mil variability of oxygen isotopes in sea water through time. Emiliani (1955,1966) took this into account when making the first direct estimates of the temperatures of ancient oceans. However, his assumption of a 0.4°/oo change in $\delta^{18}O_w$ between glacial and interglacial oceans was challenged by Shackleton (1967, 1977) and Shackleton and Opdyke (1973) who suggested that glacial values were between 1.4°/oo and 1.6°/oo heavier than today based on the isotope composition of benthonic foraminifera. The $\delta^{18}O$ value of ancient skeletal carbonates therefore cannot be interpreted solely in terms of ocean temperature.

Our inability to directly measure the oxygen isotope values of palaeowaters remains the most serious problem when using the oxygen isotope technique as a palaeothermometer. In response, various alternative techniques have been developed to quantify marine palaeotemperatures including transfer functions (Imbrie and Kipp 1971, Morley 1977), internal isotope thermometry using the temperature-dependent fractionation between aragonite and calcite (Sommer and Rye 1978, Rye and Sommer 1980; Horibe and Oba 1972) and the temperature-dependent mineral composition of mollusc shells (Dodd 1963, 1964, Cohen and Branch 1992, Cohen *et al.* 1992). Another approach to solving the δ_w problem is to estimate its value at the time period of interest. It is generally agreed (based on the early work of Shackleton 1967) that oxygen isotope records of the deep ocean reflect the changing isotope composition of sea water, in response to changes in global continental ice volume, much more than they do temperature variations. Hence, they are also considered a good first approximation of the glacio-eustatic component of sea-level change. Similarly, the glacio-eustatic component of sea-level change can be scaled to $\delta^{18}O_{seawater}$ using the calibration of 0.1°/oo per 10 m change in sea-level (Shackleton and Opdyke 1973). The $\delta^{18}O$ value of the global ocean since 18 000 yr BP was calculated by Fairbanks (1989) using a sea level curve derived from Barbados coral reefs and other Carribean island locations. The temporal resolution for the Holocene is greater in this curve than in those derived from sediment cores and I therefore refer to these data for comparison with the isotope records constructed in this thesis (Chapters 6 and 7).

3.4 General Sample Preparation and Isotope Measurement

Successful application of the palaeotemperature method depends on the very precise measurement of small differences in $^{18}O/^{16}O$ ratios. Substituting for t°C in the palaeotemperature equation shows that a temperature change of 1°C, which is significant for interannual sea surface variability, leads to a change of only about 0.2°/oo in the oxygen isotope composition of $CaCO_3$. The precision in the measurement of δ must therefore be about 0.1°/oo.

A procedure for obtaining reproducible CO_2 samples from inorganic precipitates was devised by McCrea (1950). Subsequent modifications to the McCrea technique (Shackleton 1974) and to Nier's design of the mass spectrometer (Shackleton 1965), and more recently, the development of automated carbonate analysis (for example, the VG "Isocarb" and the "Kiel device") and computerized mass spectrometery, has enabled high precision (<0.02°/oo) analysis of many samples in a shorter time (Hoefs 1987). However, the basic procedure followed by all laboratories regardless of the instrumentation available, is standard and can be divided into three stages:

1. Organic matter is removed either by roasting *in vacuo* (Shackleton 1973,1974) or digesting the powdered sample in sodium hypochlorite (Emiliani 1966).

2. The carbonate sample is then digested in 100% phosphoric acid either at 25°C or 90°C to evolve CO_2 gas, from which water vapour and traces of atmospheric nitrogen are removed by cryogenic distillation (McCrea 1950).

3. The cleaned CO_2 sample is introduced to the mass spectrometer wherein its isotope composition is compared with that of a laboratory standard gas. The raw δ value is corrected to PDB (McKinney *et al.* 1950).

Potential errors in the isotopic measurement will occur mostly during the preparation of the CO_2 gas before it is introduced into the mass spectrometer. Different methods used for the removal of organic material (Savin *et al.* 1975), grinding of the carbonate sample (Emiliani 1966), grain size distribution (Fritz and Fontes 1966) and strength of the phosphoric acid (McCrea 1950) are all reported to affect the isotopic composition of the sample to varying degrees. The $CaCO_3$ crystals in mollusc shells are imbedded and enveloped in an organic, proteinaceous matrix which may contribute between 5% and 20% of the total shell weight. Prior to acidification, the organic component is removed either by reacting with sodium hypochlorite or sodium peroxide, or by roasting the sample under vaccuum. Savin *et al.* (1975) suggested that sodium hypochlorite or "chlorox" depleted the original isotope value by up to 0.3°/oo and

Weber *et al.* (1976) expressed concern that chlorox treatment alone cannot remove all organic matter present in biogenic carbonates. However, the legitimacy of these findings are debatable as many such analyses (including that of Killingley (1981), who soaked shells in hypochlorite before boiling them!), achieve accurate and reproducible results (Shackleton, pers comm.). Emiliani (1966) evaluated different preparation techniques and concluded that whereas the absolute values of samples may vary with the technique, the reproducibility of the resulting analyses remained the same. If one considers that the final result, i.e. the isotope value obtained, is a relative rather than absolute value, then consistency and reproducibility are the critical factors.

3.5 Procedures used in this thesis for shell sample preparation and isotope analysis

In this study, preparation of shell samples, measurement of the oxygen isotope composition of cleaned CO_2 gas, calculation of the raw isotope values relative to the PDB standard and conversion of $\delta^{18}O_{PDB}$ to isotopic temperature follow the prescribed methods and equations. This project was the first in the Archaeometry Laboratory at the University of Cape Town, to concentrate on the oxygen isotope analysis of skeletal carbonates. In the early stages of the project, sample preparation procedures were adapted from those already in use in the laboratory for the analysis of bone mineral (apatite) and bone collagen (Lee Thorp 1989, Sealy 1986). These methods were appropriate for the treatment of fairly large subsamples of whole shell powders. However, as the project progressed and the need arose to adopt a serial sampling technique, a different method, described by Shackleton (1974) for the treatment and handling of small samples, was introduced. A detailed description of laboratory procedure is given below.

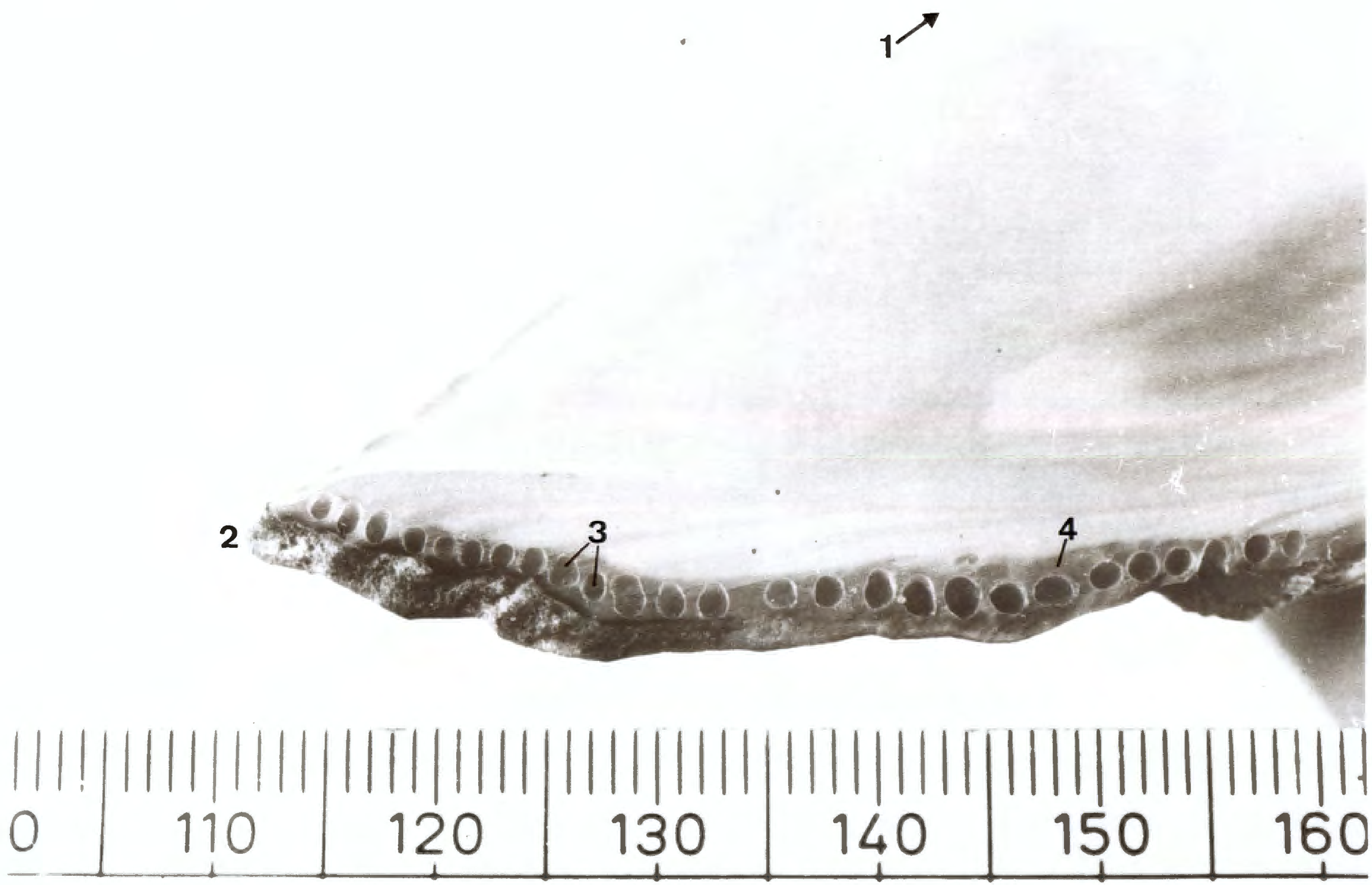
The dorsal and ventral surfaces of whole shells were cleaned using a soft toothbrush. In cases when live animals were collected, the animal was removed by cutting through the adductor muscles along the muscle scar. All shells were sectioned longitudinally with a water-cooled diamond saw. For whole-shell samples (*Patella granatina* and *Patella granularis*), a 5 mm-wide section was cut through the apex from anterior to posterior margin. Light polishing (260 μm diamond grit) of the exposed dorsal surface removed all surface flora (e.g. coralline algae) and grit which could have contaminated the sample and altered the isotope signal. The section was then ground in a Spex Model 7600 freezer mill under liquid nitrogen for three minutes. Intercrystalline organic material was removed using approximately 40 ml of 2% (v/v) sodium hypochlorite ($NaHCLO_3$) solution. The mixture was stirred throughout the reaction until effervescence ceased, usually after twelve hours. After centrifuging, the supernatant was discarded and the powder alternately washed and centrifuged until the supernatant was neutral. The shell powder was then freeze-dried overnight.

Approximately 15 mg of powder was weighed and introduced into a reaction vessel. The average vessel was about 10 cm long and 1.5 cm in diameter. Following the McCrea (1950) method, 3-4 ml of 100% phosphoric acid (H_3PO_4) was introduced into the vessel side-arm and evacuated. The sealed vessel and its contents were then placed in a waterbath at 25°C for five minutes to allow the acid to reach this temperature. The acid was then tipped into the main body of the vessel and allowed to react with the shell powder at 25°C. The reaction was completed after twelve hours. Water formed during the reaction and any traces of atmospheric nitrogen remaining after initial evacuation of the vessel were removed by cryogenic distillation, using liquid nitrogen and a slurry of ethanol and dry ice in a stainless steel vaccuum line. Each clean CO_2 sample, sealed in a glass pyrex tube, was then introduced to the laboratory VG Micromass 602E dual-inlet ratio mass spectrometer. $^{18}O/^{16}O$ ratios were measured against a secondary reference standard CO_2 calibrated against NBS standards 16, 17, 18, 19 and 20. $\delta^{18}O$ values were calculated relative to the PDB standard according to equation (1). Normal corrections for ^{17}O and machine factors were applied. Each batch of approximately 10 samples contained at least one intercomparison sample ("internal standard") of known value, acidified, cleaned and measured in the same way, on the same day. The weight and volume of this standard sample closely approximated those of the shell samples. Each sample in the batch was corrected against the known value of the internal standard. During the course of the project, NBS 20, NBS 19 and an internal laboratory marble standard, calibrated against NBS 19, were used as intercomparison samples.

Shells from which isotope profiles were constructed were treated slightly differently for practical purposes according to the method described by Shackleton (1974). *Patella tabularis* shells were sectioned longitudinally through the front rib and apex (Fig. 3.1). The calcite layer in the ribs is thickest and therefore easier to sample. The dorsal surface along the edge of the section was polished to remove surface contaminants. This step was most important as bits of encrusting algae tended to fall into the sample powder as the shell was drilled. The exposed vertical surface of the section was also polished slightly, making the structure easier to identify and follow. The shell was then washed and dried at 50°C. Shells are good heat conductors and it is essential to keep the oven temperature low at this stage to prevent alteration of the isotope composition or shell mineralogy. The drilled powder should be kept dry to prevent exchange of oxygen isotopes with water during roasting. A series of holes were then drilled into the exposed inner calcite layer (m+1) from the apex toward the margin (Fig. 3.1).

A diamond-tipped drillbit of 1 mm diameter was used to take samples approximately 1mm apart. I took care to avoid areas bored by small worms or algae or any areas of shell which had obviously been repaired by the animal. Between 1mg and 3mg of powder from each drilled hole was transferred to glass boat in a specially-designed sample holder. Approximately 13 samples at a time were roasted in a vaccuum oven at 470°C for 30 minutes. The oven was kept under vaccuum until the temperature dropped below 100°C. Each sample was then transferred to a reaction vessel and the procedure continued as described above. Initially, samples were acidified whilst in the boats but I found that the acid was too thick to penetrate the small boats within a reasonable time.

Fig. 3.1. Overleaf. Longitudinal section from the apex (1) to the margin (2) through a *Patella tabularis* shell, showing serial samples (3) drilled out from along the inner, m+1 calcite layer (4). Successive samples are spaced about 1 mm apart and both the diameter and depth of each hole are about 1 mm.



1
2
3
4
0
110
120
130
140
150
160

3.6 Ocean temperature records in the oxygen isotope composition of mollusc shell carbonate.

The wealth of information now available on past oceanic environments has been generated largely through analyses of benthic and planktonic foraminiferal tests preserved in deep-ocean sediments. Mollusc shell material has been used in relatively few studies of palaeoceanic conditions (Seward 1978, Shackleton, in Singer and Wymer 1982, Stevens and Vella 1981, Saltzman and Barron 1982, Koerper *et al.* 1985, Donner and Nord 1986, Chinzei 1987, Krantz *et al.* 1987, Muhs and Kyser 1987, Krantz 1990, Chung-Ho and Tsung-Ren 1987) probably because the archaeological and raised beach deposits in which they accumulated in large numbers did not form long, uninterrupted sequences. Furthermore, species found in these deposits usually inhabit shallow coastal environments in which localised changes in physical oceanography may find dominant expression over more regional ones.

However over the past decade, detailed examination of the oxygen and carbon isotope record in living molluscs has directed attention to the oceanographic and ecological information contained within them. The serial-sampling technique has yielded information about the rate and seasonality of shell accretion in living populations (Bianucci and Longinelli 1982, Krantz *et al.* 1984, Brand *et al.* 1987, Romanek *et al.* 1987, Margosian *et al.* 1987) and also the seasonality of shellfish collecting by prehistoric hunter-gatherers (Shackleton 1970, 1973, Killingley 1981, Deith 1983, 1985, Bailey *et al.* 1983,). Recently, Krantz *et al.* (1987) and Krantz (1991) have applied the technique to fossil molluscs from now-exposed mid-Atlantic Pliocene and Pleistocene terraces.

The analytical system described in section 3.5 makes the oxygen isotope analysis of mollusc shells relatively straightforward. However, there are several difficulties inherent in the application of the method to the reconstruction of past sea temperatures. Many of these are species-specific and it is therefore a considerable advantage to have access to contemporary specimens.

Data from contemporary specimens should be interpreted in the light of the following considerations:

equilibrium precipitation does occur. In coastal environments where the seasonal temperature range is large or the availability of nutrients for growth is highly variable (for example, in upwelling regions), growth rate and therefore shell growth rate may be optimal during some months and minimal or even cease during others. The shell can only record environmental temperatures whilst it is growing. Therefore, the temperature record in seasonal growers will be biased toward the faster growth season; temperatures of the slow-growth season, usually winter, will be under-represented and the average isotopic temperature will not be representative of the true annual average. The annual growth rate of all molluscs slows considerably with age, implying that the resolution of different months or seasons in the shell profile should become increasingly small with age and any bias toward seasonal growth may be exaggerated. The obvious answer to this problem is to use relatively young specimens in which the rate of shell deposition is greatest. Krantz *et al.* (1987) consider the mid-point between maximum and minimum values in the shell profile as the best estimate of the average annual water temperature. I have adopted this approach when constructing temperature profiles in *Patella tabularis* shells (Chapter 4) and show that it is an appropriate way to represent the seasonal range.

Shell mineralogy

The classic Epstein palaeotemperature scale (Epstein *et al.* 1953) was calibrated using isotope data from aragonitic and calcitic molluscs, with no consideration of shell mineralogy. There is evidence to show that the oxygen isotope fractionation between aragonite and water is different from that between calcite and water, for both inorganically precipitated (Tarutani *et al.* 1969) and biological (Horibe and Oba 1972, Sommer and Rye 1978, Grossman and Ku 1986) carbonates. Theoretical calculations based on observed vibrational frequencies of the carbonate in each polymorph predict an oxygen isotope enrichment of 0.79‰ in aragonite relative to calcite at 25°C (O'Neil 1969). Analyses of inorganic precipitates and of foraminifera appear to support theoretical predictions. The magnitude of the measured difference, on average about 0.6‰ (Tarutani *et al.* 1969, Grossman and Ku 1986) corresponds to a temperature difference of more than 3.5°C if Epstein's palaeotemperature equation is used. It should be noted, however, that the data upon which this "average" estimate are based yielded high standard deviations in each case. Grossman and Ku (1986) reported a standard deviation of 0.3‰ whilst Tarutani (*et al.* 1969) based their

Isotopic equilibrium

The isotopic composition of the shell should vary with temperature according to the palaeotemperature equation i.e., the shell should be accreted in equilibrium with sea water. Isotopic disequilibria have been observed and reported in several invertebrate classes (Lowenstam and Epstein 1954, Weber and Raup 1966, Wefer and Berger 1991). Urey *et al.* (1951) described the processes causing isotope disequilibria as "vital effects", referring to biological interference. McConnaughey (1989) makes a useful distinction between kinetic and metabolic isotope effects which cause isotopic disequilibrium. Kinetic effects are a consequence of rapid skeletogenesis. If crystal growth is so rapid that oxygen isotopes do not equilibrate between $CaCO_3$ and the extrapallial fluid, the isotopic composition of the skeletal carbonate will be independent of either temperature or the isotopic composition of the surrounding seawater. Since kinetic fractionation affects both the oxygen and carbon isotopes in the same direction, its effect is apparent as a strong correlation between the two. Metabolic effects may be observed if the isotopic composition of the extrapallial fluid is distinct from that of seawater. Thus, equilibrium may be achieved but not with seawater. McConnaughey (1989) suggests that this effect is small in comparison with the H_2O flux between the organism and seawater and for this reason is unlikely to become apparent. However, in molluscs whose shells function as a barrier against dessication and are able to retain water whilst sealing the animal against the environment, metabolic effects must be considered in the interpretation of the isotope record. Data available for a wide range of contemporary molluscan taxa from different environments indicate that in general, shell accretion does occur at or near equilibrium (Wefer and Berger 1991). For some species, e.g. *Strombus gigas* (Wefer and Killingley 1980), apparent disequilibrium precipitation results in a constant displacement of the observed isotope value from that expected at the growth temperature. However, disequilibrium precipitation does not necessarily preclude the species from use as a palaeothermometer provided that the departure does not change with temperature or growth rate and that other prerequisites for employing the technique are satisfied by the species.

Species-specific growth patterns

Ideally, the correspondence between isotopic temperature and "real" temperature should be so close that maximum, minimum and mean habitat temperatures can be tracked in the shell. However, aspects of the species ecology may prevent this even if estimate on only four out of the twenty-four samples originally analysed (std = 0.25°/oo). Other laboratory experiments (Epstein *et al.* 1953, Tarutani *et al.* 1969, Horibe and Oba 1972) appear to have been compromised by problems with sample reproducibility and possibly species-specific "vital effects" and there is, as a result, little consensus in the literature about the magnitude or direction of the isotopic fractionation between aragonite and calcite in biological systems.

If the isotopic equilibrium between calcite and water differed from that between aragonite and water by a constant amount of 0.6°/oo, then for aragonitic shells or calcite/aragonite mixtures the palaeotemperature equation could simply be adjusted by this amount, as in Wefer and Killingley (1980). However, Sommer and Rye (1978) showed that the difference in oxygen isotope ratios between aragonite and calcite foraminiferal pairs increased with decreasing temperature demonstrating that, at least in this case, the offset is not constant. Grossman and Ku (1981) and Grossman (1982) have developed an aragonite-water fractionation equation which has been applied successfully in studies using aragonitic molluscs (Romanek *et al.* 1987, Jones *et al.* 1983) and may go some way to resolving this problem.

Diagenesis

Mineralogical and chemical changes may occur in the $CaCO_3$ skeleton after death and deposition of the organism which preclude the application of isotopic or other palaeotemperature techniques. Factors influencing the probability and magnitude of change include original shell mineralogy, the post-depositional environment and time. Aragonite is metastable under surface temperatures and pressures (Deer *et al.* 1962) and is more susceptible to diagenetic alteration than is calcite. Usually, aragonitic layers are preferentially dissolved from the shell leaving cavities which may be later filled with reprecipitated calcite (Bathurst 1964, Friedman 1964) (Fig. 3.2) but aragonite may invert to calcite *in situ* with no loss of material or change in crystal structure (Land 1967). In this thesis, oxygen isotope measurements were made only on archaeological shells and shell layers in which the original mineral (shown by examination of living specimens) was calcite, in which the original shell crystal structure was preserved and which had remained buried in the archaeological deposit since death, as exposure may result in rapid oxidation and loss of the organic matrix (Hill 1980, in Lee-Thorp 1989). In a preliminary study of archaeological shell material, Cohen (1987) examined the microstructure, crystallinity and oxygen isotope

Fig. 3.2. Partial dissolution of the aragonite layer seen on the ventral surface of a *Patella granularis* shell from Elands Bay Cave. The shell is approximately 10 000 years old.

composition of calcitic shells from several depositional layers in Eland's Bay Cave and found no evidence of diagenetic alteration.

CHAPTER 4

AN ISOTOPIC TEMPERATURE RECORD IN RECENT *PATELLA* SPECIES FROM THE COAST OF SOUTH AFRICA.

4.1 Introduction

The shells of a variety of intertidal mollusc species are preserved in Late Pleistocene and Holocene archaeological deposits along the coast of South Africa. Numerous studies have demonstrated the potential of using stable oxygen isotope ratios in mollusc shell carbonate as palaeotemperature records and these middens can be considered a unique source of information about the recent history of coastal temperature variability in the region. In many mollusc species, the process of shell formation favours the equilibrium precipitation of oxygen isotopes (Wefer and Berger 1991) and consequently data are available for a variety of extant taxa inhabiting a wide range of environments. Nevertheless, the quality of the isotopic record of temperature is determined only by equilibrium precipitation. Accuracy and resolution are more likely to be determined by species-specific characteristics including habitat, zonation, behavioural aspects, growth rate and the temperature range favourable for growth. Shell mineralogy is also species-specific.

To date, the oxygen isotope composition of some local molluscan species have been studied in order to determine their potential as palaeotemperature indicators (Shackleton 1973, 1981, Donner and Billstrom 1988, Talma *et al.* 1992). However, limited sample size, inadequate sea temperature records and contradictory results have rendered the majority of available data inconclusive. Furthermore, studies of mussel shells are not particularly useful as shells of the common species seldom survive in archaeological deposits in suitable condition for palaeotemperature work. Nevertheless, Donner and Billstrom (1988) reported that the oxygen isotope composition of the outer shell layers of the mussels *Choromytilus meridionalis* and *Perna perna* generally reflected the temperature differences between west and south coast sites but not necessarily the absolute temperature of the seawater in which they were accreted. In a subsequent study, Talma *et al.* (1992) showed that the isotope ratios of whole-shell samples of *C. meridionalis* were invariable in habitats of varying temperature whereas $\delta^{18}O$ profiles through the outer calcite layer reflected annual changes in seawater temperature. Shells of living *Patella tabularis* and *P. perna* were collected and studied by Shackleton (1973b). The $\delta^{18}O$ variations through the shells of both species reflected the seasonal cycle of ambient seawater temperatures. The range of $\delta^{18}O$ values recorded by each species were remarkably similar considering that the shell layers analysed were of different mineral composition. In both species, the isotope values were enriched by approximately 1°/oo relative to that expected from sea temperature data collected 150km to the east of the study area. In this chapter, a study of the isotopic composition of three limpets, *Patella granatina*, *Patella granularis* and *Patella tabularis* (Fig. 4.1) is reported. The study was undertaken in order to examine the relationship between the isotope signal and habitat temperature and assess the value of these particular species as environmental indicators. Neither *P. granatina* nor *P. granularis* have been examined previously. In this study of *P. tabularis*, the relationship between the isotope data and seawater temperature was re-examined using temperature records for the immediate vicinity of the collection site.

Fourteen species of the genus *Patella* are found along the coast of southern African today, of which six are commonly found in the archaeological deposits of South Africa. Local species diversity is high compared with Britain, where three species are recognised. New Zealand and the Canary Islands each support two species (Branch 1971, Bosman *et al.* 1987). In general, isotopic studies of molluscs have concentrated on bivalves including mussels and clams. Despite the lack of comparative isotopic data, the reasons for choosing local *Patella* species as subjects for this study are well-founded. The genus dominates the composition of intertidal communities along the present-day coastline and is abundant in archaeological and raised beach deposits. The species composition of archaeological deposits is diverse but limpets and mussels feature most prominantly. Generally, the shells of limpets are well-preserved throughout the Holocene sequences relative to the more friable shells of mussels and clams. Furthermore, a considerable amount is known about the biology of several extant southern African Patellidae, most notably those inhabiting the west coast. The zonation, geographical distribution, growth patterns and behaviour of several species are well-documented (Branch 1971, 1974, 1975, 1985; Bosman and Hockey 1988a,b and Eekhout *et al.* 1992) and provide information about species-specific characters which may contribute to the isotope signal.

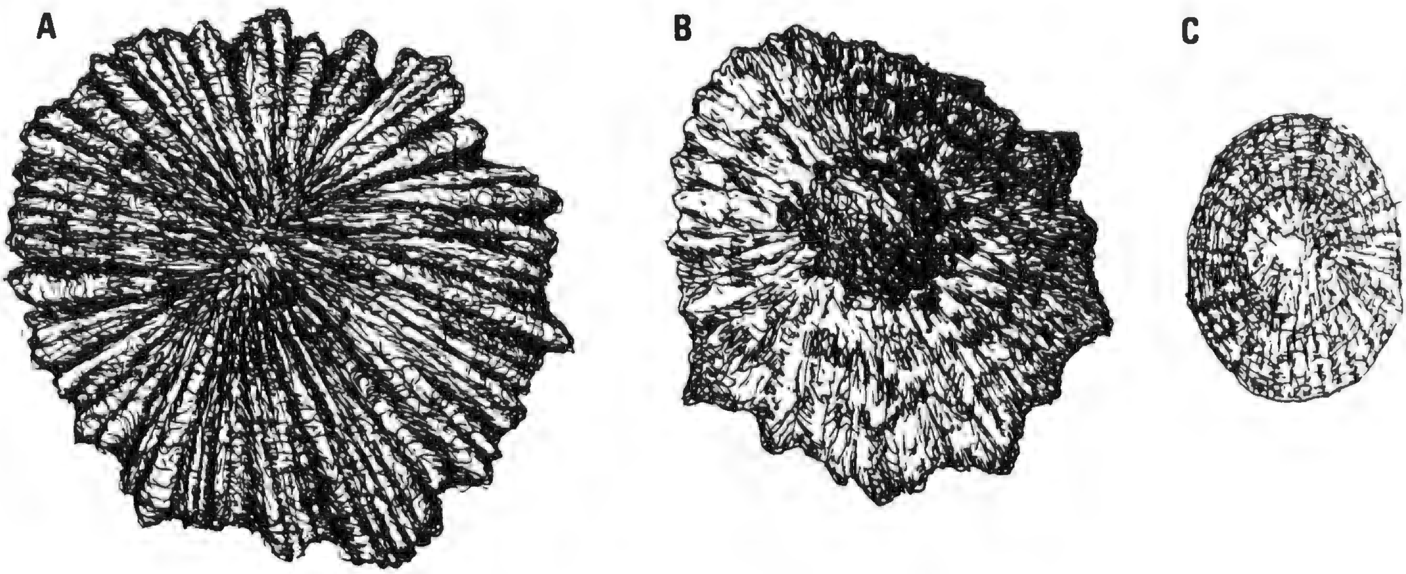


Fig. 4.1. External shell characteristics of the limpet species used in this study: sub-adult *Patella tabularis* (A), adult *Patella granatina* (B) and adult *Patella granularis* (C). (Mag. X 0.8). Illustrations by Timothy Hart, Archaeology Department, University of Cape Town.

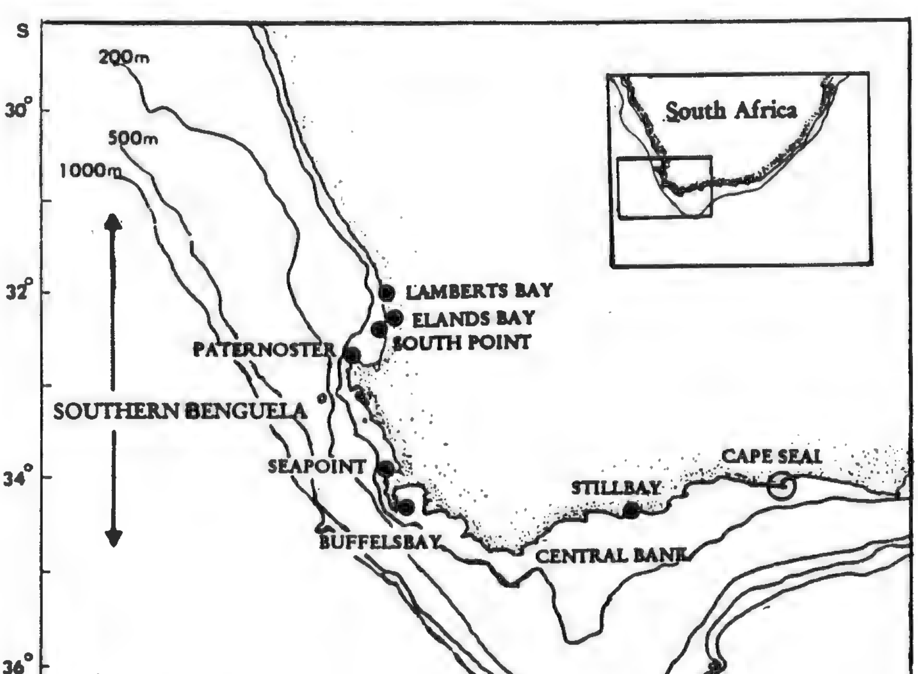


Fig. 4.2. Sites in the southern Benguela and Agulhas Bank coastal region where living Patellids were collected for isotopic and mineralogical analyses.

4.3 Methods

Two analytical techniques were employed in this study of contemporary specimens. The oxygen isotope composition of shells of all three species was measured. Sub-samples of whole shell powders of *P. granatina* and *P. granularis* were analysed the results were assumed to represent an average of between two and three years of sea surface temperature, the average age of the samples. This approach was considered appropriate for this region because, in the coastal southern Benguela, sea surface temperatures are not markedly different between summer and winter (Taunton-Clark and Kamstra 1988). Furthermore, summer and winter months are not characterised by warm and cool sea temperatures. In some years, surface temperatures are higher during summer than during winter, in other years they are lower and could only be distinguished in a palaeotemperature record on the basis of daily-scale variability. Serial samples were taken from the apex to the margin of calcitic shell layers of the south coast species, *P. tabularis* in order to extract seasonal temperature data. In contrast to the southern Benguela, surface temperatures on the Agulhas Bank *are* markedly different between summer and winter, and climatic events are most often identified in the interannual summer signal.

A second analytical technique, X-ray diffractometry (XRD) was employed to identify and quantify the mineral composition of *P. granatina* and *P. granularis* specimens. The shells of these species contain aragonitic and calcitic layers (MacClintock (1967) and the contribution of each polymorph to the whole-shell powder samples was identified in order to examine the effect of shell mineralogy on the oxygen isotope value.

Whole-shell sample preparation

Forty seven living *P. granatina* and *P. granularis* adults were collected from five sites along the west coast of South Africa: Buffelbaai, Seapoint, Paternoster, Elands Bay and South Point. (Fig. 4.2). Annual average surface temperatures vary between sites according to their proximity to upwelling centres and degree of shelteredness (bays) or exposure (capes). Sea surface temperature records for the infra-tidal region were available for three sites: Buffelsbay in False Bay, and Seapoint and Paternoster on the west coast. No records of inshore surface temperatures were available for Elands Bay and South Point at the time of this study. However, Sea Fisheries Research Institute placed a thermoscript at the exposed site of Baboon Point in 1990 and these data were used to represent surface temperatures at South Point (Fig. 4.2). VOS (Voluntary Observing Ships) data averaged over 10° squares were made available by the National Research Institute for Oceanology and used as a comparative record for Elands Bay. The average annual temperature recorded at these sites ranges from about 16°C at Buffelsbay where upwelling events are least frequent, to about 12°C at Baboon Point where upwelling may occur close to shore and its signature quickly become apparent at the sea surface. Nevertheless, the sea temperature data used here must be considered only as a guide to intertidal temperatures in each region because the origin of the data, the continuity of each record and timespans over which the data were collected are variable.

The shells were prepared for isotope analysis according to the method described in Chapter 3 and CO_2 gas analysed on a Micromass 602E spectrometer. $\delta^{18}O$ values were corrected to NBS-20 and converted to isotopic temperature using the equation of Shackleton (1974),

$$t\ °C = 16.90 - 4.38(\delta_c - \delta_w) + 0.10(\delta_c - \delta_w)^2 \qquad (1)$$

where δ_c = $^{18}O/^{16}O$ sample and δ_w = $^{18}O/^{16}O$ water. In this study, δ_w was taken to be 0.3°/oo (Talma pers. comm.). At each site where t is known, the expected $\delta^{18}O$ value of shells can be calculated by solving for δ_c which yields the following equation:

$$\delta_c - \delta_w = 21.9 - 3.162(31.06 + t)^{0.5} \qquad (2)$$

(Wefer and Berger 1991).

The precision on isotopic measurement achieved using the method outlined above, from acidification to the isotope analysis of cleaned CO_2 gas, is indicated by the average standard deviation between reference standard duplicates. In this study average deviations of ±0.12°/oo for oxygen and ±0.06°/oo for carbon were obtained on duplicate NBS-20 and accord with that obtained by Shackleton (1974) and others.

Serial sampling

A more detailed examination of the isotopic composition of *P. granatina* was undertaken at the Godwin Laboratory, Cambridge University in 1991. A single shell was collected in September 1989 near the sheltered west coast site of Lamberts Bay (Fig. 4.2) where sea surface temperature records indicated a strong seasonal signal. An oxygen isotope profile was constructed by sampling at successive 1 mm intervals through the outer calcite layer (m+2) which was visible between shell lengths of 54 mm and 74 mm. The analytical procedure employed in this laboratory follows that of Shackleton (1974) and $\delta^{18}O$ values were corrected to an internal laboratory standard calibrated against NBS-19. Independent growth rate data for the species (Branch 1974) were used to estimate the age of the animal at various sampling points. An intertidal sea surface temperature record for Lamberts Bay between January 1988 and December 1989 was supplied by the Maritime Weather Office at DF Malan Airport.

In January 1993, specimens of *P. tabularis* were collected from the site of Stillbay on the western Agulhas Bank (Fig. 4.2) for which coastal sea temperature records were available from 1986 to 1993. No temperature data were available from the seaward side of the Robberg Peninsula where Shackleton (1973) collected specimens for the original study. The samples were prepared and measured as described in Chapter 3. $\delta^{18}O$ values were corrected to an internal marble calcite standard (NM calcite) calibrated against NBS-19.

X-Ray Diffractometry

The mineralogical composition of *P. granatina* and *P. granularis* shells was assessed by X-ray diffractometry (XRD). Subsamples of whole shell powders of selected adult individuals from all sites were analysed on a Philips goniometer employing a nickel-filtered copper target at 45kV and 40mA. Receiving and divergent slits were set at 1°.

4.4 Results

Shell Mineralogy

The X-ray diffraction traces (Fig. 4.3) showed that the *P. granatina* samples were primarily calcitic whereas the *P. granularis* powders contained both calcite and aragonite. An estimate of the mineral proportions in shells from each site was obtained using Lowenstam's (1954a) calibration curve. The mineral composition of *P. granatina* shells remained constant (<5% aragonite) between sites whereas that of *P. granularis* did not (Table 4.1). In the latter species, a positive correlation was apparent between habitat temperature and aragonite content of the shell. Shells collected from the warmest site of Buffelsbay in False Bay contained the greatest proportion of aragonite (45%) whereas those inhabiting the cooler west coast sites were composed largely of calcite and only a small percentage of aragonite was measured in the shells (8%).

Oxygen isotope values in whole-shell powders

In Table 4.1, mean oxygen isotope values of all whole shells of *P. granatina* and *P. granularis* collected from different sites are shown. These data are plotted against recorded mean temperatures in Fig. 4.4 and the original values listed in Appendix 4.1. The data are compared with the expected oxygen isotope composition of calcitic shells accreted in isotopic equilibrium with seawater at the recorded temperature, according to equation (2). Both species reflected the temperature differences between sites. The correlation between actual and derived temperatures was slightly stronger for *P. granatina* ($r^2=0.88$, $p<0.001$) than for *P. granularis* ($r^2=82$, $p<0.001$). There was a strong co-variance between species ($r^2=0.99$, $p<0.001$) although *P. granatina* was isotopically lighter except at the coldest site, and *P. granularis* isotopically heavier than expected for the equilibrium precipitation of $CaCO_3$ at the recorded temperature. At all sites, *P. granularis* was isotopically heavier than *P. granatina* by an average value of $0.46^o/oo$. However, this difference was not constant between sites and tended to decrease as habitat temperature decreased, and as the amount of aragonite in the shell of *P. granularis* decreased. At all sites, the intra-specific isotopic variation was lower in *P. granatina* (on average $\pm 0.13^o/oo$) than in *P. granularis* (on average $\pm 0.36^o/oo$). There was no significant correlation between individual shell size and its isotope

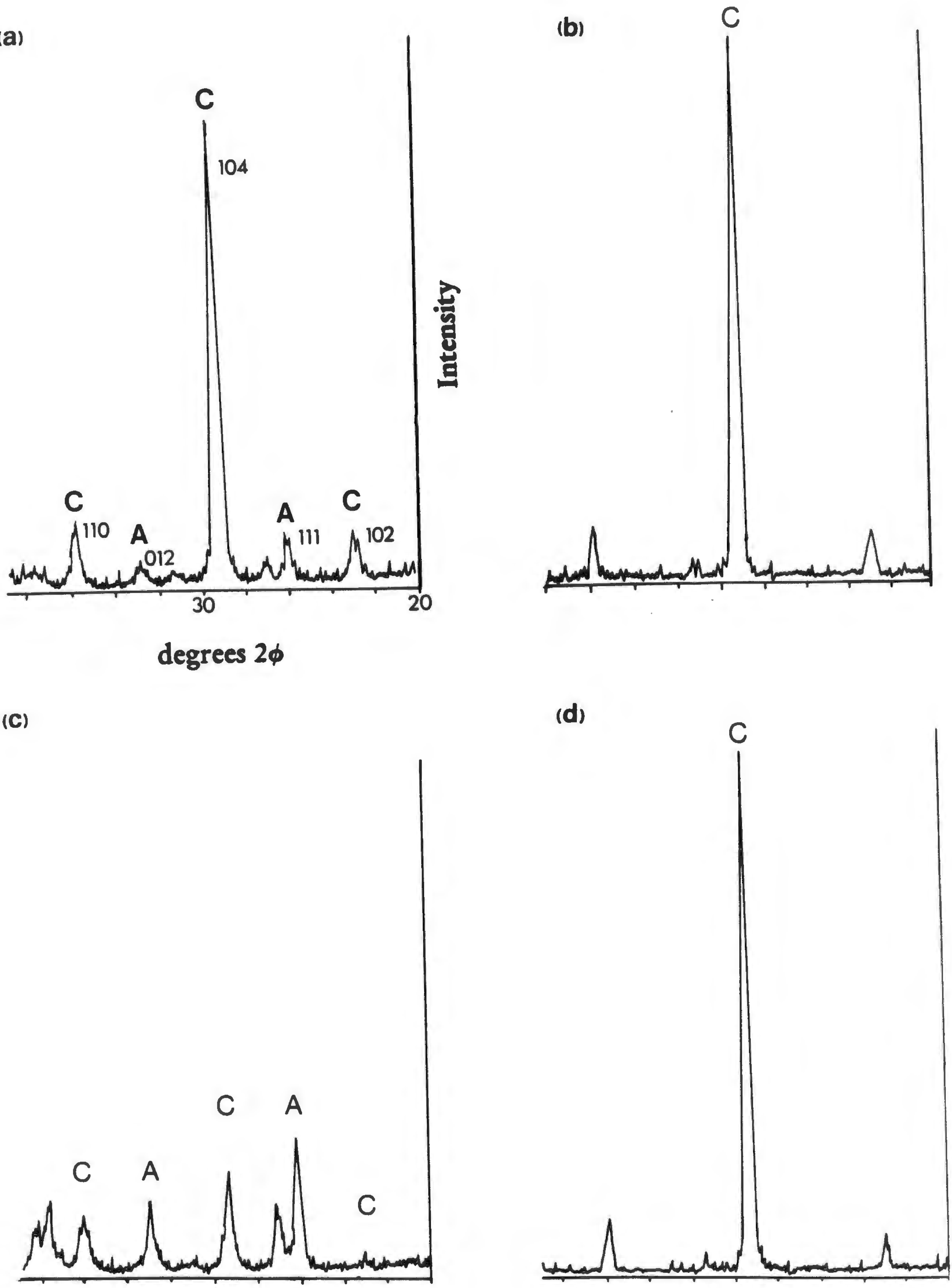


Fig. 4.3. X-ray diffraction traces of whole-shell samples of *P. granularis* from Seapoint (a) and Buffelsbay (c) and *P. granatina* from Seapoint (b) and Buffelsbay (d). C = calcite and A = aragonite. The heights of the 110 and 104 hkl reflections are related to the concentration of aragonite and calcite in the shell (Lowenstam 1954a) although the exact relationship between peak height and quantity is different for each polymorph.

TABLE 4.1: Actual recorded temperatures at each collection site, expected $\delta^{18}O$ values according to equation (2), averaged, measured $\delta^{18}O$ values of whole-shell powders of *P. granatina* and *P.granularis*, and sea temperatures derived using equation (1). Estimated % aragonite in *P. granularis* shells from each site are also given.

Collection Site	t (°C)	Expected $\delta^{18}O$	Species	No. of Samples	Measured $\delta^{18}O$	Derived t(°C)	% Aragonite
Buffelsbay[1]	15.86	0.54	*P.granatina*	4	0.35 (±0.18)	16.68	<5
			P.granularis	7	0.99 (±0.28)	13.93	45
Seapoint[2]	14.52	0.85	*P.granatina*	6	0.60 (±0.09)	15.60	<5
			P.granularis	5	1.08 (±0.26)	13.54	14
Paternoster[2]	13.20	1.16	*P.granatina*	4	0.89 (±0.25)	14.35	
			P.granularis	7	1.33 (±0.27)	12.49	8
South Point[2]	12.42	1.30	*P.granatina*	5	1.43 (±0.07)	12.08	
			P.granularis	2	1.77 (±0.08)	10.68	8
Elands Bay[3]	13.69	1.05	*P.granatina*	5	1.01 (±0.04)	13.84	
			P.granularis	2	1.42 (±0.00)	12.12	14

[1] Seaweed Research Institute, Cape Town
[2] Sea Fisheries Research Institute, Cape Town
[3] National Research Institute for Oceanology, Stellenbosch

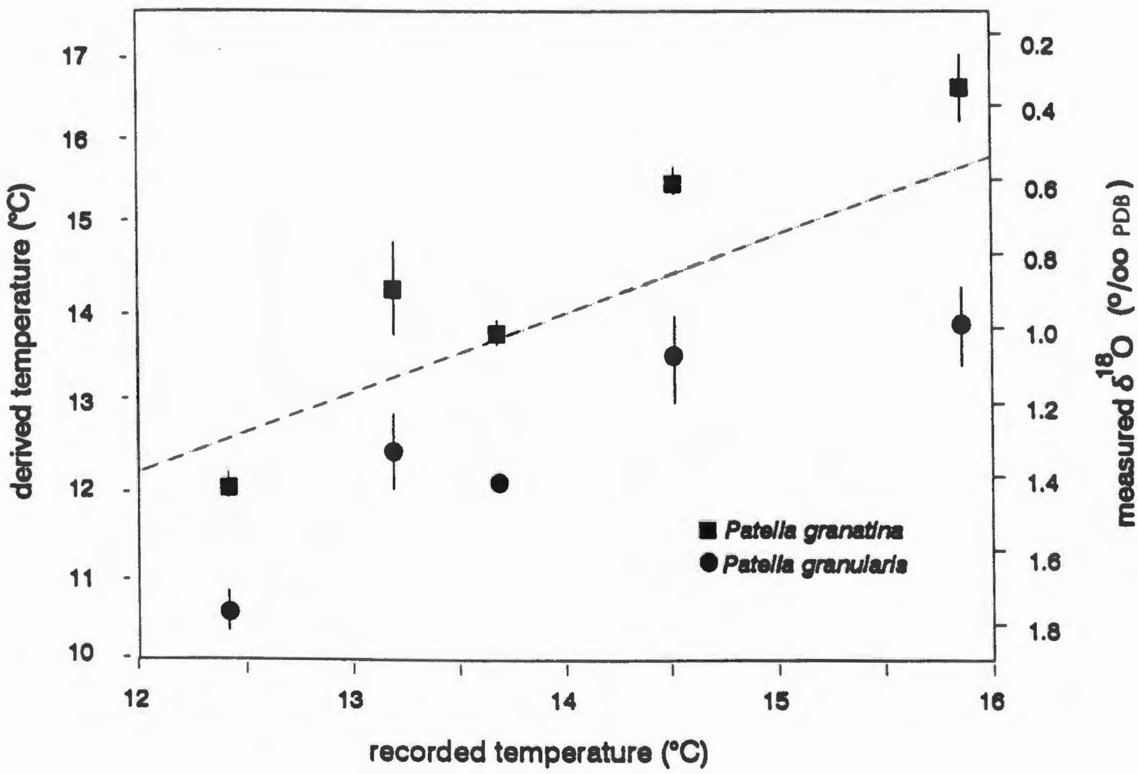


Fig. 4.4. Oxygen isotope ratios ($\delta^{18}O$) of whole-shell powders of *P. granatina* and *P. granularis* and derived temperatures, plotted against actual recorded sea temperatures. Mean values and standard errors are indicated. The dashed line indicates the values expected for $CaCO_3$ precipitated in equilibrium with seawater using a δ_w value of 0.3°/oo and equation (2).

value. Similarly, intra-specific variation was independent of habitat temperature. The correlation between $\delta^{18}O$ and the corresponding $\delta^{13}C$ for each measurement is also insignificant ($r^2=0.01$). Duplicate measurements were made on sixteen shell sample powders with an average standard deviation of 0.15°/oo. This means that the error associated with each sample value was 0.55°C.

Serial samples

The oxygen isotope profile constructed from the Lamberts Bay *P. granatina* shell is shown in Fig. 4.5B and compared with the average monthly recorded sea surface temperature at this site. The oxygen isotope values of the shell profile are listed in Appendix 4.2. Independent growth rate data for this species indicated that the last 17 months of the life of the animal were represented in the profile (Branch 1974) (Fig. 4.5A). The isotopic value of the sample taken at the shell margin was assumed representative of the sea surface temperature averaged over 1.4 months prior to the collection date (September 1989) and the profile is spaced along the X-axis according to the estimated age of the animal at specific sampling points. Intra-annual sea surface temperatures at Lamberts Bay between May 1988 and September 1989 were closely approximated by the $\delta^{18}O$ record in the shell. Isotopic temperatures derived for January 1988 and October 1988 were in good agreement with the actual temperatures recorded during these months, if the experimental error of 0.55°C was considered. The average isotopic temperature between May 1988 and September 1989, 13.34°C, closely approximated the real average temperature of 13.50°C. The isotopic depletion exhibited by whole shell powders of this species was not apparent in the isotope profile of this sample assuming a δ_w value of 0.3°/oo (as recommended by Talma pers. comm.). The isotope profile also provided information about shell growth. Clearly, this individual grew more-or-less continuously between May 1988 and September 1989 recording both summer and winter values, in agreement with the field data of Branch (1974). No obvious seasonal growth patterns were detected.

The $\delta^{18}O$ variations in the shells of living *P. tabularis* and recorded average monthly temperatures at Stillbay are compared in Fig. 4.6 and the oxygen isotope values in the shell profile are listed in Appendix 7.1. No independent growth rate data are available for this species and the spacing of isotope values along the X-axis is estimated. The present-day intra-annual sea surface temperature range at Stillbay is large. From January 1990 to January 1993, the average range between mid-summer and mid-winter

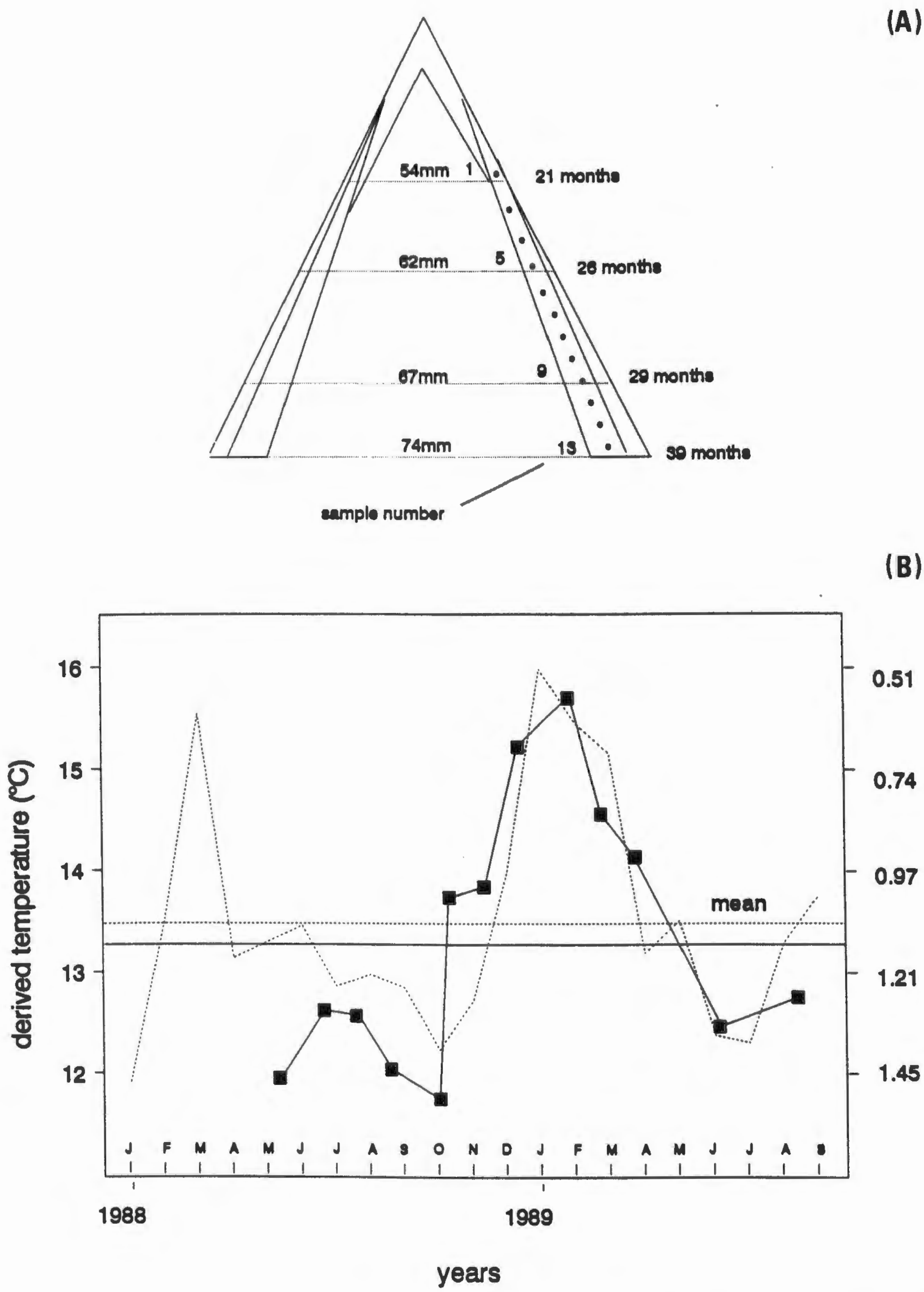


Fig. 4.5. Temperatures derived from the oxygen isotope profile values of a *P. granatina* shell (solid line) collected near Lamberts Bay in September 1989, plotted against actual temperatures recorded at this site (dashed line) (B). The spacing of isotope values along the X-axis was achieved by estimating the age of the animal at each drillhole using independent growth rate data for this species (A).

was 7.8°C. The effect of the Pacific El Niño on Agulhas Bank coastal waters resulted in above average sea surface temperatures in 1992 and 1993. This temperature elevation is apparent in the record. The $\delta^{18}O$ variations in living *P. tabularis* accorded with recorded averaged monthly temperatures at Stillbay and reflected in large measure the observed seasonal range. However, maximum and minimum $\delta^{18}O$ values were enriched by approximately 0.7°/oo relative to those expected for calcite equilibrium precipitation from seawater using Shackleton's (1974) palaeotemperature equation and a δ_w value of 0.3°/oo (Talma pers. comm.). Shackleton (1973) reported an enrichment of 1°/oo for this species relative to estimated surface temperatures at Robberg using a δ_w value of 0°/oo. Thus, isotopic temperature was recalculated using a δ_w value of 1°/oo (0.3°/oo+0.7°/oo), which as illustrated in Fig. 4.6, removes the offset. However, the average value of all samples remained lighter, by approximately 0.23°/oo (1°C), than the expected average isotope value between January 1990 and October 1993 (Fig. 4.6). The shape of the isotope profile indicated that when alive, the animal probably accreted shell throughout the year. However the rate of shell growth increases during the warm season and decreases during winter. Therefore, whereas the individual isotope values were too heavy, the mean isotope value is biased toward a lighter value.

4.5 Discussion

The oxygen isotope composition of the shells of all three species examined reflected the recorded temperatures. The isotope signals in whole-shell powders of *P. granatina* and *P. granularis* at different sites along the west coast reflected quite adequately the temperature differences between these sites. However, temperatures calculated from the isotope values were offset from the actual recorded temperature. Temperatures obtained from *P. granatina* shells were generally about 0.5°C warmer than actual temperatures whereas those obtained from *P. granularis* were cooler by about 1.5°C. The best available recorded temperature data were used in this study but should nevertheless be considered a relative guide rather than the absolute temperatures experienced by the animal. Records of intertidal temperature were not available for these sites and west coast and False Bay temperatures were measured in the infra-tidal zone which is expected to be slightly cooler than intertidal waters. Depleted $\delta^{18}O$ values of *P. granatina*, equivalent to water temperatures about 0.5°C higher than expected, probably reflect this difference between intertidal and infratidal conditions.

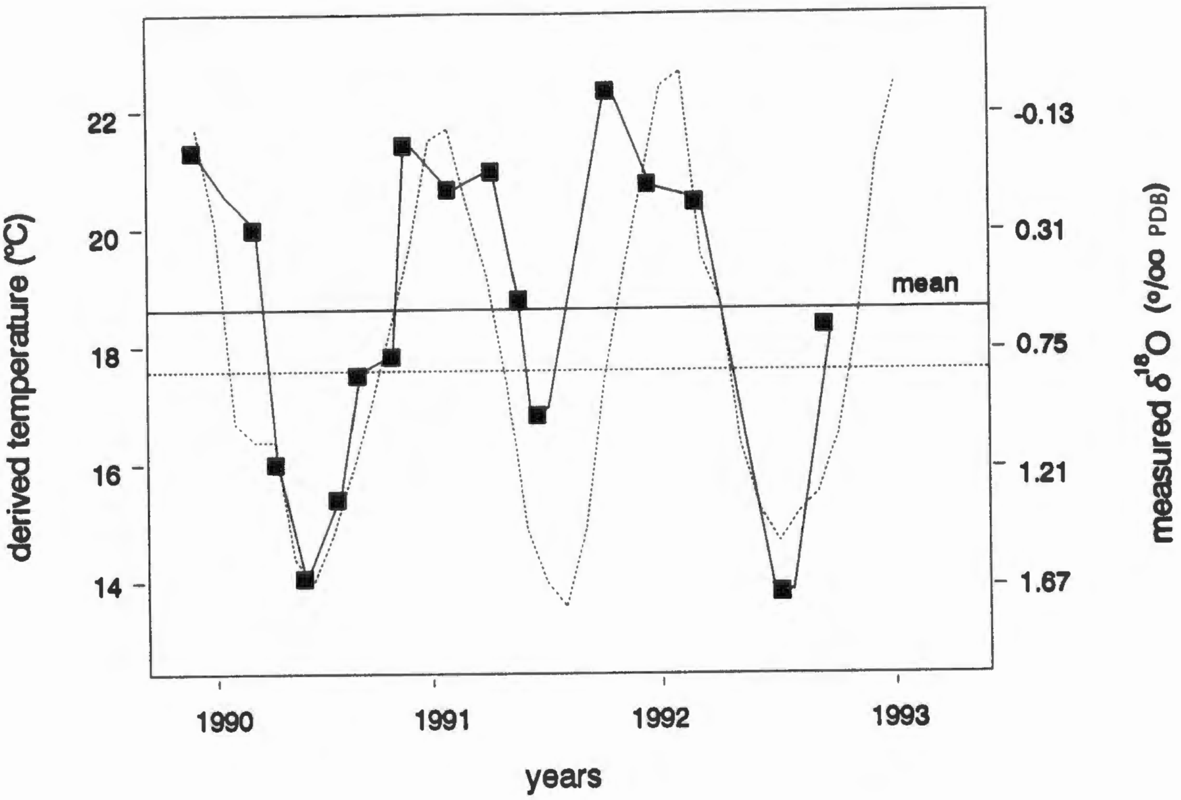


Fig. 4.6. The oxygen isotope profile and derived temperatures (solid line) from a living *P. tabularis* shell collected at Stillbaai in January 1993, plotted against actual temperatures recorded at this site (dashed line). δ_w in the palaeotemperature equation is $+1^{\circ}/_{oo}$.

An alternative explanation may be that more shell was accreted during the warmer months although this is not borne out by actual growth measurements which imply that shell growth occurred continuously throughout the year (Branch 1974). The results of a more detailed analysis of *P. granatina* from Lamberts Bay, where daily intertidal temperatures were measured, support the former explanation. Temperatures derived from oxygen isotope ratios of successive samples in the profile agree almost exactly, within experimental error, with those actually recorded in the intertidal zone. The nature of the profile suggests that this species accretes shell continuously throughout the year and supports previous growth measurements made in the field (Branch 1974).

XRD analyses showed that *P. granularis* shells contain significant and variable amounts of aragonite, increasing from 8% at the cooler sites to 45% at the warmest site (Table 4.1). A relationship between whole-shell mineral composition and habitat temperature has been reported for other mollusc species (Lowenstam 1954a,b; Dodd 1963) and is explored further in Chapter 5. Theoretical prediction and empirical analyses indicate that aragonite concentrates the heavier oxygen isotope relative to calcite resulting in an enrichment of between 0.6°/oo and 0.8°/oo at 25°C (Tarutani *et al* 1969, O'Neil 1969, Grossman and Ku 1986). The presence of aragonite in *P. granularis* shells may explain their enrichment relative to both the expected $\delta^{18}O$ and the primarily calcitic *P. granatina* shells. However, the difference between *P. granatina* and *P. granularis* was greater at all sites and for all percentages of aragonite than that reported in the studies cited above. Therefore it is suggested that the isotopic enrichment exhibited by *P. granularis* was probably not only a function of the presence of aragonite in the shell. Aspects of the biology of this species, especially its preferred zonal distribution and behavioural characteristics may have contributed to the enriched isotope signal. *P. granularis* is widely distributed within the intertidal zone although most large individuals are concentrated in the high shore region. Furthermore, *P. granularis* never occupies intertidal pools but remains exposed during low spring tide (Branch 1971, 1975). Shell material accreted during hours of exposure is therefore expected to be isotopically enriched relative to that accreted when the animal is submerged. In contrast, *P. granatina* is found lower down on the shore and is aerially exposed less often and for shorter time periods. Furthermore, some individuals of this species tend to take refuge in rock-pools during low tide (Branch 1971).

Intraspecific variability in the oxygen isotope composition of *P. granatina* shells is considerably lower than that observed in *P. granularis*. This result may also be explained by different behavioural characteristics between the two species. Both species migrate up the shore as they age although *P. granularis* migrates more readily and covers a greater distance than *P. granatina* (Branch 1971). The isotopic composition of different *P. granularis* shells in the same population are therefore expected to exhibit a greater degree of variability.

Shackleton (1973) constructed oxygen isotope profiles through the calcitic shell layers of *Patella tabularis* specimens collected live at Robberg. He found that the $\delta^{18}O$ fluctuations within the shell accorded with those expected. However, the absolute $\delta^{18}O$ values were enriched by approximately $1^{o}/oo$ relative to those expected when compared with actual temperature data from Cape St Francis, about 150km east of Robberg. Aragonitic shells of the low to mid-shore dweller, *Perna perna*, yielded isotope values with a similar offset against equilibrium (Shackleton 1973). In this study, the oxygen isotope profile of the calcitic layer in a *P. tabularis* specimen from Stillbay was compared with temperature data also from Stillbay. A $1^{o}/oo$ enrichment was also apparent in these data thus supporting Shackleton's finding. The enrichment reported by Shackleton (1973) cannot therefore be attributed to the source of the temperature record he used. The reason for this offset remains unclear. The explanation offered for isotopic enrichment in *P. granularis* i.e. frequent aerial exposure, is not applicable to *P. tabularis* as this species occupies the infratidal region and is most often, if not always, submerged (Branch 1971). Furthermore, *P. tabularis* is a non-migratory species and occupies the same position throughout its lifetime (Branch 1975).

Temperatures derived from the oxygen isotope composition of *P. tabularis* agreed well with those actually recorded if a δ_w value of $1^{o}/oo$ was assumed (Fig. 4.6). However, the data indicated that this particular individual accreted more shell during the warmer months and as a result, the average derived temperature was warmer than the actual average. Reduced shell accretion and therefore, reduced resolution of the sampling method during slow winter growth, may explain why the minimum temperature in the second year was not represented in the record. For these reasons the suggestion of Krantz *et al.* (1987) is followed in that quantitative analyses of the palaeotemperature record (Chapter 7) utilize only the maximum and minimum values in each profile.

4.6 Conclusion

The oxygen isotope composition of the three southern African limpet species all showed a strong correlation with ambient temperature. Whole-shell analyses of *P. granatina* yielded temperatures which were, except at South Point, slightly warmer than those actually recorded. This offset probably reflects a small difference between inter- and infratidal temperatures. A comparison between surf-zone temperatures and the isotope profile through *P. granatina* supports this explanation as maximum, minimum and average temperatures were closely approximated by this species. *P. granularis* also reflected habitat temperature but in all cases the isotope values were enriched relative to those expected. The degree of enrichment observed was not explanable only in terms of shell mineralogy but was probably exaggerated by metabolic effects described by McConnaughey (1989). However, the amount of aragonite in the shell of this species was variable as are the ecological circumstances which result in metabolic interference with the attainment of isotopic equilibrium. Probably for these reasons, intraspecific variability was higher in the P. granularis sample than in *P. granatina* and the latter species is suggested to be a more reliable isotope thermometer.

The isotopic record in *P. tabularis* from Stillbay supports the conclusion of Shackleton (1973b) that this species is particularly suitable for isotope studies. The derived temperatures were lower than actual recorded temperatures and may be due to an underestimate of the oxygen isotope composition of present-day Agulhas Bank surface water. This particular specimen grew slightly faster during the summer than during the winter months which, after adjustments were made to the δ_W value in the palaeotemperature equation, resulted in an average temperature biased toward the warmer months. It is suggested that maximum and minimum values obtained using the serial sampling technique represent, most accurately, the variability in the natural environment.

CHAPTER 5

TEMPERATURE-DEPENDENT CHANGES IN THE SHELL MINERALOGY AND MICROSTRUCTURE OF *PATELLA GRANULARIS*: AN ALTERNATIVE PALAEOTHERMOMETER

5.1 Introduction

The mineral composition and structural arrangement of marine mollusc shells are influenced by the physical and chemical conditions of the environment. These aspects of shell composition are therefore of considerable interest and value in the reconstruction of past oceanic environments. Lowenstam (1954a,b) and Dodd (1963, 1964, 1966) have shown that changes in mineral ratios (aragonite:calcite) and the extent of development of different shell layers in certain species are related to sea temperature and can be quantified and used as palaeothermometers. One advantage of this method over oxygen isotope palaeothermometry is that it is sensitive only to sea temperature changes such as those associated with upwelling events, whereas the oxygen isotope ratio reflects a combination of both sea temperature and ice volume (salinity).

The effect of temperature on mineralogy differs from species to species (Dodd and Stanton 1981) and a detailed study of living representatives of each group is neccessary. In this chapter the feasibility of using *Patella granularis*, an intertidal limpet, as a palaeotemperature indicator is tested. *P. granularis* is the most widely distributed of all the southern African limpet species, extending from Angola to Northern Natal and possibly into Mocambique (Kensley and Penrith 1973, Kilburn and Rippey 1982). It is abundant in the high and mid-intertidal zones of the present coastline (Stephenson 1937, Branch 1971) and is found in archaeological and raised beach deposits accumulated since the last Interglacial approximately 125 000 years ago (Tankard 1975, Voigt 1982). Its present range includes the cold, nutrient-rich waters of the west-coast Benguela upwelling system and the warm, low-nutrient waters of the Agulhas current (Fig. 5.1). Variations in the shell size and inner shell morphology occur through this range and appear to coincide with differences in the oceanic environment (Stephenson

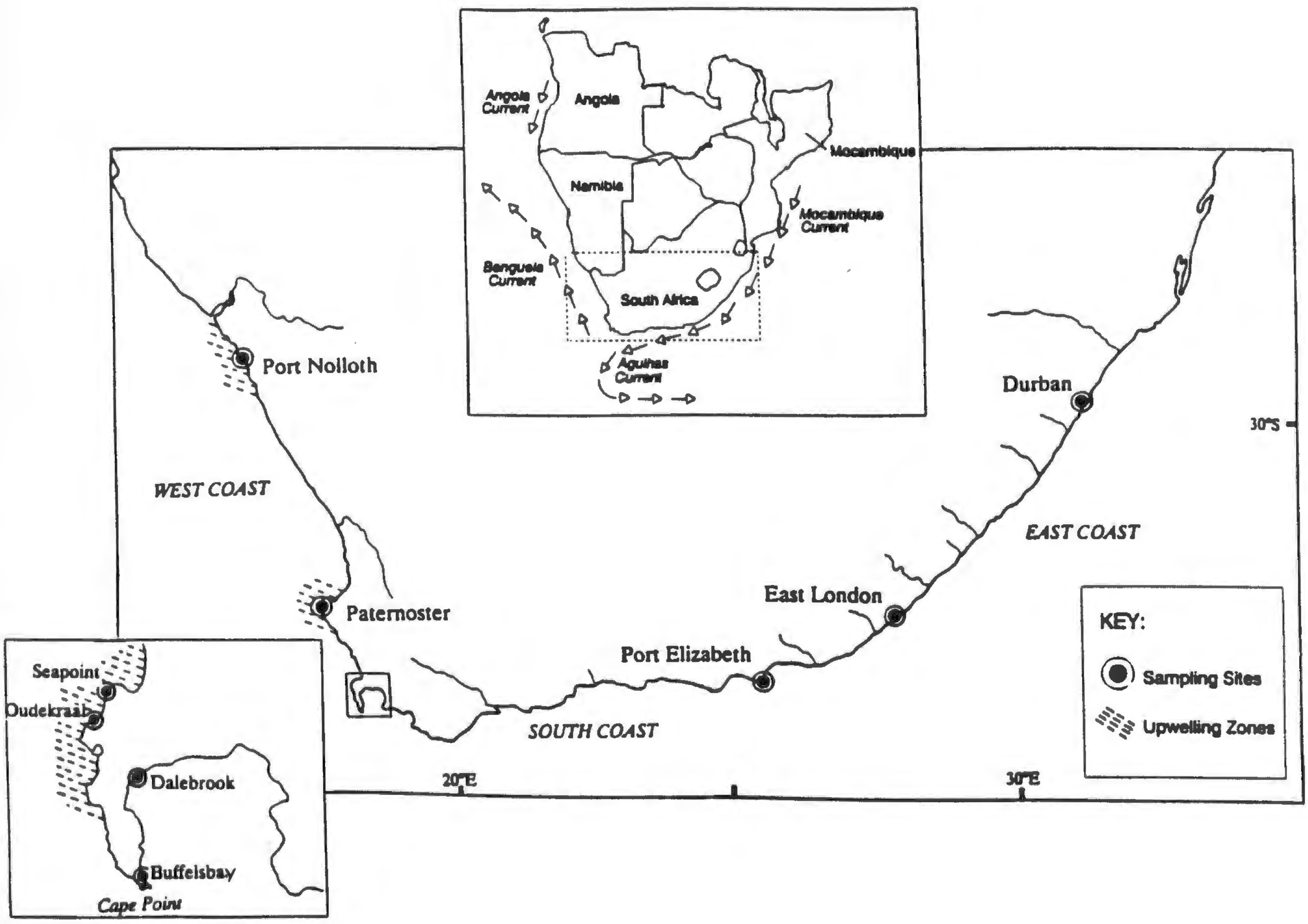


Fig. 5.1. Positions of collecting sites for *P. granularis* shells along the coast of South Africa, with respect to the major ocean currents and the important upwelling zones in the southern Benguela.

1937, Kilburn and Rippey 1982). West-coast individuals grow faster and are larger than those on the south and east coasts (Branch 1974, 1976). However, because the radular structure and anatomy remain constant between populations, taxonomists consider that a single species is involved (Koch 1949).

In Chapter 4 and Cohen (1988), variations were reported in the aragonite:calcite ratio of adult specimens of this species with changing sea temperature of the habitat. In this chapter, earlier studies are extended to include quantification of the structural and mineralogical changes in populations over much of the geographic range. It is shown that while both aspects of shell composition vary with sea temperature, shell structure has the greater potential as a palaeothermometer as it is better correlated with temperature, can be more reliably estimated and is easier to measure.

5.2 Method

Living animals were collected at each of nine sites extending from Port Nolloth on the west coast to Durban on the east coast (Fig. 5.1, Table 5.1.). All sites have reliable and long-term sea-temperature records which were obtained from various sources. All samples were collected at approximately mid-tide level on shores experiencing comparable, moderate exposure to wave action. No differences in shell structure was evident between the sexes, so males and females were pooled for analysis.

MacClintock (1967) has previously described the shell layers visible on the ventral surface of *P. granularis*. He defined each layer according to its position relative to the muscle attachment scar (myostracum, m) (Fig. 5.2). In this study, measurements were made of the widths of the shell layers where they crop out on the inner shell surface. In this study, only on those layers occurring outside of the myostracum, i.e. m+1, m+2 and m+3, were examined for three reasons. Firstly, they are the most accessible. Second, the m-1 layer is sometimes covered by an m-2 layer and is not visible on the ventral surface. Third, accretion of the m-2 layer does not occur throughout the range under study. The m+1 and combined m+2 and m+3 layers were measured with vernier calipers across the mid-point of each shell (Fig. 5.2). The relative width of the m+1 layer is expressed as :

$$\% \, m+1 = b/(a+b) \times 100$$

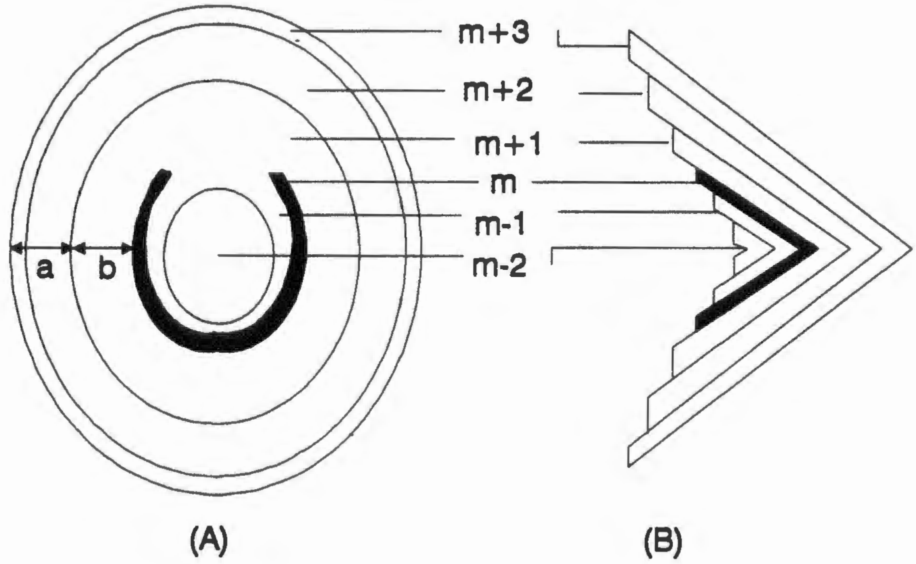


Fig. 5.2. Stylised ventral view (A) and transverse section (B) through *Patella granularis* showing arrangement of layers in the six-layer structure. The position of measurements made of the outer shell layers are shown by the arrows : b = m + 1; a = m + 2 and m + 3 combined; m indicates the myostracum.

where a and b are defined in Fig. 5.2

The relative width of the m+1 layer increases with shell length in some populations (pers. obs.). Partly for this reason, but also to control for size differences between populations, only shells between 20-40 mm were used. The average size of all shells measured was 29.6 mm (± 2.6 mm). In smaller specimens, especially those from the east coast, the m+2 and m+3 layers are so narrow that they are difficult to measure accurately with the naked eye. For this reason, all measurements were taken under 6x magnification.

For comparison, the whole-shell aragonite:calcite ratio was measured using X-ray diffractometry (XRD) on powdered samples. Shells were ground for three minutes under liquid nitrogen to prevent possible aragonite inversion to calcite under thermal stress. A Phillips goniometer was employed with a nickel-filtered copper target at 40kV and 30 mA. Receiving and divergent slits were set at 1°. The ratio of principle peak heights of aragonite ($2\Theta = 26.2°$) and calcite ($2\Theta = 29.4°$) were measured directly from the recorder charts and converted to % aragonite using Lownstam's (1954a) calibration curve. An error of ±10% was assigned to this calibration data (Lowenstam, 1954a:288).

Microstructural comparisons of samples from the west, south and east coasts were made using thin, polished sections viewed under polarised light. Aragonite was distinguished from calcite using Feigls solution which is absorbed by aragonite and leaves a silver stain (Schneidermann and Sandberg 1971). In darkly pigmented areas of the shell, the stained regions were difficult to identify on the basis of the stain colour only. However, because the stain gives a granular texture to aragonite layers, these are easily distinguished under low magnification.

5.3 Results

Microstructural analysis

The microstructural characteristics of west-coast shells accorded with the earlier description by MacClintock (1967) who recognised six shell layers (Figs. 5.2 and 5.3). Each layer is composed of either simple crossed-foliar or simple crossed-lamellar structures which MacClintock recognised by the size and dip-angle of their crystal aggregates. Visually, these structural types can be easily distinguished on the ventral surface. The foliar crystals are large and discrete while the lamellar crystals are small, and form a shell-layer which is porcelaneous in appearance. Foliar crystals are restricted to m+2, m+3 and m-2 layers and their large size is also evident in longitudinal section (Fig. 5.3A,B). Lamellar crystals are found in the m+1 and m-1 layers, and in section appear small and compact (Fig. 5.3C). Crystal aggregates are arranged concentrically (parallel to the shell margin) in the m+1 and m+2 layers and appear columnar in longitudinal section (Fig. 5.3B,C). The m-2, m-1 and m+3 layers have radially (perpendicular to the shell margin) oriented crystal aggregates and appear irregular in section (Fig. 5.3A). The muscle attachment scar was very thin and only just visible in thin section. MacClintock (1967) identified the myostracal micro-structure as complex-prismatic.

Mineralogy

The lamellar and myostracal layers (m+1, m, m-1) rapidly absorbed Feigls solution identifying them as aragonitic. The foliar layers (m-2, m+2, m+3) are calcitic. This observation is in agreement with Watabe (1984) who considers the crossed-lamellar and crossed-foliar layers of MacClintock (1967) equivalent to the aragonitic crossed-lamellar and calcitic crossed-lamellar structures recognised by other, later authors.

Microstructural variations

There are two significant microstructural differences between specimens collected from the west coast and those from the south and east coasts. Firstly, shells collected west of Cape Point (Fig. 5.4C,D) have six discrete structural layers (as described above) whereas those collected east of Cape Point have five (Fig. 5.4A,B). The calcitic, m-2, radial crossed-foliated layer (see Fig. 5.3A) is absent from the shells of south and east coast specimens. Secondly, in south and east coast shells the aragonitic m+1 and m-1 layers are well-developed (Fig. 5.4B) and several stacked rows of crystals separated by lines of growth are recognised within them (see Fig. 5.3C). In contrast, shells from the west coast have a well-developed outer foliar layer (m+2) whereas the m+1 and m-

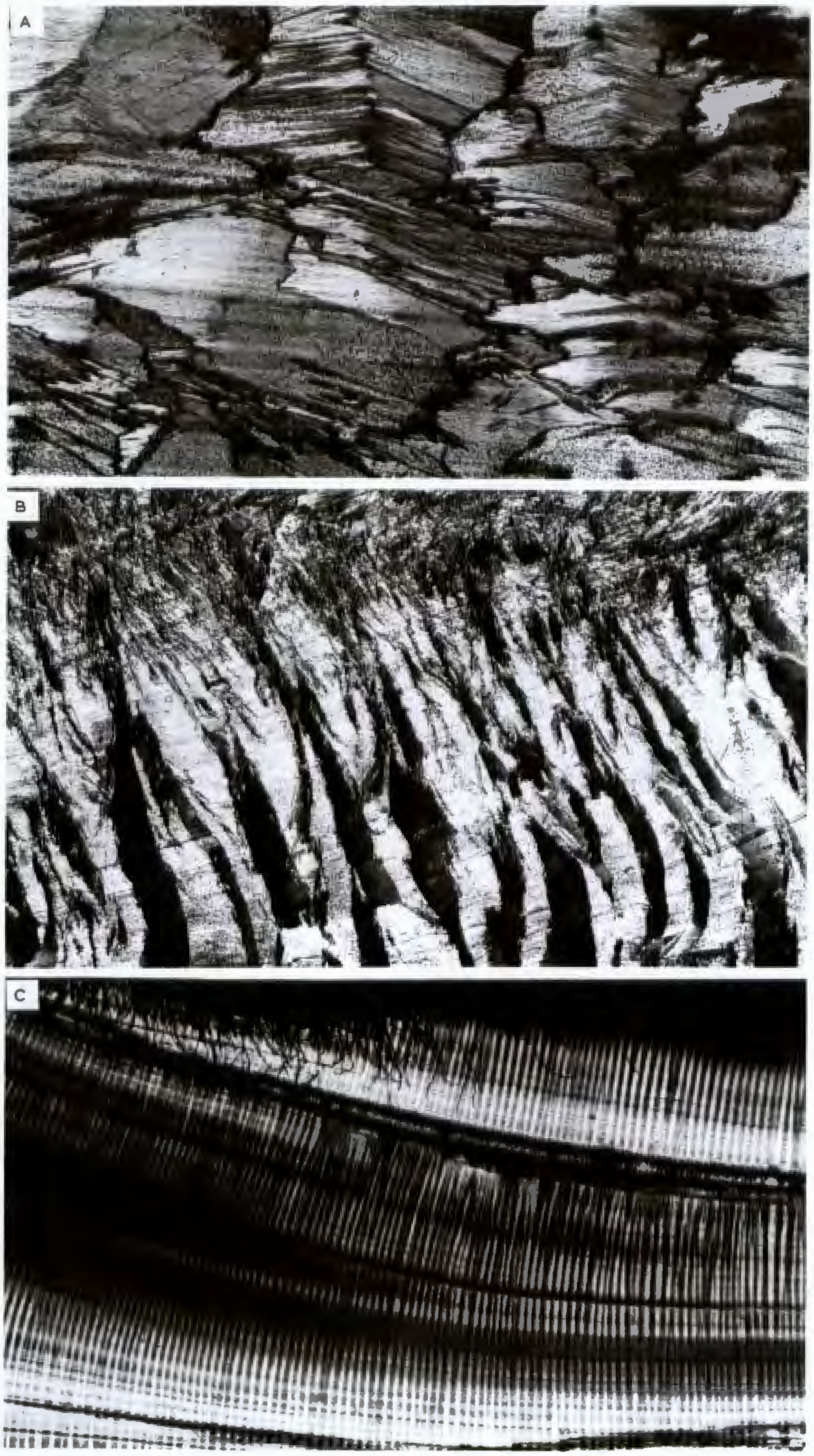


Fig. 5.3. Thin, polished longitudinal sections through the shell of *P. granularis.* (A) Large, radial crossed-foliated crystal aggregates of the m-2 layer. (B) Concentric crossed-foliated aggregates in the m+2 (columnar in appearance). Aggregates in the m+3 layer are oriented at right angles to those in the m+2. (C) Small, regular and compact aggregates of the lamellar m+1 layer. In A,B and C, the primary magnification in the film plane is 22.5X.

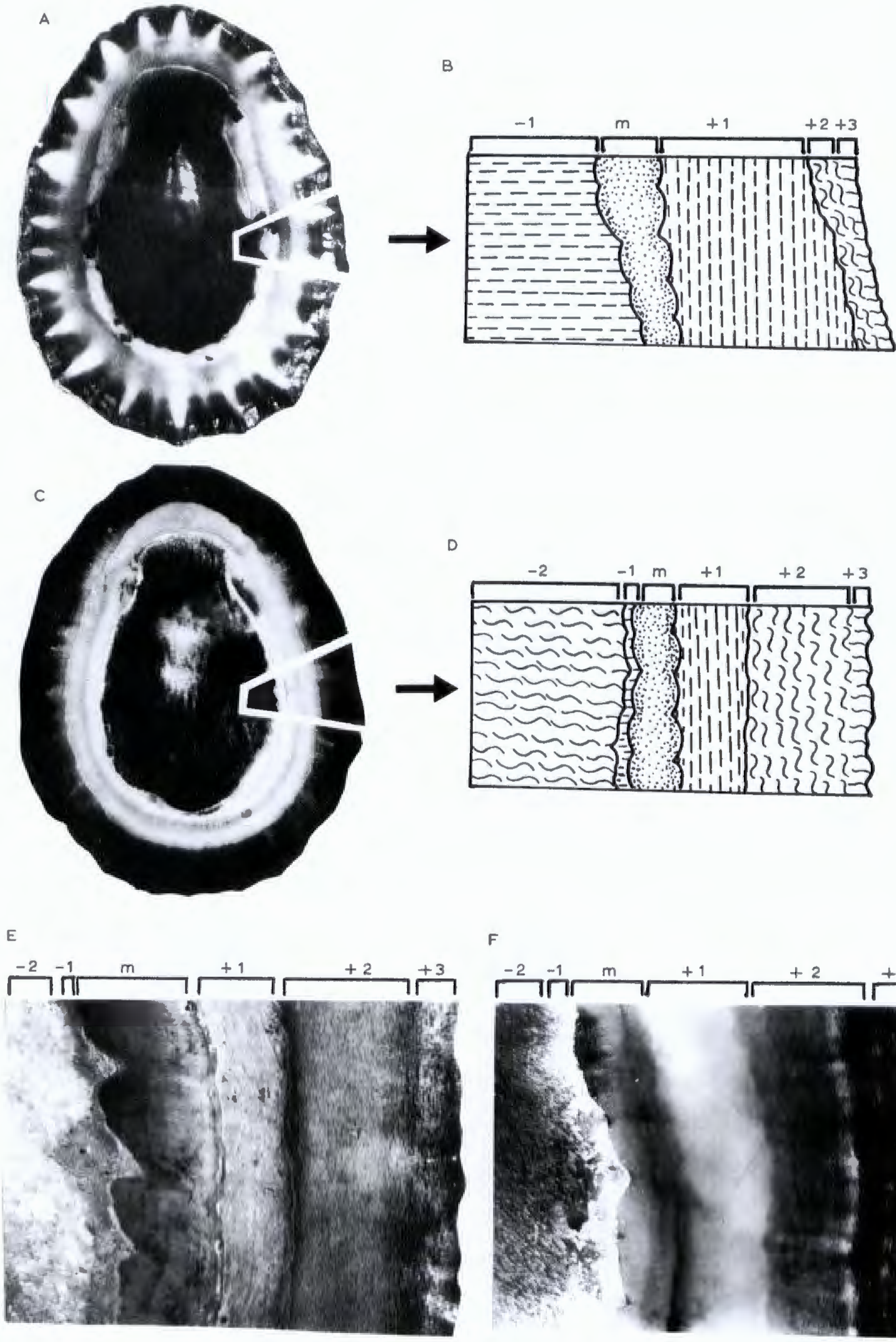


Fig. 5.4. Visible differences in gross shell morphology between south and east-coast (A,B) and west-coast (C,D) specimens of *P. granularis* reflecting differences in the relative development of different shell layers. Details of the shell layers of a 10 000- year old west-coast specimen (E) still reveal the layers evident in modern west-coast specimens (F). The myostracum, m-1 and m+1 layers are aragonitic; the m-2, m+2 and m+3 layers are calcitic.

1 layers are relatively thin (Fig. 5.4D). In all the shells examined, the m+3 layer was eroded and quantitative differences between samples were difficult to estimate.

TABLE 5.1: Results of the layer width measurements and mineralogical estimates of *P. granularis* shells at each collecting site. t(°C) = average annual sea surface temperature between 1984 and 1989. Recorded temperature data were supplied by the South African Maritime Weather Office[a], Sea Fisheries Research Institute (SFRI)[b] and the Seaweed Research Unit of SFRI[c]

Collection Site	t(°C)	%m+1 /m+	n	*s.e.	% aragonite	n	s.e.
Oudekraal (1)	11.7[c]	57.82	25	1.23	30.38	8	2.17
Port Nolloth (2)	12.1[b]	36.86	22	2.74			
Paternoster (3)	12.8[a]	45.57	19	2.78	9.90	10	1.49
Seapoint (4)	13.3[b]	51.63	23	2.29	13.14	8	3.64
Buffelsbaai (5)	15.2[c]	67.60	24	1.66	50.48	10	5.30
Dalebrook (6)	16.3[b]	73.28	19	1.30	75.00	12	4.81
East London (7)	17.9[b]	73.45	23	1.62	84.00	8	1.23
Port Elizabeth (8)	18.2[b]	80.67	36	0.94	68.56	9	4.29
Durban (9)	21.7[b]	86.05	19	1.15	73.00	13	2.12

*s.e. = standard error

Quantification

Results of the X-ray analyses and shell layer measurements are given in Table 5.1. and Appendices 5.1 and 5.2. The relative width of the m+1, lamellar layer outside of the myostracum is strongly correlated with increasing average annual sea surface temperature ($r^2=0.83$, $p \leq 0.001$) (Fig. 5.5A). Whole-shell mineralogy exhibited a similar, though less strongly-correlated trend ($r^2=0.66$, $p \leq 0.01$) (Fig. 5.5B). In both cases, the measurements for Oudekraal shells predict warmer sea temperatures than were actually recorded. This is probably because temperatures at this site were recorded at 8m depth and are not, in fact, a reflection of sea-surface temperatures in the intertidal zone (R. Anderson pers. comm.).

5.4 Discussion

The correlation between mean sea temperature and both structural and mineralogical measurements show that such measurements taken from *P. granularis* can predict mean sea temperatures and may be usefully applied to palaeotemperature studies. The application of this method to a palaeotemperature reconstruction of the southern Benguela is reported in Chapter 6 and Cohen *et al.* (1992).

Dodd (1963) used bivalve species to show that whole-shell aragonite:calcite ratios vary with sea surface temperature. However, this method cannot be used reliably for a number of reasons. Firstly, palaeotemperature assessments based on whole-shell mineralogy are only useful where the original mineral is preserved. Aragonite is metastable under surface temperature and pressure conditions (Deer *et al.* 1962) and is susceptible to diagenetic alteration. Initially, aragonitic layers are preferentially dissolved from the shell leaving cavities which are later filled with reprecipitated calcite (Bathurst 1964, Friedman 1964). In such samples the original aragonite:calcite ratio cannot be measured using XRD. Secondly, errors will always arise in species which deposit aragonite and calcite in discrete shell layers which are differentially eroded during the life of the animal. For example, in *P. granularis*, the erosion of calcitic material from the exposed dorsal surface complicates estimates of whole shell mineralogy because it increases the apparent percentage aragonite.

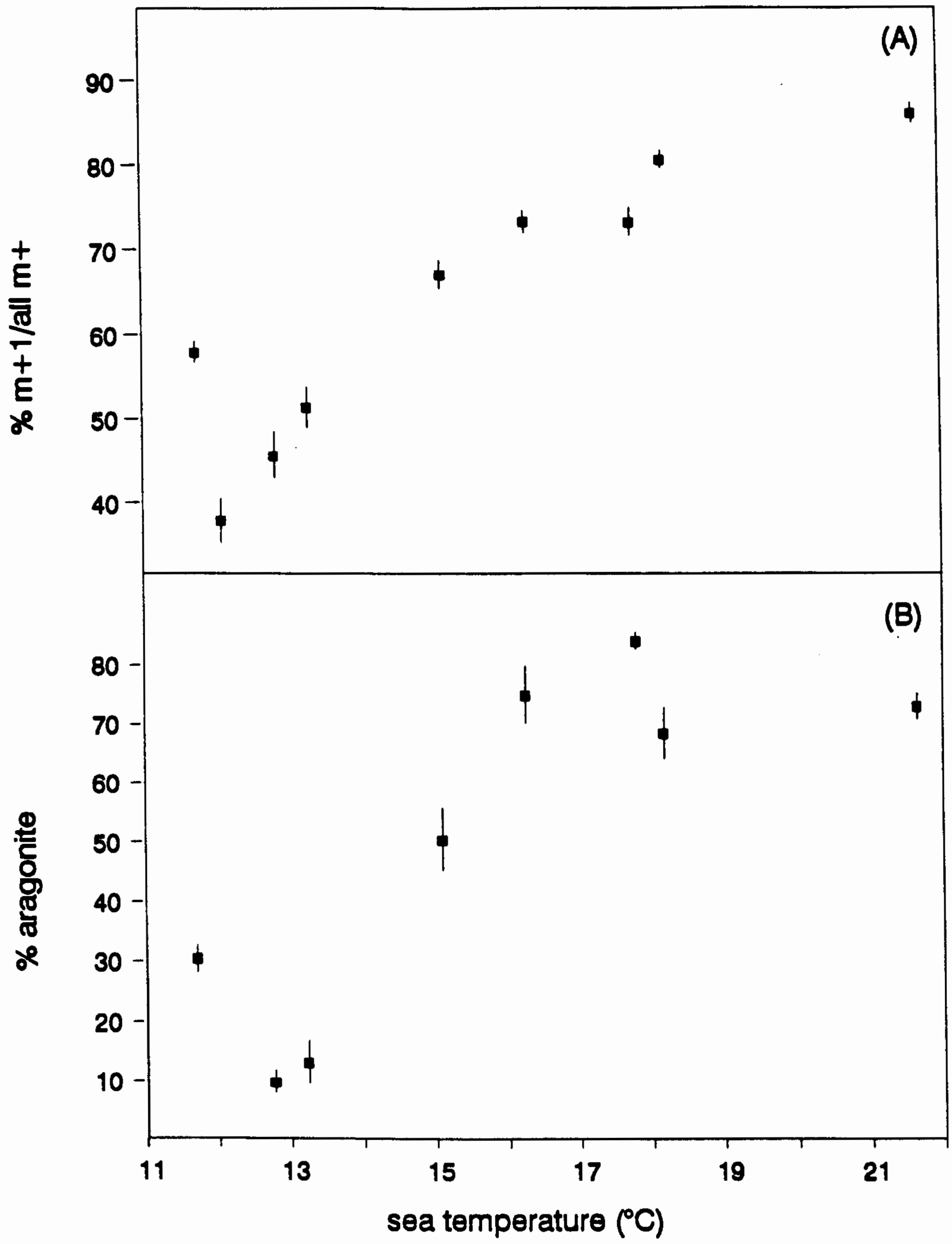


Fig. 5.5. Relative widths (mean and standard error) of the m+1 lamellar layer (A) and total % aragonite (B) in *Patella granularis* shells collected at sites along the coast, shown relative to sea surface temperature.

An additional complication in this species is that west-coast specimens deposit a calcitic "apical scar" (m-2 layer) in the centre of the shell, increasing the whole-shell estimates of calcite. The m-2 layer in *P. granularis* is equivalent to the inner prismatic layer of *Mytilus californianus* described by Dodd (1964). He reported an inverse relationship between the extent of development of this layer in *M. californianus* and sea temperature. However, he also noted that the inner prismatic layer may be thickened in response to abrasion of the outer layers. Similarly, we suspect that *P. granularis* may accrete the m-2 in response to erosion of the outer calcitic m+2 and m+3 layers, although the absence of an m-2 layer in south- and east-coast specimens makes it clear that erosion is not the only factor accounting for its deposition.

Whole-shell XRD analyses of modern *P. granularis* shells do yield a positive and significant correlation with temperature (Fig. 5.5B). However, this correlation is not as close as that obtained from simple, linear measurements of shell layers (Fig. 5.5A). Differential erosion of calcite and aragonite layers from the shell dorsal surface, and the accretion of m-2 material in west coast specimens may account for these different results.

Changes in shell layer width is a useful indicator in shells where diagenetic alteration of the original mineralogy has occurred, as the layer boundaries often remain intact and can still be measured. This technique is also practical, non-destructive and does not require laboratory conditions. In principle, the approach is similar to a later method used by Dodd (1964) for *Mytilus californianus*, in which structural types, based on the thickness of the inner prismatic layer, were recognised from thin-sections and related to sea temperatures. His approach does overcome many of the limitations posed by XRD but is time-consuming and impractical when dealing with the large numbers of samples required for this type of analysis.

Many authors have recognised that aragonite deposition is favoured in warm water. However, factors other than temperature are thought to determine the formation of either calcite or aragonite crystals in the shells of molluscs. These include chemical or physical characteristics of the organic matrix, which are different in aragonitic and calcitic shells (Carlstrom 1963), the concentration of inorganic ions, including Mg, Sr and PO_4 in sea water (Watabe 1974, Dodd and Stanton, 1981), sea water salinity (Eisma 1966) and phylogenetic history (Carter 1980, Lindberg 1988). Taylor and Reid (1990) suggested that the different solubilities of calcite and aragonite govern the relative contribution of each mineral to the shells of littorinids at different latitudes. In the case of *P. granularis*, growth rate may indirectly affect the proportions of aragonite and calcite in the shell. The widths of the outer lamellar and foliar layers may be a function of their relative and variable rates of accretion, independent of their mineralogical composition. Additions to the shell margin (i.e. the outer foliar layers) contribute to the growth of the animal in both length and height whereas accretion of the inner aragonite layers does not. Therefore, the relative amount of outer foliar material may be higher in large, fast-growing individuals. On the west coast of South Africa, localised sea temperatures vary according to the proximity of an upwelling cell and the intensity and longevity of each upwelling event which brings cold, deep (South Atlantic Central) water to the sea surface (Fig. 5.1). Upwelled waters are rich in nutrients which enhance algal growth and increase the available food supply to grazers, including limpets, which respond by growing faster (Bosman *et al.* 1987). The relationship between lamellar width and sea temperature may therefore be an indirect expression of the effect of nutrient-rich waters on shell growth rate. This proposal remains to be tested independently. Irrespective of whether temperature exerts a direct effect on the width of different shell layers or an indirect effect via modifications of productivity, the relative width of the shell layers and the relative proportions of aragonite and calcite remain valuable tools in the study of palaeoclimates. It is suggested that structural variation may be a more useful indicator of palaeotemperatures as it is less affected by erosion and diagenesis than is whole-shell mineral composition. The data reported here refer specifically to *P. granularis*. However, the approach employed should find application to all shells, including other gastropods and bivalves, which have discrete shell layers that are differentially accreted in response to different environmental conditions.

CHAPTER 6

A HOLOCENE SEA SURFACE TEMPERATURE RECORD IN MOLLUSC SHELLS FROM THE WEST COAST OF SOUTH AFRICA

6.1 Introduction

Details of short-term climatic variability are often lost from marine sediments through bioturbation in the upper, aerobic sediment layers. Alternatively, a high resolution and dated record of climatic events may be obtained using material preserved in archaeological deposits. In this chapter, archaeological midden shells preserved in a number of sites along the western Cape coast of South Africa, adjacent to the southern Benguela upwelling system, are used to reconstruct a Holocene history of coastal sea surface temperature variability in the region. The aims of this study are twofold. First, to assess the quality of information and temporal resolution to be gained using materials excavated from archaeological deposits for palaeoclimate studies. Second, to compare the sea surface temperature record yielded through application of the aragonite:calcite palaeothermometer developed in Chapter 5 and compare it with that constructed from the oxygen isotope analyses of contemporary shells. I propose that the aragonite:calcite thermometer may be a better indicator of surface temperatures especially during the early Holocene, as this measurement is independent of changes in ice volume and salinity. The data are interpreted in terms of processes affecting sea surface temperature varibility in the region during the present-day, a full description of which was given in Chapter 2.

Oceanic setting

The Benguela Upwelling System is one of four major upwelling systems of the World's oceans (Andrews and Hutchings 1980). It is divisible into northern and southern regions on the basis of the seasonality of upwelling events (see Fig. 2.1). The oceanography of the southern Benguela (south of about 31°S) is dominated by a strongly seasonal regime (Shannon 1985). Interannual sea surface temperature (SST) variability in the nearshore environment is associated with the intensity and duration of summer upwelling events which bring cold (8°-10°C) water to the surface, and with

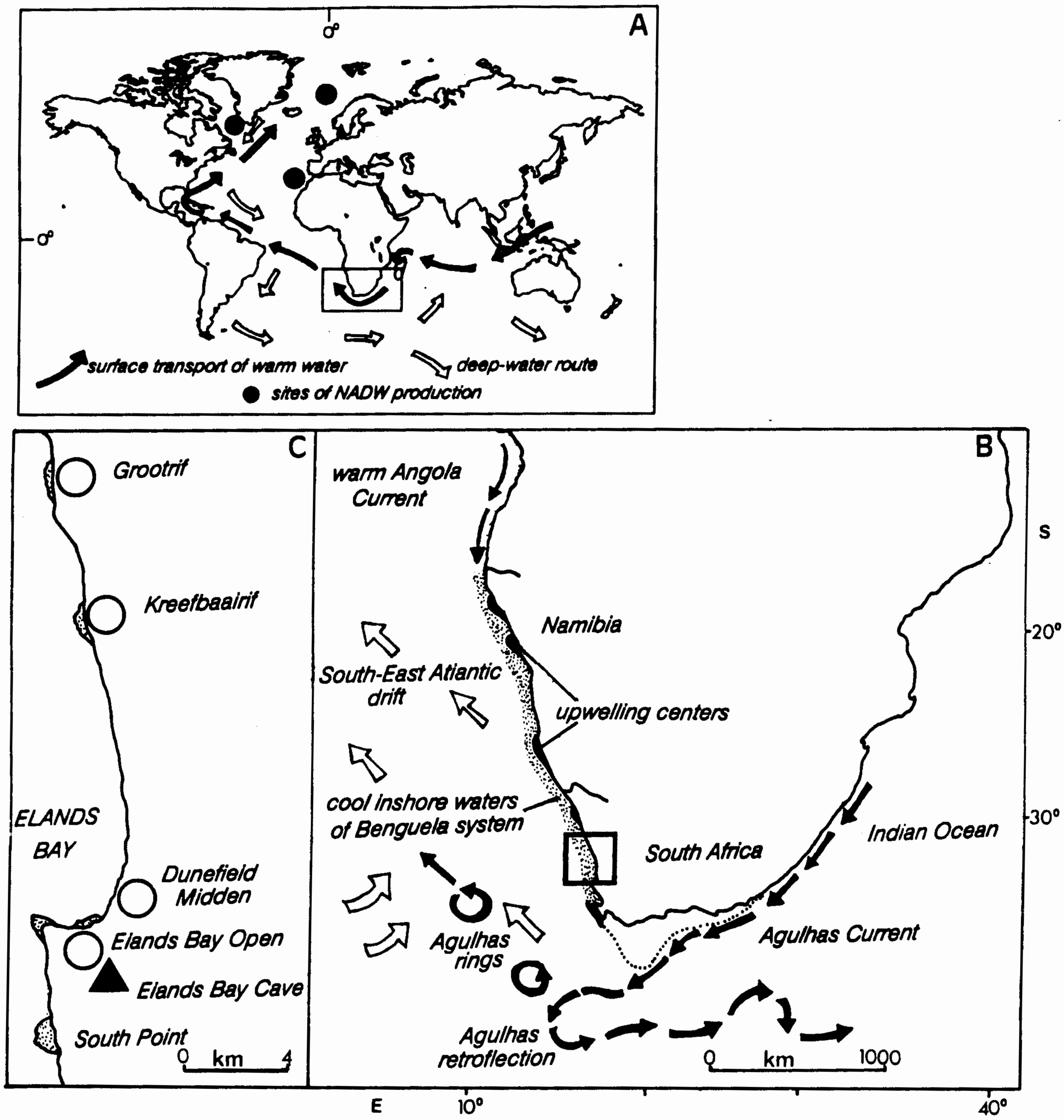


Fig. 6.1. Maps showing important features of the oceanic "conveyor belt" and the positions of the Agulhas and Benguela systems along the surface water route (A); the location of the sampling area with respect to the Agulhas-Benguela exchange and the west coast upwelling system (B,C).
In (C), ○ open middens; ▲ cave site.

the frequency and extent of episodic Agulhas Current intrusions which carry warm, Indian ocean water around the Cape of Good Hope into the Benguela region (Shannon 1985, Shannon *et al.* 1990) (Fig. 6.1B). Upwelling events are pulsed which means that SST'S at the coast are more variable during summer than during winter. However, there is no marked seasonal temperature signal because summer peaks in insolation and coastal upwelling tend to cancel each other's effect on SST (Taunton-Clarke and Kamstra 1988).

Despite the extent and importance of this upwelling system, its history, especially that of the southern region, remains unstudied. In this chapter, marine mollusc shells from Holocene middens along the west coast of South Africa are used to construct an isotopic and thermal history of the southern Benguela. The middens are located in the vicinity of Elands Bay (Fig. 6.1C) and were excavated and radiocarbon-dated prior to this study (Table 6.1). Sampling does not include the period between 7900 and 4300 yrs B.P. as no occupational debris accumulated at any site on the west coast during this time. All early Holocene material came from the Elands Bay Cave deposit (Parkington 1977) and samples from the nearby open middens were included for data after 4000 yr B.P. (Fig. 6.1C).

6.2 Techniques employed

Two independent palaeotemperature techniques were employed in this study; oxygen isotopes and aragonite-calcite ratios. The relationship between the oxygen isotope composition of skeletal carbonates and seawater temperature was discussed in Chapter 3. A major problem with the isotope palaeothermometer is the contribution of the oxygen isotope value of seawater (δ_W), past values of which cannot be measured directly, to the palaeotemperature equation. Deviations from the present value of δ_w occurred during periods of glacial expansion when isotopically light water was extracted from the oceans and remained on land as ice (Shackleton 1967). During warm periods in the earth's history, glacial melting released isotopically light, fresh water into the world's oceans. As Northern hemisphere glaciers and mountain snowlines advanced and retreated several times during the time period covered in this study (Denton and Karlen 1973, Broecker and Denton 1989), alternately removing and releasing isotopically depleted water into the marine environment, the Holocene ocean isotope record cannot be interpreted solely in terms of sea surface temperature.

To identify local inshore sea-temperature fluctuations, a second technique was employed: aragonite:calcite thermometry, which is based on the correlation between the relative amounts of each mineral in the shell and the temperature during growth. Lowenstam (1954a) and Dodd (1963) showed that the percentage of aragonite in certain mollusc species increases with increasing temperature although the use of this relationship as a palaeothermometer has had little success up to now for two main reasons. First, the mineral-temperature relationship differs between species and it is necessary to quantify the temperature-mineral relationship using live animals growing under controlled or recorded conditions. Second, the aragonitic sections of ancient shells sometimes dissolve or invert to calcite and the original aragonite:calcite ratio cannot be accurately measured (Dodd and Stanton 1981) (see Fig. 3.2).

These problems have been addressed in this study by using an extant limpet species, *Patella granularis*, in which discrete aragonite and calcite layers were easily identified and measured on the inner shell surface (Fig. 6.2). The relative width of the outermost aragonite layer (*a* in Fig. 6.2) increases by 45% with an increase in temperature of 10°C (Cohen and Branch 1992, Chapter 5). Some shells of this species recovered from the early Holocene levels in Elands Bay Cave showed partial dissolution of the aragonite layer (See Fig. 3.2) which excluded the possibility of using the X-ray diffraction technique to measure whole-shell aragonite:calcite ratios. Instead, an alternative method, described in Chapter 5, was employed which involved measuring the relative widths of the aragonite and calcite shell layers outside of the muscle scar (Fig. 6.2). In shells where partial dissolution of the aragonite phase had occurred, the original layer boundaries were still recognisable and could be measured (see Figs. 3.2 and 5.4F).

For oxygen isotope analysis, shells of the limpet *Patella granatina* were used for two reasons. First, the oxygen isotope values of recent shells of this species reflect the ambient sea surface temperature (Cohen 1988, Chapter 4) and second, the shells are primarily (>95%) calcitic and are less susceptible to diagenetic alteration than are aragonitic shells. The samples were prepared as described in Chapter 3. Briefly, a 5 mm wide section was cut along the length of the shell, ground under liquid nitrogen and the powder sub-sampled for isotope analysis. *P. granatina* accretes shell material throughout the year (Branch, 1974). We selected specimens between 40 and 60 mm in length i.e. 1-2 years old (Branch, 1974) which means that each isotope value represents an average over one to two years.

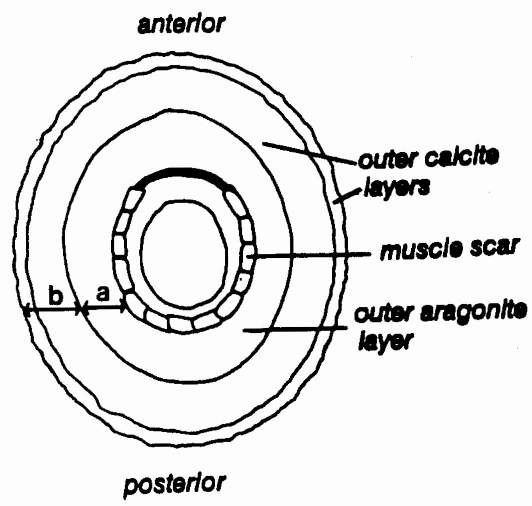


Fig. 6.2. View of the inner shell surface of *Patella granularis*. West coast specimens have six shell layers; three are calcitic and three are aragonitic. The relative width of the aragonite, *a*, and calcite layers, *b*, outside of the muscle scar increases with temperature. The relative percentage aragonite in the layers is calculated as follows:

$$\% \text{ aragonite} = a/(a+b)*100$$

$$\text{and } t°C = (\% \text{ aragonite} + 6.2)/4.5$$

(The details of this method were described in Chapter 5)

6.3 Results

Results of the isotope and mineral analysis of *Patella* shells are shown relative to the mean value for modern samples from South Point (Fig. 6.1), a rocky outcrop located about 2 km south of Elands Bay Cave (Table 6.1, Fig. 6.3). The data are listed in Appendices 6.1 and 6.2. The general decrease in oxygen isotope values between 12 500 yrs B.P. and present as shown in Fig. 6.3A, was expected and reflects the recovery of the oxygen isotope composition of seawater from the glacial maximum value. Three discrete episodes of isotopic enrichment in *P. granatina* occurred between 11 000 and 10 000 yrs B.P., 4 000 and 2 000 yrs B.P. and between 750 and 400 years ago. Their timing and duration corresponded to periods of Holocene glacial expansion: the Younger Dryas advance, traditionally associated with major although localised climatic deterioration in the Northern Atlantic and adjacent European continent between 11 000 and 10 000 years ago (Duplessey *et al.*, 1981; Broecker *et al.*, 1985; Dansgaard *et al.*, 1989); a worldwide neo-glacial advance between 3 000 and 2 000 yrs B.P. (Lamb 1982) and the Little Ice Age, which reached a maximum at about 400 years ago (Grove 1988).

The aragonite:calcite ratios were significantly different ($p \leq 0.05$) from the modern mean value 9950 yrs B.P. ($t = 5.05$), 3190 yrs B.P. ($t = 3.96$) and 500 yrs B.P. ($t = 3.69$) (Fig. 6.3B). Using a temperature conversion equation based on aragonite:calcite ratio's of recent material (Cohen and Branch 1992, Fig. 6.2), the average, annual inshore sea surface temperature at these times is estimated to have been approximately 1.5°C lower than it is today in the Elands Bay area. According to Fairbanks (1989), the global ocean $\delta^{18}O$ value during the Younger Dryas, was about 0.65°/oo heavier than it is today. The maximum $\delta^{18}O$ value in the Elands Bay record during this period was 2.18°/oo, 0.91°/oo more enriched than the modern value. Subtracting the ice volume effect leaves a residual value of 0.26°/oo, which corresponds to a temperature drop of 1.07°C. This value agrees well with that inferred by the change in shell mineral composition during this period and indicates that approximately one-third of the Younger Dryas signal observed in the $\delta^{18}O$ record was caused by a drop in local sea surface temperature. On the other hand, no significant enrichment of the oxygen isotope composition of seawater is evident in the Fairbank's curve around 3000 years ago and 650 years ago when both the oxygen isotope record and the shell mineral record indicate short periods of rather severe cooling. In both records, the degree of cooling during the Neoglacial Advance (>2°C) between 3000 and 2000 years ago was

TABLE 6.1: Mean $\delta^{18}O$ values *in Patella granatina* and % aragonite in *Patella granularis* shells from radiocarbon-dated strata in archaeological deposits on the west coast of South Africa.

Site	Radiocarbon Age (yr B.P.)	Sample No.	$\delta^{18}O$ (°/oo, PDB)	s.e.	Sample No.	% Aragonite	s.e.
SOUTH POINT	Recent	5	1.27	0.07	16	50.15	1.37
EBC(1)	315±50(Pta-1815)	5	1.15	0.08	23	45.61	1.96
DFM 3	420±50(Pta-4481)[a]	3	1.57	0.05	12	47.47	1.38
DFM 1	500±50(Pta-4479)[a]	3	1.53	0.06	19	42.54	1.56
EBO	590±50(Pta-2460)	5	1.41	0.09	15	42.97	1.94
EBO	705±45(Pta-2465)	4	1.05	0.11	16	46.33	1.29
DFM 2	750±50(Pta-4480)[a]	3	1.05	0.15	16	50.87	1.11
DFM 4	950±50(Pta-4801)[a]	2	1.25	0.07			
EBO	1470±50(Pta-2469)	5	1.28	0.10	10	50.38	1.93
GRM D(A)	2290±50(Pta-4075)	2	1.21	0.07	6	47.21	2.71
GRM D(B)	2470±60(Pta-4085)	3	1.51	0.05	5	48.80	2.82
GRM D(C)	2540±50(Pta-4083)	2	1.78	0.03	17	46.51	2.42
GRM D(D)	2680±60(Pta-4060)				18	47.47	1.84
GRM B(E)	2700±60(Pta4068)	2	1.81	0.01			
SC	2970±60(Pta-4033)	2	1.50	0.05			
KBM C(I)	3190±60(Pta-4045)	3	1.59	0.08	11	39.5	2.32
EBC(8)	3510±60(Pta-737)	5	1.48	0.03	6	52.4	3.10
EBC(8)	3940±60(Pta-5317)	5	1.31	0.09			
EBC(8)	4370±60(Pta-5313)	3	1.23	0.13			
EBC(11)	7910±80(Pta-1872)	5	1.45	0.05	18	48.54	2.12
EBC(11)	8300-8860				9	52.28	2.40
EBC(11)	8860±90(Pta-5305)	3	1.47	0.07	12	55.59	2.71
EBC(12)	9600±90(Pta-686)	5	1.53	0.06	23	47.23	2.30
EBC(12)	9640±90(Pta-5306)	8	1.52	0.08			
EBC(10)	9950±270(Pta-2592)	4	1.87	0.09	20	41.06	1.23
EBC(13)	10,640±110(Pta-732)	5	2.02	0.01	38	44.91	1.04
EBC(13)	10,640±110(Pta-732)	2	2.14	0.06	19	46.49	1.01
EBC(13)	10,640±110(Pta-732)	5	2.18	0.04			
EBC(13)	10,640±110(Pta-732)	4	1.99	0.05	18	49.25	2.30
EBC(15)	11,070±140(Uw-192)	5	1.83	0.04	21	44.63	1.24
EBC(16)	12,450±280[b]	4	2.02	0.04			

EBC (1) = Elands Bay Cave, Level 1, DFM 3 = Dunefield Midden 3, GRM D(D) = Grootrif Midden D, sample D, EBO = Elands Bay Open, KBM C(I) = Kreefbaai Midden C, sample I, SC = Spring Cave

[a] Dates on sea shell corrected for the apparent age of sea water by subtracting 400 years.

[b] The age of layer 16 in EBC was estimated on the basis of its association with Spit 2 in EBC which has a date of 12,450±280 yrs B.P. (GaK-4338).

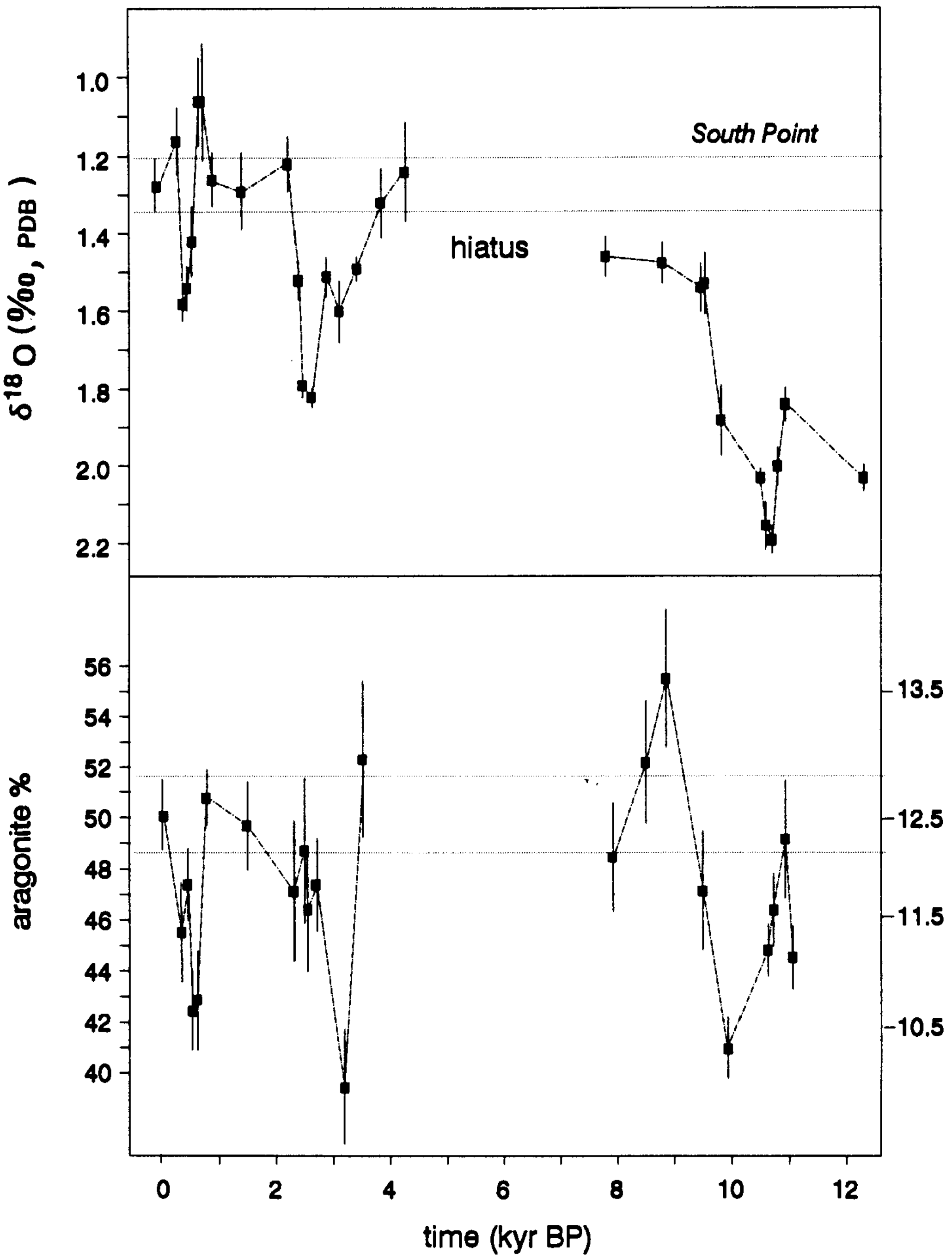


Fig. 6.3. Oxygen isotope values of *Patella granatina* shells (A) and structural changes, expressed as % aragonite, in *Patella granularis* shells (B) from west coast archaeological middens, plotted against radiocarbon age. No corrections have been made to the oxygen isotope values for changes in δ_w through time.

greater than that during the Little Ice Age (>2°C) which, in the southern Benguela, appears to have reached a maximum around 420 yr BP.

Warming of surface waters at 8860 yr BP is apparent in the aragonite:calcite data but not obviously so in the oxygen isotope record. This is because the isotope values are not corrected for changes in the oxygen isotope composition of seawater which, 8860 years ago, was about 0.34‰ more enriched than it is today (Fairbanks 1989). The corrected oxygen isotope value of the *P. granatina* shells at this time was 1.13‰ which does, in fact, convert to a slightly higher sea surface temperature (~0.5°C) than that of today.

6.4 Discussion

The correspondence between the isotope and mineralogical records, and Holocene climatic events recorded in the northern hemisphere suggest a link between global climatic events and local oceanic temperatures. Such a link may be served by the global thermohaline circulation cell ("oceanic conveyor belt") which transports warm, surface water from the Pacific via the Indian ocean into the North Atlantic (Gordon 1986) (Fig. 6.1A). The passage of Indian ocean water into the south-east Atlantic depends largely on ring-shedding at the Agulhas retroflection (Shannon *et al.* 1990) which contributes an estimated 5×10^{14} W into the Benguela system (Gordon 1985). Furthermore, the rate of North Atlantic Deep Water (NADW) production, which drives the conveyor system, matches the strength of Agulhas current flow into the south-east Atlantic (Gordon 1985, 1986).

The role of the conveyor in regulating global climate has been emphasised by Broecker and Denton (1989) and Broecker *et al.* (1990). They suggested that rapid climatic oscillations, such as the Younger Dryas, resulted from a shut-down of the conveyor system and the consequent redistribution of heat in the oceans and in the atmosphere. While this hypothesis has received much attention, little is yet known about the potential effects of such a shut-down on regions outside of the North Atlantic. It is suggested that during periods of reduced NADW production, cooler sea surface temperatures would be expected in the southern Benguela as entrainment of warm Agulhas water around the Cape diminished and the south-east Atlantic cooled (Fig. 6.4b). Evidence exists for a reduction in the amount of Indian ocean water transported into the Benguela system during the last glacial (Berger and Vincent 1978, Charles and Morley 1988) when NADW production was significantly lower than it is today (Boyle and Keigwin 1987). It is therefore possible that the interruption of NADW production during the Younger Dryas, and probably during later periods of glacial re-advance, resulted in a reduction of Agulhas heat input to the southern Benguela, as reflected in the isotope and mineralogical records (Fig. 6.4).

It is equally possible that these cool water anomalies were caused by an increased frequency and/or intensity of upwelling events off the west coast of South Africa, in response to strengthened anticyclonic circulation in the southern Benguela region. The intensification or extension of the present upwelling season would increase the relative frequency of cool water episodes at the coast. Parkington (1986) suggested that such conditions prevailed during the Holcene Climatic Optimum which was then thought to have obtained between 11 000 and 8 000 years ago in the southern hemisphere (Lorius 1979, Salinger 1981). More recent palaeoclimatic evidence from South Africa suggests quite strongly that this event occurred much later in South Africa, somewhere between about 8000 and 5000 years ago (Partridge *et al.* 1990). Nevertheless, between 11 000 and 10 000 years ago, during the Neoglacial Advance and the Little Ice Age, different types of proxy data indicate that the general atmospheric circulation intensified during these periods of worldwide cooling (Crowley and North 1991) and there is some oceanic evidence for regional increases in upwelling intensity between 12 000 and 10 000 years ago (Peterson *et al.* 1991) and during the Little Ice Age (Leventer and Dunbar 1988). The techniques employed in this study do not enable a distinction to be made between upwelling-induced temperature change in the surface waters of the southern Benguela and that caused by variations in the input of Agulhas water. In the following chapter, a conceptual model is proposed which shows that atmospheric conditions favouring pronounced coastal upwelling in the southern Benguela may also have been associated with decreased transport of Agulhas Current water into the Benguela system.

6.5 Conclusion

Analyses of midden shells preserved in archaeological deposits on the west coast of South Africa have provided a high-resolution, dated record of climatic change in the southern Benguela, covering a substantial part of the Holocene. The identification of the Younger Dryas on the record was in fact, the first documentation of this event in South Africa. In general, these results extend the range of palaeoclimatic events

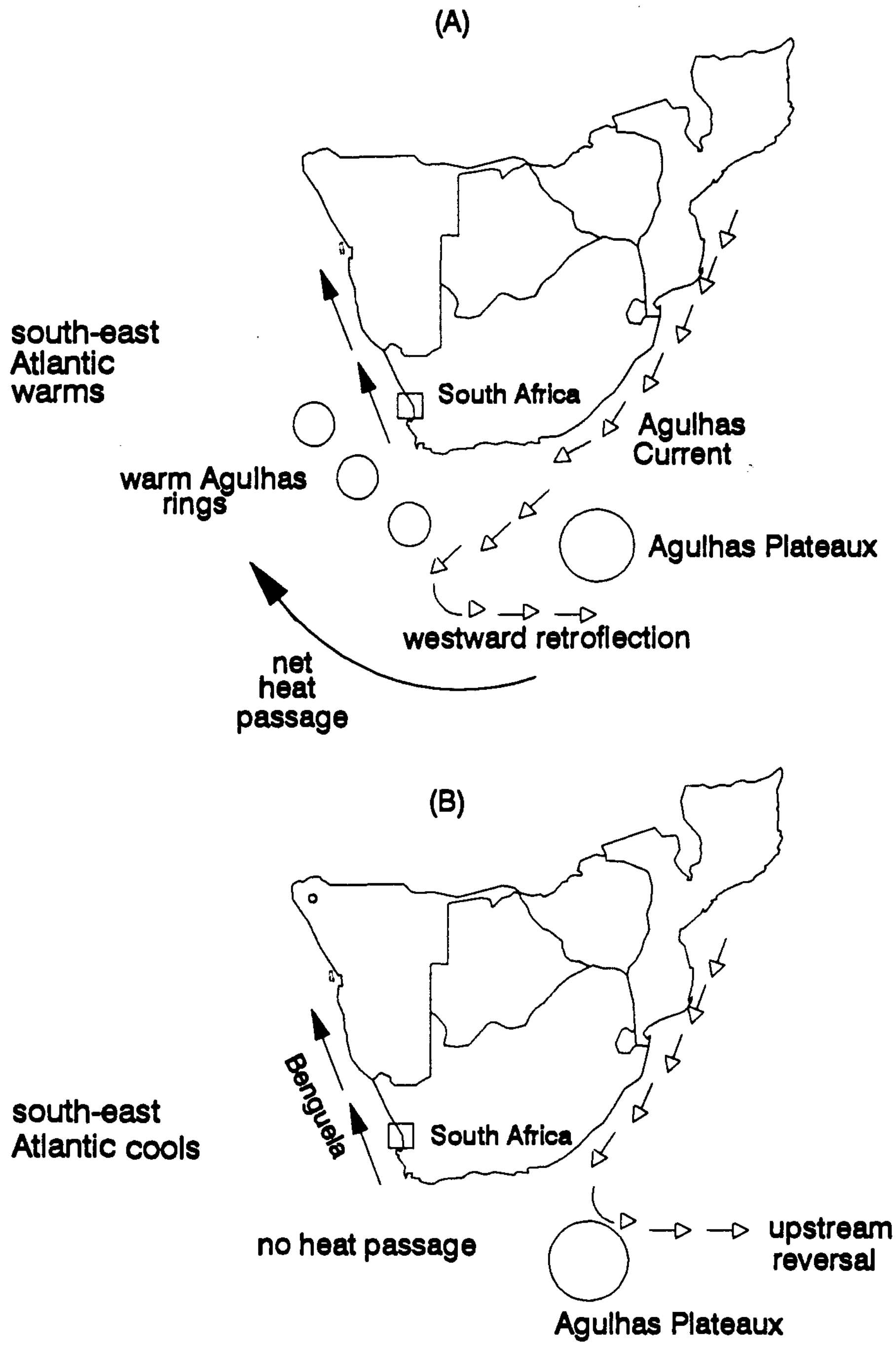


Fig. 6.4. Interruption of North Atlantic Deep Water production and hence the global ocean thermohaline circulation which, according to Broecker *et al.* (1985), caused the abrupt and dramatic Younger Dryas cooling, may have affected the oceanic circulation around southern Africa. The present-day characteristic position of the Agulhas retroflection is to the west of the sub-continent (A) but may have been further to the east (upstream) during the Younger Dryas and glacial periods (B). ☐ Elands Bay

previously recorded in oceanic records only from the northern hemisphere and provide further evidence for the global nature of the Younger Dryas. The alternative palaeothermometer described in Chapter 5 has been successfully employed to show that events in the oxygen isotope record, which probably reflect global changes, were associated with changes in local sea surface temperatures. Indeed, the remarkable correlation between the isotope and mineralogical records demonstrates the value of the mineralogical technique to ocean palaeothermometry.

CHAPTER 7

HOLOCENE SEA SURFACE TEMPERATURES ON THE SOUTH COAST OF AFRICA: IMPLICATIONS FOR TERRESTRIAL CLIMATE AND RAINFALL.

7.1 Introduction

In the previous chapter, a record of sea surface temperatures in the coastal southern Benguela was constructed, which covered a large part of the Holocene period. Three episodes of abrupt cooling of surface waters since 12 500 years ago were documented, which coincided with periods of widespread atmospheric cooling and the advance of glaciers. The oceanic response was probably due to enhanced upwelling and/or a reduction in the amount of warm Agulhas Current water intruding into the southern Benguela. It was not possible to examine surface temperatures in the upwelling region during the mid-Holocene warm period, the hypsithermal, owing to an occupational hiatus between 8 000 and 4 000 years ago, which affects all west coast archaeological deposits excavated to date. Information for this time period was recovered from an extensive archaeological cave deposit, Nelson Bay Cave, situated on the south coast of South Africa, adjacent to the eastern Agulhas Bank. In this chapter, a mid-Holocene sea surface temperature record is presented, derived from the oxygen isotope analyses of mollusc shells preserved in this deposit.

The data are used to address three problems. First, I shall attempt to constrain the temporal boundaries of the Holocene Climatic Optimum in South Africa. At present, different types of terrestrial data indicate that air temperatures between 8 000 and 5 000 years ago were approximately 2°C higher than they are today (Partridge *et al.* 1990) The high-resolution sea surface temperature record may provide new insight into the timing and duration of the event. Secondly, the data are considered in terms of two conflicting modelled predictions of the response of upwelling to increased global atmospheric temperatures (Bakun 1990, Hsieh and Boer 1992). Of course, it is necessary to know the exact timing of past episodes of atmospheric warming before the palaeoclimate data can be used to test the conflicting hypotheses. Uncertainty regarding the timing and duration of the Holocene Climatic Optimum in South Africa is therefore problematic. Thirdly, the sea temperature data are used to test an hypothesis proposed by independent authors to explain precipitation patterns during the Late Quaternary in southern Africa. I propose a combined ocean-atmosphere conceptual model to link sea surface temperatures in the southern Benguela and eastern Agulhas Bank, to rainfall patterns over the adjacent sub-continent. Using this model, the sea surface temperature record can be extrapolated to the terrestrial environment.

7.2 The Holocene Climatic Optimum in South Africa

Temperature

The climate of southern Africa since the Last Glacial Maximum is known largely from reconstructions of the terrestrial palaeoenvironment (see Tyson 1986, Cockroft *et al.* 1987, Deacon and Lancaster 1988). A number of authors have attempted to synthesise the available records, deduce regional patterns of temperature and precipitation and compare the data against modelled predictions of the nature of climatic change in the region (van Zinderen Bakker 1982, Tyson 1986, Cockroft *et al.* 1987, Partridge *et al.* 1990, Partridge 1993). However, numerous disparities remain; many records covering different time periods in different parts of the country do not fit the expected pattern and thus call into question the accuracy of the palaeoclimate database, the feasibility of comparing sequences which have different chronological resolutions, and the interpretation of the meaning and age of the material evidence. These problems apply to our current understanding of the nature, timing and duration of the Holocene Climatic Optimum in southern Africa. According to Partridge *et al.* (1990, 1993), most evidence points to a period of maximum warmth, approximately 2°C higher than today, between 8 000 and 5 000 BP. Their interpretation is supported by the results of multivariate statistical analyses of micromammal and pollen species abundance (Scott and Thackeray 1987) (Fig. 7.1A) and agrees with the very generalised trend in average global temperatures at mid-latitudes presented by Folland *et al.* (1990) (Fig. 7.1B). However, Scott (1993) suggested that the timespan of the period of maximum warmth can be further constrained in the pollen record to between 7 000 and 6 500 yr BP whereas Thackeray (1987) showed, using small mammal evidence from Byeneskranskop on the south-west coast and from Wonderwerk Cave in the northern Cape, that in these regions, maximum temperatures obtained around 6 300 yr BP and certainly not before. The data of Thackeray (1987) are in agreement with

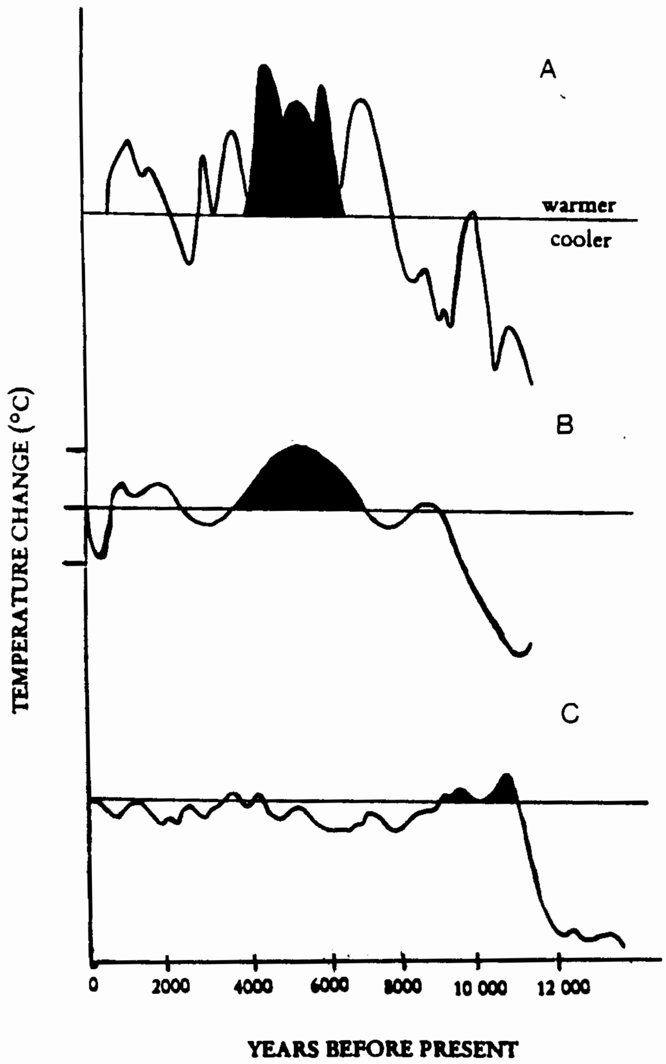


Fig 7.1 Proxy records of air temperature fluctuation through the Holocene. The amplitude of temperature changes since 10 000 yr BP, were not greater than ±2°C in each record. 7.1(A) is based on pollen species abundances at the Wonderkrater site in South Africa (Scott and Thackeray 1987). 7.1(B) is an estimated global average record after Folland et al. (1990) and 7.1(C) shows changes recorded at Antarctica (after Ciais et al. 1992). A Climatic Optimum is apparent in all three records but its timing and duration is not consistent between them.

the timing of the event in some other regions of the mid-latitude southern hemisphere where maximum warming on land was obtained around 6 000 years ago and endured for not longer than 1 000 years (Clapperton 1989, Birnie 1990, Wasson and Donnelly 1991). On the other hand, isotope data from Antarctic deep-ice cores indicate an early Holocene thermal maximum between 10 000 and 7 500 yr BP (Ciais *et al.* 1992) (Fig. 7.1C) and sea surface temperatures in the Indian sector of the Southern Ocean were highest between 10 300 and 8900 yr BP (Labracherie *et al.* 1989). The early Holocene warming recorded at high southern latitudes coincides with the timing of the event in the high northern latitudes; the latter occurred in response to increased solar radiation at 60°N in the summer months (July) around 9 000 yr BP (COHMAP 1988). Interestingly, there was little change in solar radiation at 60°S during the Antarctic warm period. The mid-latitudes of the southern hemisphere received more solar radiation in July (winter) between 12 000 and 6 000 years ago (Berger 1978) than they did over the past 6 000 years but the difference was slight, of the order of 0.1%.

Upwelling

Apart from the data presented in Chapter 6, there are no published reports regarding conditions in the coastal oceans around South Africa during the Holocene. However, the impact of global changes in atmospheric temperature on the biological productivity of the world oceans has been addressed against general circulation models and can be tested using the Holocene sea surface temperature record from the southern Benguela and that from the Agulhas Bank, which is presented in this chapter. Two conflicting scenarios have been proposed regarding the response of coastal upwelling to global warming. Bakun (1990) suggested that coastal upwelling will increase in a warmer world, responding to strengthened land-sea breezes as the air pressure gradient between continental and oceanic circulations increase. Shannon *et al.* (1990) used the Bakun model to predict the response of upwelling in the oceans around South Africa under conditions of global warming. In contrast, Hsieh and Boer (1992) proposed a general weakening of coastal upwelling as winds diminish owing to weakening of the equator-to-pole temperature gradient under greenhouse conditions. Palaeoceanographic studies in the northern Benguela (Oberhansli 1992, Schneider 1993) and off the north-west African coast (Berger *et al.* 1978) showed that coastal upwelling during the Late Quaternary increased during cool, glacial periods and decreased during warm interglacials thus supporting the hypothesis of Hsieh and Boer

(1992). Sea surface temperatures in the southern Benguela also fit this pattern, having decreased significantly during periods of Holocene cooling (Cohen *et al.* 1992, Chapter 6).

Precipitation

Palynological data from southern Africa suggests that precipitation did not necessarily fluctuate in harmony with temperature changes during the mid-Holocene nor were the transitions between wetter and drier periods uniformly timed throughout the subregion (Scott 1993). However, syntheses of all available terrestrial palaeoclimatic data from a variety of sources and sites in southern Africa by Cockroft *et al.* (1987) and Partridge *et al.* (1990), suggested that, in general, the period between 8 000 and 5 000 yr BP was associated with increased summer rainfall (December-February) over most of the country and a decrease in rainfall during winter (June-August). They imply that the summer rainfall region, which includes the north-western interior and east coast, was generally wetter when air temperatures were highest. In contrast, the winter-rainfall region encompassing the west coast of southern Africa would have been drier than it is today. Tyson and Lindesay (1992) provided a synthesis of all available evidence for the Little Ice Age in southern Africa. They suggested that, contrary to conditions during the Holocene warm period, the summer rainfall region was drier and the winter rainfall region wetter about 650 years ago.

The Tyson model

Cockroft *et al.* (1987) used the Tyson (1986) model to suggest that the mechanisms forcing Late Quaternary climatic conditions over southern Africa were analogous to those responsible for extended wet and dry spells of near-decadal duration that have occurred during the twentieth century (Tyson 1986). An important aspect of the model involves anomalies in the zonal Walker circulation through which the El Niño-Southern Oscillation exerts a considerable influence over present-day rainfall variability in southern Africa (Lindesay 1990). Anomalies in the meridional circulation involve shifts in the position of the westerly winds and changes in the position and strength of the South Atlantic Anticyclone (SAA). During the high phase of the Southern Oscillation and extended wet spells the ascending limb of the African Walker cell is situated over tropical Africa, the westerlies shift southward and the SAA strengthens. Under these atmospheric conditions, rainfall increases over the summer rainfall region whereas dry conditions prevail over the winter rainfall region. During the low phase of the Southern Oscillation (Pacific El Niño) and extended dry spells, zonal and meridional circulation are opposite in all respects. Thus, Cockroft *et al.* (1987) proposed that atmospheric conditions associated with present-day wet spells were dominant during the Holocene Climatic Optimum in South Africa. Tyson and Lindesay (1992) extended the use of the model to explain the distribution of rainfall over the country during the Little Ice Age. They suggested that atmospheric conditions associated with present-day, extended dry spells were dominant at this time.

The Tyson (1986) explanation of present-day, decadal-scale precipitation patterns over southern Africa is not the only one currently available in the literature (Jury and Pathack 1993, Jury and Levey 1993). However, it is currently the most detailed, proposed explanation of Late Quaternary climates in southern Africa. The nature of terrestrial palaeoclimatic data used by Cockroft *et al.* (1987) to test applicability of the model to palaeoclimates are limited because they give no direct information about the atmospheric conditions prevailing during past wet and dry periods. Wind strengths and direction have had to be determined by inference. In order to strengthen the predictive and interpretative powers of the model, it must be tested against palaeoclimate data from which the *mechanism* forcing past rainfall changes may be deduced. In this chapter, I suggest that the Agulhas Bank is well-placed to record changes in the latitudinal position and strength of the circumpolar westerlies and anticyclonic circulations over the South Atlantic and South Indian oceans. The ocean-atmosphere conceptual model links the ocean and atmospheric systems and together with sea surface temperature data from the Agulhas Bank, provides a means by which the atmospheric circulation model can be tested directly.

7.3 The Cohen conceptual model

The details of the Tyson model refer only to atmospheric circulation over the sub-continent and in applying the model to climate of the Late Quaternary, Cockroft *et al.* (1987) have considered only the response of the terrestrial climate to anomalies in the atmospheric circulation. In this section, I describe an "ocean-atmosphere conceptual model" which links the atmospheric circulation anomalies during wet and dry spells to sea surface temperatures on the eastern Agulhas Bank. The model is speculative but is based on the independently published predictions of mathematical models and observations of the present-day coastal oceanography around South Africa. Using the model posited here, it is also possible to predict the simultaneous response of sea surface temperatures in the southern Benguela to the proposed changes in the atmospheric circulation through the Holocene.

The relationship between interannual sea surface temperature variability on the eastern Agulhas Bank, the surface wind field and the Southern Oscillation Index was described in Chapter 2. Briefly, cool coastal waters are associated with upwelling forced by winds from the east, which blow along the coast when the South Atlantic Anticyclone ridges east and south of the sub-continent. This situation is especially pronounced during high index phases of the Southern Oscillation (La Niña). In contrast, sea surface temperatures increase when the frequency of easterly wind anomalies is low and westerly winds mix the surface and subsurface waters. This situation is especially pronounced during low index phases of the Southern Oscillation (El Niño). It is highly probable that the volume transport in the Agulhas Current also affects sea surface temperatures on the Agulhas Bank but this is more difficult to prove or quantify through lack of data. It is suggested that when the volume transport in the current is high, water upwelling over the shelf-edge to form the basal layer on the Agulhas Bank, is cooler and from greater depth than that forced over by a weaker current. The former would enhance the upwelling signal at the coast whilst the latter scenario would dampen the upwelling signal and perhaps enhance the warming effects of mixing especially in winter. Using this information, and that predicted by modelled simulations of oceanic circulation around southern Africa, the following ocean-atmosphere conceptual model is proposed.

During past dry periods (Fig. 7.2A), in response to weakened atmospheric circulation over the south-west Indian Ocean, the Agulhas Current may have weakened (Shannon *et al.* 1990) and retroflected to the west of its present-day range, moving over the Agulhas Bank and into the southern Benguela (Lutjeharms and van Ballengooyen 1984). Cooling processes including shelf-edge upwelling and coastal upwelling on the eastern Agulhas Bank may have been compromised by a weakened Agulhas Current and reduced incidence of eastward ridging of the South Atlantic Anticyclone. Strengthened westerly winds associated with a northward-expanded circumpolar vortex would have caused mixing of the water column and may have favoured the onshore advection of Agulhas Current surface water, increasing surface temperatures

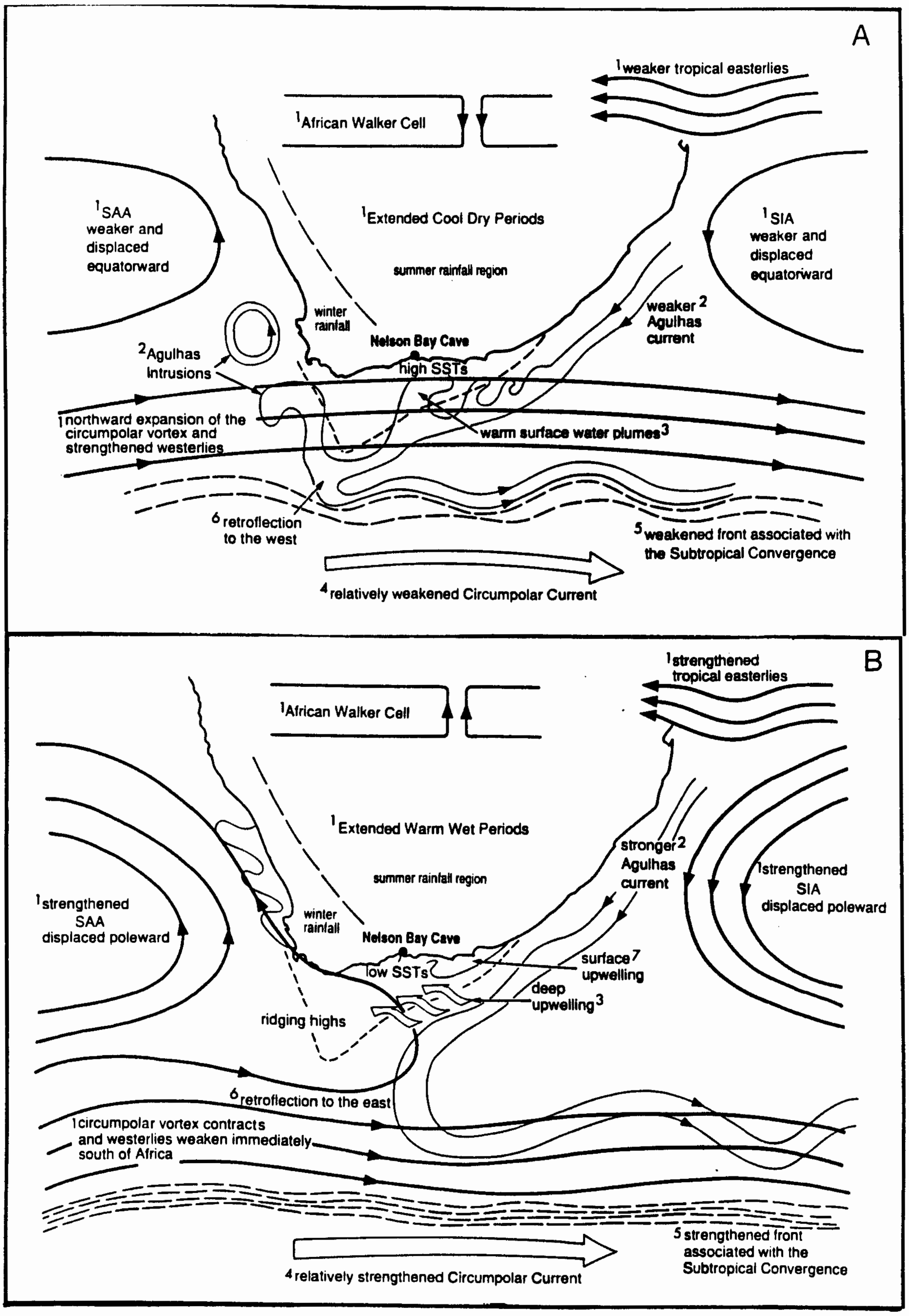


Fig. 7.2 A conceptual model of the response of oceanic circulation and coastal sea surface temperatures to atmospheric circulation anomalies responsible for extended dry spells (A) and extended wet spells (B) in South Africa. All aspects of the atmospheric circulation depicted here are after Tyson (1986) and Cockroft *et al.* (1987). Oceanic conditions in (A) result in anomalously high sea surface temperatures in the vicinity of both Nelson Bay Cave on the south coast and Elands Bay Cave on the west coast. Those in (B), including shelf-edge and coastal upwelling, result in anomalously cool surface waters in both regions. 1=Tyson (1986), Cockroft *et al.* (1987); 2=Shannon *et al.* (1990); 3=Swart and Largier (1987); 4=Wearn and Baker (1980); 5=Matano and Philander (1993); 6=Lutjeharms and van Ballegooyen (1984); 7=Schumann *et al.* (1982).

especially in winter. In the south, the Antarctic Circumpolar Current, driven by the westerlies (Wearn and Baker 1980) would have weakened and the Subtropical Convergence Front may either have moved southward (Matano and Philander 1993) or decreased in intensity. Sea surface temperature changes in the southern Benguela coastal region would also be expected to occur in response to the same atmospheric anomalies. Temperatures were likely to have increased as the incidence of nearshore intrusions of Agulhas Current water increased and upwelling-favourable winds weakened.

In contrast, Cockroft et al. (1987) suggested that during extended wet spells (Fig. 7.2b) the anticyclonic circulations strengthened and moved poleward with the contraction of the circumpolar vortex, and the westerlies withdrew to the south. The possible oceanic response to these atmospheric conditions would have been as follows. The Agulhas Current strengthened consequent upon a steepened geostrophic gradient and fed by greater volumes of water transported on the northern and eastern periphery of the South Indian Anticyclone. Water upwelling over the shelf-edge would have originated at greater depth (Swart and Largier 1987) and the bottom water layer over the Agulhas Bank would have been cooler. This, together with a greater occurrence of eastward ridging highs from the strengthened SAA and increased frequency of alongshore winds meant that coastal upwelling was more frequent and the cooling of surface waters, more pronounced. At the same time, and in the same way, the increased frequency of stronger south-easterly and southerly winds on the west coast would have forced upwelling and lower sea surface temperatures in the southern Benguela. Cooling in the southern Benguela would have been exacerbated by the early retroflection of the Agulhas Current, decreasing the amount of warm Indian Ocean water entering the Benguela. To the south, the Antarctic Circumpolar Current may have strengthened in response to strengthened westerlies above it (Wearn and Baker 1980) and the Subtropical Convergence Front may have intensified or moved northward (Matano and Philander 1993). Cool surface waters on the eastern Agulhas Bank are therefore suggested, by the model, to have been associated with increased rainfall in the summer rainfall region of South Africa but dry conditions along the west coast, in the winter rainfall region. Warm surface waters were associated with dry conditions in the summer rainfall region of South Africa but increased rainfall along the west coast.

The combined ocean-atmosphere model provides a means to test the feasibility of applying Tyson's model to Late Quaternary palaeoclimates of southern Africa, using sea surface temperature data. The advantage of using sea surface temperature records constructed from rapidly-accumulated midden shells is that the potential chronological resolution to be gained is high. Also, the exact age of climatic events in the record can be pinpointed by radiocarbon-dating individual shells. Furthermore, mollusc shells are ideal candidates for the serial-sampling technique described in Chapters 3 and 4, by which detailed, seasonal information can be extracted. In the following sections, the Holocene sea surface temperature record in mollusc shells from Nelson Bay Cave is presented.

7.4 Data and Method

The Holocene sea temperature record was constructed from the oxygen isotope composition of marine mollusc shells preserved in an archaeological deposit at Nelson Bay Cave, on the seaward side of the Robberg Peninsula (23°E, 34°S) (Figure 7.2). The mouth of the cave faces south and its lip is presently about 18m above mean sea level. The lowest layers of the deposit contain artifacts characteristic of the Middle Stone Age in southern Africa, indicating that the cave was occupied at least 90 000 years ago. No visible pieces of marine shell are preserved in these early levels. Shell fragments appear in the deposit around 12 000 years BP but are partially decalcified (Klein 1972). The first dense concentrations of shell occur in layers dated to 10 500 years BP when the coastline probably came within reach of the cave. Marine shell continues to dominate the deposit into the upper levels until the final human occupation which terminated about 650 years ago. Nelson Bay Cave was occupied intermittently, rather than continuously, over the past 10 500 years and spread of radiocarbon dates through the sequence suggests the periods in which the cave was inhabited by people were relatively short. The 4 000-year long mid-Holocene hiatus which is characteristic of coastal deposits on the western Cape coast (Parkington 1986) is not apparent in Nelson Bay Cave. Over 2.50 m of material accumulated in the cave since the appearance of the first dense shell middens which translates to a sedimentation rate of about 2cm per 100 years.

The mollusc species collected from the rocky outcrops of the Robberg Peninsula and deposited in the cave by people during the last 9 000 years of occupation are representative of the gastropod and bivalve species present in this region today. Amongst them, *Patella tabularis* is the largest southern African limpet with adults often attaining a diameter of 140mm (Kilburn and Rippey 1982). The species' present-day geographical distribution is restricted to the southern Cape coast, between False Bay to the west and Transkei to the east. Water temperatures in this region fluctuate between an average of 14°C in winter and 20°C in summer. *P. tabularis* inhabits the low-tide level of the inter- and infratidal zones down to 4m depth (Kilburn and Rippey 1982, Branch and Branch 1981) and is therefore almost constantly submerged. The shells are thick and robust, composed of two outer calcitic layers and two inner aragonitic layers separated by the myostracum or muscle scar which is also aragonitic (MacClintock 1967). They are therefore well-preserved in the archaeological deposit relative to the more friable shells of mussels and clams (Klein 1972, Shackleton 1973). These characteristics make *P. tabularis* an attractive species for isotope analysis.

Archaeological shells were excavated from the Nelson Bay Cave deposit by Klein (1972) and Inskeep (1987). Shell samples for this study were obtained from the collection now housed at the South African Museum in Cape Town. Despite Klein's (1972) indication that *Patella tabularis* was present in layers dating between 5 000 yr BP and 12 000 yr BP, only shells from layers dated between 9 000 yr and 650 yr BP were available for examination. Radiocarbon dating of strata in the archaeological sequence was commissioned by the excavators. Discrepancies existed between stratigraphy and associated dates obtained for some strata in the early Holocene levels and for this reason, shells from these layers which were used for isotopic analysis were dated individually (Table 7.2 and Appendix 7.2).

Both modern and archaeological samples were prepared for isotope analysis according to methods described in Chapter 3. Whilst independent growth rate data for this species are not available, it is possible to identify up to three annual cycles in some shells.

7.5 Results

In Table 7.1, the average annual maximum and minimum temperatures recorded at Knysna over the past twenty years are indicated. The original dataset is given in Appendix 2.1. The highest temperature recorded in each year was on average 21.15°C (± 1.02) and the lowest temperature was on average 14.51 °C (± 0.60). Data from the

TABLE 7.1: Sea surface temperatures at Knysna, eastern Agulhas Bank extracted from recorded data for the period 1972 to 1992. Temperatures during extreme El Niño and La Niña years are indicated separately.

Site/ Event	Time period	Temperature (°C) Max.	Min.	Departures January	July	Average (T°C)	* c.v.
Knysna	1972-1992	21.15 (±1.02)	14.31 (±0.60)			17.29	13.29
El Niño	1982/83	22.90	14.20	2.52	-0.84	17.98	15.68
La Niña	1988/89	18.00	13.30	-2.74	-1.95	15.95	7.00

TABLE 7.2: Sea surface temperature data inferred from the oxygen isotope composition of *Patella tabularis* shells between approximately 650 and 8700 years ago at Nelson Bay Cave. All values were corrected, where neccessary, for changes in the oxygen isotope composition of seawater through time according to Fairbanks' (1989) global ocean $\delta^{18}O$ curve.

Layer Name	No. of Samples per profile	Corrected ^{14}C Age	Inferred Temperature (°C) Max.	Min.	Standardised Departures Max.	Min.	Average Temperature (°C)	c.v.
Alex	15	650	20.79	13.08	-0.35	-2.05	17.23	10.96
E11a2	11	2400	19.43	15.98	-1.69	2.78	17.44	6.40
Bert	14	2950	19.83	14.18	-1.29	-0.22	17.03	13.00
Lucy	18	3270	20.20	14.91	-0.93	1.00	18.10	12.40
Mary	11	3350	20.15	14.39	-0.98	0.13	16.98	10.50
Reg	20	4333+	21.52	14.56	0.36	0.42	18.08	10.10
Rice A	9	4376+	21.15	16.29	0.00	3.30	18.45	8.90
Paul	9	4520	21.33	15.55	0.18	2.07	18.35	12.30
Rice B	12	4693+	19.97	14.39	-1.16	0.13	17.66	9.10
Ivan	11	4886+	21.79	13.38	0.63	-1.55	17.16	6.10
Rose	14	5200	21.66	14.65	0.50	0.57	18.12	10.63
Willey	23	5800	24.02	15.64	2.81	2.22	20.33	10.35
Rice A	12	6246+	20.83	12.75	-0.31	-2.60	17.39	17.90
Jake	12	8760+	20.24	12.70	-0.89	-2.68	16.00	15.30

* c.v. = coefficient of variation

+Radiocarbon dates on individual shells commissioned for this study. The original values were corrected according to the difference between dates on shell and charcoal of the same age (Talma, pers. comm and Appendix 7.2) and are thus comparable with the other dates on charcoal. The age of undated layers are approximated according to their stratigraphic position in relation to other, dated layers.

El Niño year of 1982/83 and the La Niña year of 1988/89 are also shown. The maximum sea surface temperature recorded at Knysna during 1982/83 was 22.90°C, almost 2°C higher than normal although the lowest temperature (14.20°C) was not significantly different from the average winter temperatures recorded during non-anomalous years. During the strong La Niña event of 1988/89, the maximum recorded temperature (18°C) was more than 3°C lower than the average recorded value and the minimum temperature (13.3°C) was also significantly lower. The degree of variability is expressed by the coefficient of variation (c.v.) which is defined as the ratio of the standard deviation of all measurements taken during the specified time period relative to the mean. Intra-annual variability during the El Niño event was higher and that during the La Niña event, lower than average.

The isotopic temperature profile of each archaeological sample analysed is plotted against radiocarbon age in Figure 7.3A and the maximum, minimum and mean temperatures are given in Table 7.2 and plotted in Figure 7.3B. The isotope values are also listed in Appendix 7.1. *Patella granularis* were absent from the Nelson Bay Cave deposit and the alternative palaeothermometer developed in Chapter 5 could not be applied in this study. Instead, the original oxygen isotope values were corrected for changes in the isotope composition of seawater since 8 700 years ago according to the global ocean isotope curve of Fairbanks (1989). The present-day temperature data from Knysna were used as a datum, to define means, maxima and minima representative of the present-day, non-anomalous situation. The isotope data from the living *P. tabularis* shell were not used as a datum because both 1991 and 1992 were anomalous, El Niño years.

Seasonal maxima and minima are evident in all archaeological samples and the amplitude of the signal varies through time. Shells aged approximately 8 700 years and 6 300 years, recorded lower summer and winter temperatures than those of today (Figure 7.3B). Around 5800 years ago, the sea surface was significantly warmer and both summer and winter temperatures exceeded, by more than 2°C, those recorded in the region today during non-El Niño years. On average, temperatures remained high for the next 1 500 years. Shells excavated from layers accumulated between 3 300 and 2 400 years ago yielded profiles in which the maximum temperatures obtained were about 1°C lower than they are today. Both summer and winter temperatures were low 650 years ago. Owing to the 1 500 year-long sampling interval between 2 400 and

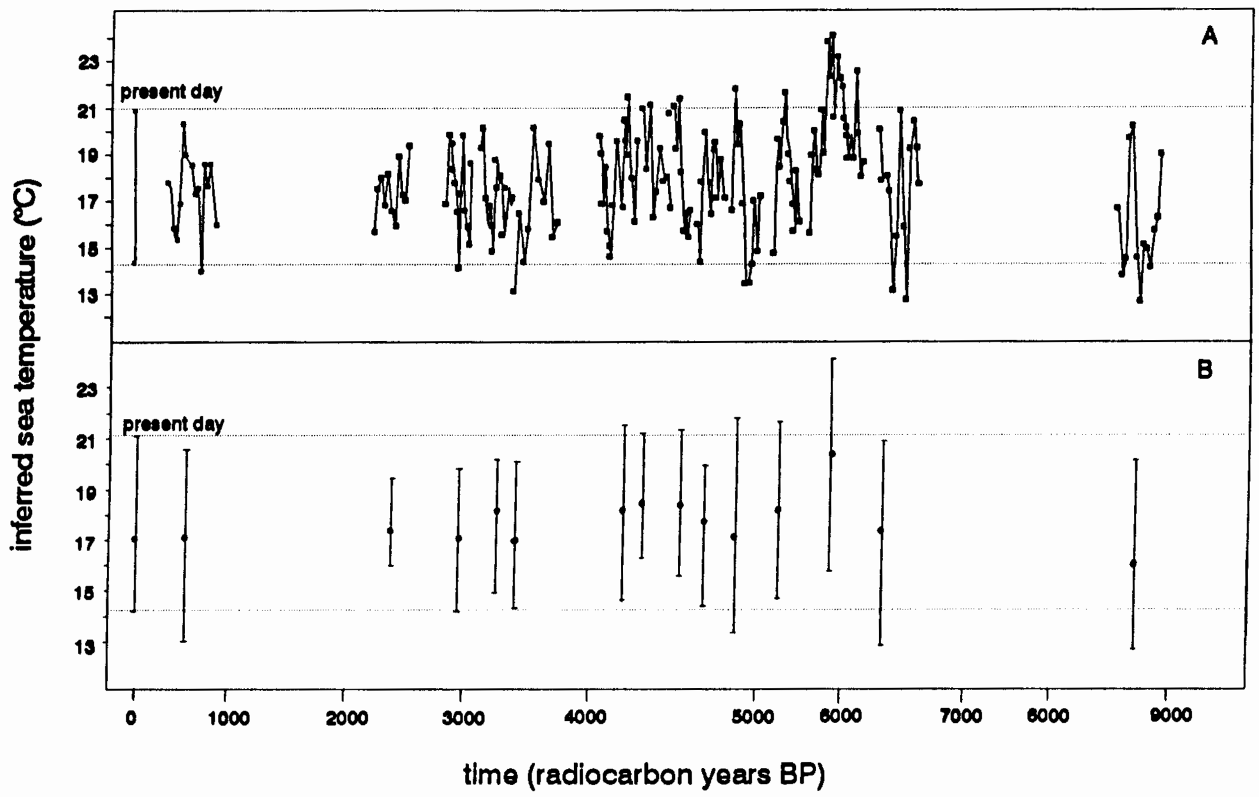


Fig. 7.3 The isotopic temperature profile through each *Patella tabularis* shell in the archaeological sample (A) and the average and range of values in each shell (B), plotted against radiocarbon age. Present-day values were calculated from Knysna sea surface temperature records of the past 20 years (Appendix 2.1). The oxygen isotope values were converted to temperature using a palaeotemperature equation Shackleton (1974) and adjusted for changes in the oxygen isotope composition of sea water since 9000 yr BP (Fairbanks 1990).

650 years ago, it is not possible to say whether or not the cool episode was continuous between 3 300 yr and 650 yr BP.

Applying the serial-sampling technique to biological organisms has several inherent problems which are evident in the record and especially in Figure 7.3A. First, different shells may include different combinations of the yearly cycle depending on their age, the distance of the first drillhole to the shell apex and the season in which the shell was collected. Secondly, the number of values extracted from each shell varies depending on its size and on the length of the calcite layer. For these reasons, the suggestion of Krantz *et al.* (1987) is followed in that quantitative analyses of the data utilize only the maximum and minimum values in each profile. Maximum and minimum values are used to calculate the standardised departures of sea surface temperatures (Figure 7.4). The magnitude of the departure indicates the significance of the temperature anomaly independent of the seasonal signal. In general, the magnitude and direction of standardised departures in the palaeotemperature record lend support to the observations made earlier i.e. that sea surface temperatures at Robberg were lower than they are today prior to 6 000 years ago and after 4 300 years ago. Between 5 800 and 4 700 years ago, the sea surface at Nelson Bay Cave was warmer than it is today, significantly so 5 800 years ago.

The degree of variability in individual shell profiles is expressed by the coefficient of variation (c.v., Table 7.2) which is defined as the ratio of the standard deviation of all measurements in the shell profile to the mean. The degree of variability is independent of within-shell sample size ($r^2 = 0.03$). The temperature records in most of the early Holocene shells exhibit the greatest variability (c.v. > 15) whereas intra-annual variability in records from many of the late Holocene (2 400 yr BP - 650 yr BP) are extremely low (c.v. < 10). High c.v. values in the early Holocene are the result of very low winter temperatures. Low c.v. values in the later Holocene are the result of low summer maxima and high winter maxima. These results are most interesting because they offer the first observations of changes in seasonal variability through time in the southern African region. They should, however, be interpreted with caution as the series from individual shells on which they are based are short.

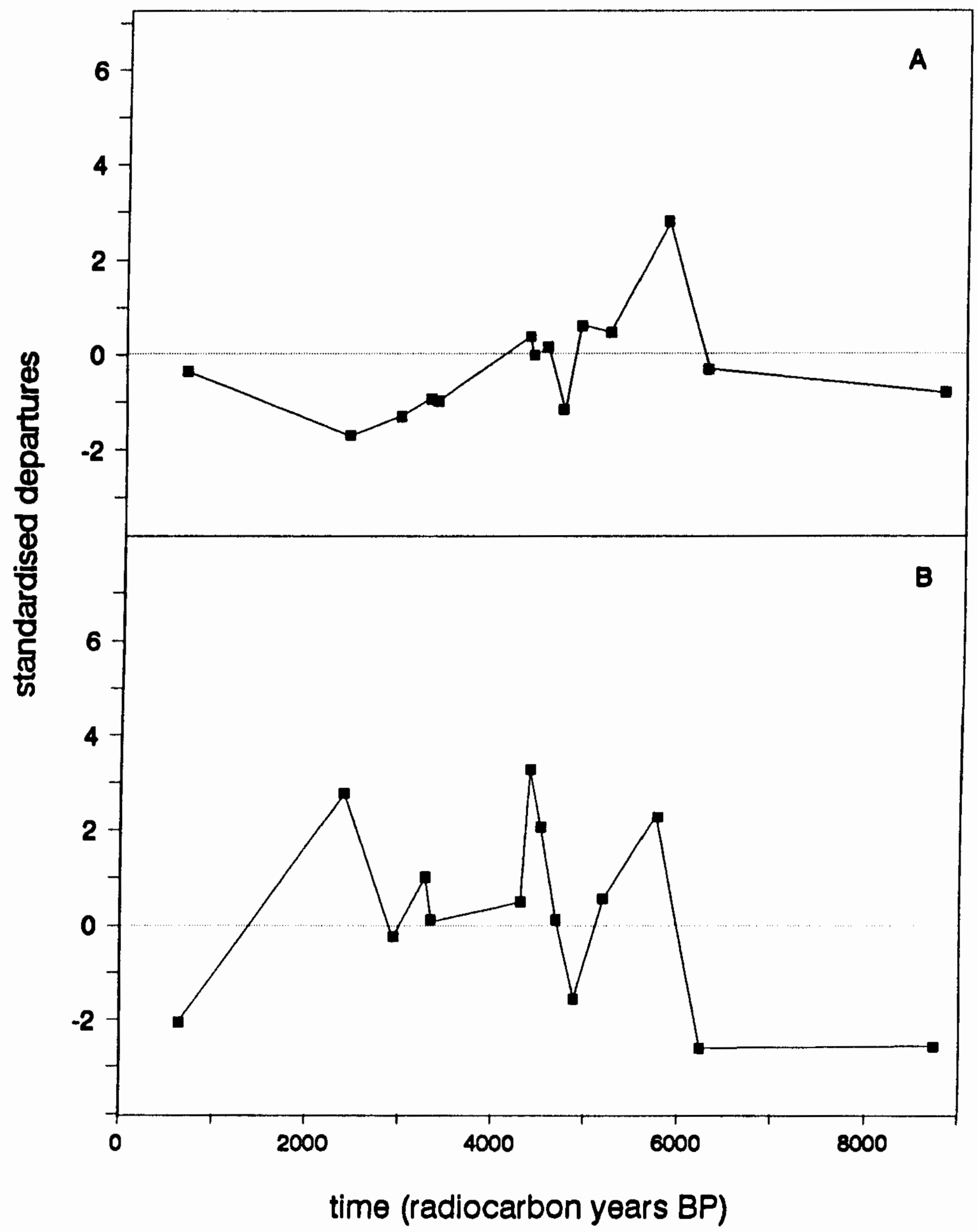


Fig. 7.4 "Summer" sea surface temperature anomalies in the Nelson Bay Cave record were calculated by subtracting the averaged maximum temperature recorded at Knysna during the past 20 years from the maximum value in each shell profile and dividing by the standard deviation among the warmest month in each of the 21 summers in Appendix 2.1, which yields a standardised departure (A). "Winter" anomalies were calculated in the same way but using the minimum values in each dataset (B). This method removes the seasonal signal from the data and indicates whether temperature anomalies have occurred over and above the normal seasonal changes, which are exaggerated by changes in air temperature. Departures $\geq \pm 0.5$ are regarded as significant by some authors (for e.g. Walker *et al.* 1984). One of the most anomalous years on record in the oceans around South Africa was the 1982/83 "warm event" associated with a Pacific El Niño. The magnitude of summer sea surface temperature departures in both the coastal southern Benguela and on the eastern Agulhas Bank, exceeded a value of +1.

7.6 Discussion

The sea surface temperature data from Nelson Bay Cave has provided a comparatively high-resolution record of changing conditions in the coastal ocean through the Holocene period. By radiocarbon-dating individual shells, a high degree of chronological resolution has been achieved for the mid-Holocene which is unmatched by any terrestrial records presently available for this time period in South Africa. Around 8 700 years ago and again at 6 300 years ago, summer and winter sea surface temperatures on the eastern Agulhas Bank were than they are today. No data were recovered for the period between these two dated events. However, by 5 800 years ago, surface temperatures had increased dramatically and in general, remained high for the next 1500 years with the exception of a cool event about 4 700 years ago. Cool summer anomalies were recorded in all shell profiles aged between 4 300 and 650 years although, without more data, it is impossible to tell whether this cool period was continuous between 2 500 and 650 yr BP.

In this section, the sea surface temperature data are used to address three questions posed in section 7.1: (1) What does this record tell us about the timing and duration of the Holocene Climatic Optimum in South Africa ? (2) What does this record, and that from the southern Benguela tell us about the response of coastal upwelling to changes in atmospheric temperature ? and (3) What does the sea surface temperature record tell us about climatic conditions on the adjacent sub-continent during the Holocene ?

The Holocene thermal optimum and upwelling along the coast of South Africa

In order to examine the regional response of upwelling and continental climate to changes in atmospheric temperature, it is necessary first to identify the precise timing and duration of these changes. Whereas post-glacial cool episodes (the Younger Dryas, Neoglacial and Little Ice Age) appear to have been relatively uniformly timed in both hemispheres and at high- and mid-latitudes, there is sufficient evidence now available to suggest marked geographical differences in the timing of the Holocene Climatic Optimum. In the northern and southern high latitudes, air temperatures were highest during the early Holocene, around 9 000 years ago (Bell and Walker 1992) and conditions at Antarctica were cool again by 6 000 yr BP (Ciais *et al.* 1992). However, at South Georgia Island (Clapperton 1989, Birnie 1990), in northern Queensland and Papua New Guinea (Wasson and Donnelly 1991), maximum warming on land was obtained around 6 000 yr BP and endured for not longer than 1 000 years. In general, terrestrial records from South Africa indicate warming between 8 000 and 5 000 years ago (Partridge *et al.* 1990) although some datasets indicate that maximum warmth was attained only in the latter part of the period and persisted for a shorter time. It is unclear whether these disparities stem from difficulties with the interpretation of the proxy data, from the different temporal resolution of sequences or lagged responses of vegetation and fauna to the increase in air temperature. The possibility that different regions experienced these changes at different times, cannot be discounted (Partridge 1993, Scott 1993).

The sea surface temperature data can only contribute to our knowledge of these changes if the oceanic response to air temperature changes is understood. Whereas surface waters of the open oceans appear to have warmed as insolation increased after 12 000 yr BP, the response may have been different in coastal upwelling regions where sea surface temperatures are determined primarily by the surface wind field. Indeed, Bakun (1990) suggested that coastal upwelling would increase, with a concommitent drop in sea surface temperature, as air temperatures increase. Shannon *et al.* (1990) suggested that upwelling along southern Cape coast would increase in a warmer world. The results of mathematical modelling however, have indicated the opposite. Hsieh and Boer (1992) proposed a contrasting scenario in which the effects of weakened large-scale atmospheric circulation systems on suppressing coastal upwelling, would far outweigh, at least in the longer term, the positive influence of strengthened land-sea breezes. Some palaeoceanographic data recovered from the west African coast appear to support the latter hypothesis (Berger *et al.* 1978, Abrantes 1991, Oberhansli 1991, Schneider 1991), indicating that the frequency and extent of upwelling in some regions during past warm periods was less than that during cool periods in the earth's recent history. It should be stressed that the magnitude and direction of the response to air temperature and atmospheric circulation changes may vary in different upwelling regions around the world. However, the Holocene sea surface temperature record from the southern Benguela presented in Chapter 6, strongly suggests that, here too, upwelling increased during periods of recent near-global cooling. On the eastern Agulhas Bank, as in the southern Benguela, summer sea surface temperatures were lower than they are today during the Neoglacial Advance between 3 000 and 2 000 years ago and at the time of the Little Ice Age. It is therefore feasible to suggest that during warm periods, the opposite scenario would have prevailed, with a suppression of upwelling-favourable winds and consequent increase in coastal ocean temperatures. If this is true, then the warming of surface water temperatures between 5 800 and 4 700 years ago in the Nelson Bay Cave record may indicate that the Holocene Climatic Optimum was attained only in the latter part of the 8 000 to 5 000 year-long period presently regarded as the Climatic Optimum in South Africa. This interpretation would also suggest that the event endured for only about 1 000 years, in agreement with evidence from South Georgia Island (Clapperton 1989, Birnie 1990), northern Australia (Wasson and Donnelly 1991) and some parts of South Africa (Thackeray 1987, Thackeray and Lee Thorp 1992). Of course, it is possible that the timing and duration of the period of maximum warmth was different in different parts of the country, as suggested by Scott (1993) especially between the extreme northern and the extreme southern regions. The strong possibility of a lag response of the ocean to changes in air temperature must also be considered.

Sea surface temperatures, terrestrial climate and rainfall

Extreme sea surface temperatures were lower around 8 700 and 6 300 years ago than they are today and from what is known about the oceanography of the Agulhas Bank, it is likely that these were caused by increased shelf-edge and coastal upwelling, higher volume transport of the Agulhas Current and increased easterly wind anomalies. According to the ocean-atmosphere conceptual model (Figure 7.2), these oceanic conditions are associated with increased rainfall over the interior of South Africa but drier conditions along the west coast brought about by strengthened anticyclonic circulations over the South Atlantic and South Indian Oceans and weakened circumpolar westerlies to the south. This inference thus supports the application of the Tyson (1986) model by Cockroft *et al.* (1987) to explain much of the palaeoclimatic evidence from these regions at these time periods. It also agrees with some of the more recently published evidence for wetter and warmer conditions prevailing in the summer rainfall region after 8 500 yr BP (Avery 1987, Partridge 1993). However, such generalisations do mask apparent discrepancies in the database which are particularly evident in the pollen records. At Wonderkrater in the Transvaal, at Badsfontein and at Blydefontein both at the edge of the summer rainfall region, the data reported by Scott and Thackeray (1987) and Scott (1990) indicate that dry conditions persisted until at least 6 000 yr BP. Whilst such discrepancies cannot persisted until at least 6 000 yr BP. Whilst such discrepancies cannot be discounted, they might be explained by the often inadequate and problematic dating of pollen sequences as Scott, himself, has suggested (Scott 1989).

The Nelson Bay Cave record shows that sea surface temperatures were anomalously high by 5800 years ago, during both winter and summer. This situation was likely to have resulted from a weakening of the oceanic semi-permanent high pressure systems and the ridging highs they produce, decreased volume transport of the Agulhas Current and an equatorward expansion of a strengthened circumpolar vortex. A reduced occurence of easterly winds along the southern Cape coast would have resulted in a concommitant decrease in the incidence of upwelling, thus contributing to the overall increase of sea surface temperature. Surface plumes shed from the northern boundary of the Agulhas Current and advected across the bank by strong south-westerly winds, may also have contributed to warming of the surface waters in winter. Furthermore, if the Agulhas Current were weaker, then water upwelling over the shelf-edge would have been warmer and from shallower depth and as a result, mixing of surface and subsurface layers by winter winds would have resulted in higher winter sea surface temperatures than are recorded in this region today. Such conditions would have been associated with dryness over much of the summer rainfall region of southern Africa. At the same time, the winter rainfall region of the south-western Cape would have been wetter.

This result is unexpected as it indicates a reversal of the apparent mid-Holocene trend identified in the syntheses of Cockroft *et al.* (1987) and Partridge *et al.* (1990) and suggests that the application of the Tyson model, at least for the short period between 5 800 and 4 700 years ago, is inappropriate. However, it should be noted these syntheses succeed only in identifying broad trends over multimillenial-scale time periods and it is unlikely that such an abrupt and short-lived event would be recognised in the majority of the palaeoclimate records used. Indeed, well-resolved palynological sequences and independent geomorphological interpretations which <u>do</u> cover the period between 6 000 and 4 000 years ago, show that dry conditions prevailed in the summer rainfall region of South Africa for this short time (Butzer 1984a,b; Scott 1993). Micromammal remains at Nkupe on the east coast of South Africa indicate a trend toward drier conditions after 8500 yr BP (Avery 1990) and at Wonderwerk Cave in the northeastern Cape, both micromammal and isotopic data indicate drier conditions at 6 000 yr BP (Thackeray 1987, Thackeray and Lee-Thorp

1992). Further evidence to suggest that conditions were drier in the summer rainfall region comes from an marine sediment core off the mouth of the Orange River, which shows that the influx of dust from the Namib Desert into the Benguela at approximately 5 800 yr BP decreased dramatically, indicating weakened tropical easterlies (Gingele 1992). The implications of anomalously high sea surface temperatures at Nelson Bay Cave around 6 000 years ago for drier conditions in the summer rainfall region of South Africa are therefore supported by a sufficiently large body of direct evidence for such a situation on land. As more highly-resolved terrestrial and marine sequences become available, it is probable that an increasing number of such climatic reversals may be identified in the Holocene record.

This interpretation of the sea surface temperature record between 5 800 and 4 700 years ago also has implications for climate in the winter rainfall region of South Africa, which includes Elands Bay. The ocean-atmosphere conceptual model predicts that cool water anomalies on the eastern Agulhas Bank are associated with dry conditions in the winter rainfall region and such a scenario would have prevailed 8 700 years ago and again 6 300 years ago. In contrast, warm water anomalies would have been associated with increased rainfall in the winter rainfall region. Thus, despite the absence of data from the southern Benguela during this time period, the ocean-atmosphere model allows extrapolation of the Nelson Bay Cave sequence to the western Cape coast of South Africa. Parkington (1986) suggested that the occupational hiatus at Elands Bay Cave and other west coast archaeological sites between about 7 900 and 4 300 years ago, was in part, a response by people to extreme aridity in the region. My interpretation of the sea surface temperature record from Nelson Bay Cave suggests that conditions may have been favourable for occupation of the west coast of South Africa a few hundred years prior to the time when the region was in fact reinhabited. Unfortunately, but partly as a result of the lack of archaeological material, there is at present, no independent, firm record from the west coast of South Africa of conditions of the terrestrial climate system during the mid-Holocene. Klein (1991) suggested, on the basis of dune-molerat sizes, that the winter-rainfall region was drier between 8 000 and 4 000 years ago. However, the interpretation is based on analyses of a single sample from Byeneskranskop, on the south coast of South Africa with an associated date of 6 300 yr BP, clearly not applicable to the entire mid-Holocene. Furthermore, whether these data are applicable to the winter rainfall region is debatable.

The sea surface on the eastern Agulhas Bank cooled again 4 700 years ago indicating conditions similar, although possibly weaker, than those prevailing before 8 000 years ago. After about 4 300 years ago, sea surface temperatures dropped and remained low until deposition was terminated around 650 years ago. Thus, atmospheric conditions associated with a wetter summer rainfall region prevailed between 3 500 yr and 2 400 yr BP and again 650 years ago. Unfortunately, no isotope data are yet available for the period between 2 400 yr and 650 yr BP which includes the Medieval Warm Epoch in southern Africa. There may well have been one or more reversals toward higher oceanic temperatures during this time period.

Low sea surface temperatures 650 years ago were undoubtably associated with the Little Ice Age, initiated at about this time in Southern Africa (Tyson and Lindesay 1992). Upwelling along the coasts of southern California (Kipp and Towner 1975, Keorper *et al.* 1985), north-west Africa (Berger *et al.* 1978) and the west coast of South Africa (Cohen *et al.* 1992, Chapter 6) increased during this period of global cooling probably due to strengthening of the general atmospheric circulation (Lamb 1979). The implications of the Nelson Bay Cave record for atmospheric circulation over the subcontinent during this period, are not in agreement with those proposed by Tyson and Lindesay (1992). However, their explanation of atmospheric conditions prevailing at this time does not account for evidence from a number of sites in the summer rainfall region of South Africa (Scott and Thackeray 1987, Scott 1989, Scott and Bousman 1990, Thackeray and Lee-Thorp 1992, Avery 1990) which indicate a trend toward wetter conditions after 1 000 yr BP and are thus in agreement with the predictions of the ocean-atmosphere model posited earlier i.e. that weakened anticyclonic circulations and strengthened westerlies prevailed over South Africa during the Little Ice Age.

Whilst no isotopic data are yet available for oceanic conditions on the eastern Agulhas Bank prior to 8 700 years ago, the dramatic decrease in numbers of the cold-water mussel, *Choromytilus meridionalis* valves in the deposit and the appearance of the warmer-water species, *Perna perna*, at the beginning of the isotope record (Klein 1972) is informative. Independent experiments have shown that *C. meridionalis* fails to thrive at temperatures below 18°C (Clarke and Griffiths 1990) Today populations of this species are restricted almost entirely to the cool waters of the Benguela. Its presence in the deposit prior to 9 000 years ago suggests that sea surface temperatures on the eastern bank were even cooler then than they are today and the coastal oceanography may have been similar to that of the present-day southern Benguela system with pronounced seasonal upwelling. Similarly, the apparent absence of *P. tabularis*, a warmer-water species, from these early layers suggests that the sea surface temperatures on the eastern Agulhas Bank were cooler prior to 9 000 yr BP probably because upwelling events were more frequent and the influence of Agulhas Current surface waters was reduced. The SST record from the southern Benguela is in agreement with this hypothesis inferred from mollusc species frequency. Between 12 000 and 10 000 yr BP, SST decreased by between 1°C and 2°C in the southern Benguela responding to stronger anticyclonic circulation over the south Atlantic Ocean and less Agulhas Current water intruding into the coastal region (Cohen *et al.* 1992, Chapter 6).

7.7 Summary

The oxygen isotope profiles in shells from the Nelson Bay Cave deposit provide the first ever Holocene sea surface temperature record for the eastern Agulhas Bank region. The Agulhas Bank was identified as a particularly useful area for studying changes in the atmospheric circulation over South Africa because here, coastal sea surface temperatures respond to latitudinal shifts and changes in the strength of the surface wind field. Interannually, these variations are linked to phase changes of the Southern Oscillation, a powerful phenomenon which affects the climate of many regions around the world (Philander 1983). The data were used to address three aspects of Holocene climate in South Africa, namely the timing and duration of the Climatic Optimum, the response of coastal upwelling to changes in atmospheric temperature and the application of Tyson's atmospheric circulation model to explain longer-term rainfall trends over the sub-continent. It is clear that the former two processes cannot be addressed independently. In order to identify a thermal optimum in the sea surface temperature record, it is neccessary to understand the response of coastal upwelling to changes in atmospheric temperature. On the other hand, a firm record of the timing, duration and magnitude of atmospheric temperature changes is required if the nature of the oceanic response is to be understood. Thus, the two models of upwelling cited in this chapter are of limited use in this context until the Climatic Optimum in South Africa is better defined, because their predictions are contradictory. Nevertheless, evidence from other upwelling regions, including the southern Benguela, indicated that wind-driven coastal upwelling increased during past periods of global cooling, but decreased during past warm periods, thus supporting the predictions of Hsieh and Boer (1992). In terms of this model, warm surface water anomalies recorded at Nelson Bay Cave between 5800 and 4700 years ago must have occurred during the warmest part of the Holocene at this latitude in South Africa. The sea surface temperature data, interpreted in terms of the ocean-atmosphere conceptual model posited in this chapter, support the application of the Tyson atmospheric circulation model to explain rainfall patterns over South Africa prior to 6 000 years ago. However, the data suggest that conditions between 8 000 and 5 000 years ago were not uniform and for the period 5 800 to 4 700 yr BP, the Tyson model is not applicable. The data were also used to provide some information about climatic conditions at Elands Bay during the time of the major occupational hiatus. Here too, conditions do not appear to have been uniform throughout the mid-Holocene and it is quite likely that a combination of factors perhaps both climatic and cultural, contributed to the decision made by inhabitants of the region to move elsewhere for almost 4 000 years.

CHAPTER 8

SUMMARY

In this thesis, records of Holocene sea surface temperature have been constructed for two South African coastal regions. Palaeotemperature information was preserved in the shells of marine molluscs. Variations in the isotopic composition, crystal structure and mineralogy of the shells of local species were shown to be related to the temperature of the water in which the shell was accreted. In Chapter 1, I explained why this particular approach to palaeoclimate reconstruction was taken. I suggested that climate of the Holocene may represent an unusual, stable "mode" of climate, of a kind not apparent in reconstructions of the last or penultimate glacial periods nor for a large part of the Last Interglacial. Reconstruction of terrestrial, atmospheric and oceanic systems during major climatic events of the Holocene, including the Holocene Climatic Optimum and Little Ice Age therefore may provide useful information about the potential responses of the system to relatively small perturbations in the present climate; perturbations of the amplitude expected over the next century.

Of particular interest, due to the situation of the southern African subcontinent between three major oceanic systems, is the response of coastal sea surface temperatures to changes in global atmospheric temperature. Sea surface temperature records also provide information about climate and rainfall patterns over South Africa and therefore can be considered as indicators of terrestrial as well as oceanic climate. Thus, model predictions of the response of oceanic conditions to global change have been compared against the data presented in this thesis. The applicability of an atmospheric circulations model to explain Late Quaternary terrestrial climates of southern Africa, has also been considered in terms of these records of coastal ocean temperature.

There have been no previous attempts to reconstruct sea surface temperatures of the Holocene off the coast of South Africa probably because Holocene climates up until fairly recently, have been of interest largely to archaeologists and less so to local marine geologists. Furthermore, much of the offshore sedimentary environment is not conducive to retrieving Holocene sediments suitable for constructing high-resolution records. For this reason I have suggested that archaeological deposits along the South African coast present an untapped, alternative source of material for reconstructing a detailed history of coastal conditions. Whereas archaeologists and archaeological deposits are a primary source of information about Late Quaternary palaeoenvironments in southern Africa, the vast amount of shell which lies preserved in middens, cave shelters and raised beaches of the Last Interglacial, has been largely ignored with the exception of three isolated studies.

Shells from archaeological middens also provide several advantages for coastal palaeoceanographic studies which elsewhere have utilised microfossils such as foraminifera or coccolithophores. Most of the mollusc species preserved in archaeological sites have living representatives inhabiting the present coastline and therefore are amenable to modern experimentation. This, and the availability of information about the ecology and biology of local species, enabled me to examine and interpret the relationship between the isotopic and structural composition of the shells and environmental temperatures. In coastal deposits, shell material is present in large quantities which is easily accessible at fairly low cost. Shell middens accumulated rapidly; at Nelson Bay, over 2.5 m of shell were deposited in less than 9 000 years. The deposition rate in Elands Bay Cave was higher, about 1 m in 3 000 years, providing ideal material for construction of the high-resolution record presented in Chapter 6. Mollusc shells are larger and longer-lived than foraminifera and thus the potential exists to extract seasonal information from a single animal (Chapter 7). Furthermore, precise dating of events in the palaeoclimate record has become of such paramount importance that individual microfossils are radiocarbon-dated using accelerator facilities. In a large mollusc, such as *Patella tabularis*, sufficient $CaCO_3$ is present in a single shell for radiocarbon dates to be obtained conventionally, without the need for accelerator facilities.

Some problems associated with the use of archaeological material for palaeoclimatic reconstruction were encountered during this study. Temporal gaps in midden deposits, where no material accumulated for several millennia, presented problems for the construction of records at both Elands Bay and Nelson Bay Cave. In the former, gaps in the Late Holocene deposit were filled using material excavated from adjacent sites. However, hypotheses about west coast climate and sea surface temperatures during the mid-Holocene presently remain untestable by direct means. An approach such as that taken in Chapter 7, where links were established between climatic parameters of different regions, may go some way to resolving this problem. The chronological resolution of the Nelson Bay Cave record was comparatively low and as a result, climatic episodes appeared to be more gradual and longer-lived. It is likely that the low resolution of this sequence was partly a function of the nature of the excavation and that the full potential of, and variability in the isotope record was not realised in this sequence.

Aspects of present-day sea surface temperature variability in the regions under study, i.e. the southern Benguela and the eastern Agulhas Bank, were discussed in Chapter 2. The aim of this literature review, and presentation of previously unpublished data, was to describe the important mechanisms forcing intra- and interannual sea surface temperature variability in these regions. The positions and strengths of atmospheric circulation systems, the South Atlantic Anticyclone and the circumpolar wind belt are important factors influencing sea surface temperatures in the southern Benguela on time scales from days to decades. The South Indian Anticyclone may account for some of the interannual variability in the southern Benguela through its role in determining the quantity and flowpath of Agulhas Current water transported into the south-east Atlantic. Of particular interest is the apparent teleconnection between El Niño events in the Pacific Ocean and warm water anomalies in the southern Benguela, especially since recent studies have demonstrated a strong link between phase changes of the Southern Oscillation and rainfall patterns over southern Africa.

Owing to a paucity of information about similar processes and relationships for the eastern Agulhas Bank, time-series of sea surface temperature, wind and the southern oscillation index were analysed by myself and two colleagues, and some of these unpublished data were presented in this chapter. The study supported the conclusions of previous reports that, unlike the southern Benguela, seasonal temperature fluctuations on the eastern Agulhas Bank were marked, and advective processes, such as upwelling or the onshore movement of warm water plumes, were not as important as solar radiation in forcing the intra-annual signal. However, interannual sea surface temperature anomalies were clearly related to phase changes of the southern oscillation and to regional surface winds.

A discussion of the theory and application of the oxygen isotope thermometer, one of two thermometers used in this thesis, was provided in Chapter 3. Details of the method employed in Chapters 4, 6 and 7 were given here. Inherent difficulties in applying the method to mollusc shells, including the uncertainty of the relationship between $\delta^{18}O_{aragonite}$ and seawater temperature, the susceptibility of aragonitic shell structures to diagenetic alteration and our inability to measure the oxygen isotope composition of ancient seawater, were discussed. Potential means to overcome such difficulties were considered which introduced the subjects of the following two chapters: modern experimentation and the development of an alternative palaeothermometer.

The results of oxygen isotope analyses of shells of living molluscs, collected from different sites along the South African coast, were presented in Chapter 4. By comparing the isotope measurements against actual temperatures, local limpet species were shown to be reliable indicators of intra- and interannual coastal sea surface temperatures. Nevertheless, the presence of large and variable amounts of aragonite in the shell of *P. granularis* may limit the usefulness of this species for oxygen isotope thermometry.

The development of an alternative palaeothermometer, one which was independent of the isotopic composition of seawater, was described in Chapter 5. The thermometer was based on temperature-dependent structural and mineralogical changes in the shell of *Patella granularis*. Thus, the feature that made this species unsuitable for oxygen isotope thermometry, allowed the development of another, perhaps even better, thermometer. The idea of aragonite:calcite thermometry was not new; a few attempts were made in the 1950's and 1960's to quantify and apply the relationship between mineral composition and temperature. However, these attempts met with limited success and were never pursued. In this chapter, I have shown that a stronger correlation exists between the widths of the outer aragonite and calcite shell layers, and sea surface temperature than between temperature and whole-shell mineralogy. I suggested that this technique will be more useful than X-ray diffraction when measurements are made of ancient shells which have undergone partial diagenesis of the aragonite layers.

The construction and interpretation of a Holocene sea surface temperature record from the southern Benguela was presented in Chapter 6. The record covered three episodes of global cooling but excluded the period most likely to have been associated with highest air temperatures during the Holocene in South Africa. Two different techniques were employed: the oxygen isotope analyses of *P. granatina* shells and the measurement of outer aragonite and calcite shell layers of *P. granularis*. The records constructed using each technique were remarkably similar, indicating the usefulness and accuracy of the alternative thermometer developed in this thesis. The magnitude of temperature fluctuations indicated by changes in shell layer widths were equivalent to the magnitude of temperature fluctuations in the oxygen isotope record when the latter was adjusted according to changes in the oxygen isotope composition of seawater. The data also showed that sea surface temperatures in the southern Benguela responded in the same way and with the same magnitude to three discrete episodes of global cooling which occurred during the Holocene. Two possible mechanisms were proposed to explain the oceanic cooling: reduced input of Agulhas Current water into the southern Benguela and increased upwelling. These mechanisms need not be mutually-exclusive, as illustrated in Chapter 7, but with the techniques used in this study, I was unable to distinguish between these processes.

In Chapter 7, a coastal sea surface temperature history of the eastern Agulhas Bank between about 8 700 years ago and the present was constructed. Only the oxygen isotope technique could be applied in this study because *P. granularis* shells, required for application of the alternative palaeothermometer, were not found in the deposit. Instead, the oxygen isotope values were adjusted according to a global ocean isotope curve (Fairbanks 1989) and the data were presented as sea surface temperatures. Owing to the strong seasonal fluctuations in this region, the approach to palaeotemperature reconstruction was different from that used in the southern Benguela. Seasonal temperature profiles were constructed for individual shells and the magnitude of standardised departures of the maximum and minimum values in each profile were considered to be a reflection of anomalous conditions at the sea surface. The results showed that sea surface temperatures departed from the "usual" present-day pattern several times during the Holocene. The most interesting of these events was an apparent warming around 5 800 years ago, which coincided with evidence from other southern hemisphere regions for a Holocene Climatic Optimum. Although winter insolation was higher and summer insolation was lower 6 000 years ago at 30°S compared with today, these changes were too small to explain the warm event in the oceans adjacent to Nelson Bay Cave. This, and other anomalies evident in the record, were explained in terms of processes which have caused anomalies of similar magnitude during the past twenty years.

Theoretical responses of sea surface temperatures in the southern Benguela and on the eastern Agulhas Bank to the atmospheric conditions thought, by Cockroft *et al.*

(1987), to have prevailed during millennial-scale wet and dry periods of the Late Quaternary in southern Africa, were indicated using an "ocean-atmosphere conceptual model". The actual sea surface temperature data did not always support the model predictions with the exception of the early stages of the Holocene Climatic Optimum. Nevertheless, these data alone did not disprove the atmospheric circulation model or its applicability to Late Quaternary palaeoclimates of southern Africa. I showed that the results and interpretation of several records of Holocene palaeoclimate were clearly inconsistent with the regional scenarios proposed by several authors, upon which the model predictions are based. It is possible that individual datasets have been misinterpreted or that regional variability is far greater than previously realised. It is also clear that the poor and variable temporal resolution of many palaeoclimate records poses severe limitations on attempts to construct regional scenarios.

Modelled predictions of the response of coastal upwelling to global climate changes were also considered and compared with the palaeotemperature records constructed in this study. In the southern Benguela, the response of sea surface temperatures to episodes of worldwide cooling during the Holocene was unambiguous: sea temperatures decreased rapidly. Whether increased upwelling, reduced input of Agulhas Current water into the southern Benguela, or both processes caused sea temperatures to change, cannot be tested with these data. Nevertheless, the "ocean-atmosphere conceptual model" indicates that it is not unlikely for atmospheric circulation conditions which favoured both processes simultaneously, to have prevailed during the Holocene. In contrast, the response of sea surface temperatures on the eastern Agulhas Bank to warming during the time period currently thought to have been the Holocene Climatic Optimum in South Africa, was more complex. Sea surface temperatures were anomalously low during the early phase of warming, prior to 6 300 years ago, consistent with intense upwelling. However, as the warming continued the surface waters warmed and remained anomalously warm until about 4 700 years ago. The timing of the warm episode in the coastal zone adjacent to Nelson Bay Cave corresponded with the timing of maximum terrestrial warmth on the western Agulhas Bank and in other regions of the mid-latitude southern hemisphere. Thus, there exists a strong possibility that the Holocene Climatic Optimum occurred somewhat later in the southern regions of South Africa than is currently believed, one which deserves further investigation.

In conclusion, a Holocene sea surface temperature record in the coastal oceans around South Africa has been constructed by applying palaeothermometric techniques to mollusc shells preserved in archaeological deposits. The data have provided the first longer-term perspective on sea surface temperature changes in the southern Benguela and eastern Agulhas Bank coastal regions and indicated how the local oceanography may have responded in the past and may respond to future changes in global climate. These data have also been useful in assessing the predictions of models of past and future climates. Furthermore, the potential now exists to test ideas regarding mid-Holocene climate on the west coast of South Africa despite the lack of direct information from this region.

Important issues have arisen from this study which should be identified as priorities for future investigation. These include the development of techniques to distinguish between different mechanisms forcing past sea surface temperature changes in this region. Another is to examine more closely the nature, timing and duration of the Holocene Climatic Optimum in the terrestrial environment of southern Africa. The archaeological record is clearly a unique and valuable source of information about past climate. Archaeologists should be encouraged to adopt sampling strategies appropriate for the degree of temporal resolution required for palaeoclimatic reconstruction. Furthermore, the remains of a variety of other marine organisms, including crayfish mandibles and barnacle tests, are preserved in archaeological deposits, and may provide different and complementary information about past coastal environments. With regard to this study, it is clear that the approach taken is a profitable one. By increasing the number of sampling sites and the size of the dataset, patterns evident in the Holocene record could be established with a greater degree of confidence.

APPENDIX 2.1

AVERAGE MONTHLY SEA SURFACE TEMPERATURES AT KNYSNA

JANUARY 1972 TO DECEMBER 1992*

YEAR	1972	1973	1974	1975	1976	1977	1978	1979	1980	1981	1982	1983	1984	1985	1986	1987	1988	1989	1990	1991	1992	Mean	std
January	22.83	16.53	19.67	20.97	19.55	22.05	21.06	19.23	20.90	20.80	22.10	22.90	18.50	21.10	20.30	20.50	21.70	17.40	21.40	20.50	21.73	20.56	1.60
February	20.97	15.49	19.59	17.40	18.93	20.42	21.45	20.70	20.00	19.40	21.50	22.10	19.90	19.30	20.10	22.20	17.70	14.10	19.10	19.80	21.39	19.60	2.00
March	17.75	18.49	15.48	18.40	19.98	19.30	20.77	19.54	19.20	19.60	19.30	21.40	16.60	20.20	18.40	20.00	15.30	17.70	14.80	18.90	20.16	18.63	1.76
April	18.58	13.72	14.28	18.10	18.66	19.32	15.96	21.77	18.70	19.40	16.60	18.70	15.80	19.10	18.70	18.80	16.00	16.60	14.90	17.20	18.05	17.57	1.92
May	16.65	14.83	14.60	16.50	16.98	16.34	15.19	16.77	17.80	16.40	16.10	16.50	16.30	16.70	17.20	17.40	16.70	15.20	16.50	16.70	16.13	16.36	0.79
June	18.66	15.80	13.47	16.12	14.07	16.40	15.66	17.22	16.10	14.60	16.70	15.10	15.60	15.70	16.40	15.10	15.30	14.50	15.30	14.10	16.41	15.63	1.15
July	14.47	14.69	14.44	14.90	14.11	15.33	13.81	13.69	15.30	14.90	14.20	14.20	15.50	14.50	14.90	15.20	15.20	13.30	15.40	14.00	15.60	14.65	0.64
August	14.31	13.82	15.21	14.85	15.04	14.55	14.02	13.52	15.50	14.40	14.60	14.80	14.10	14.90	15.40	15.50	15.60	14.60	15.50	14.00	14.38	14.70	0.60
September	14.75	14.47	15.58	15.83	15.74	15.75	14.88	14.78	15.90	15.70	15.00	15.90	15.80	16.20	16.20	15.80	15.20	16.10	16.00	15.80	15.65	15.57	0.50
October	16.74	15.45	17.69	16.44	16.66	18.06	15.84	16.58	17.00	17.50	16.90	16.60	17.00	17.70	17.00	16.60	16.40	16.70	16.80	17.00	15.67	16.78	0.63
November	15.11	16.75	18.97	18.45	17.77	19.00	18.83	17.63	18.00	19.10	18.90	19.40	16.80	17.40	18.00	16.90	15.50	18.00	17.60	18.90	18.02	17.86	1.13
December	18.21	18.02	20.37	18.40	19.84	20.28	20.68	20.67	20.50	19.20	20.60	21.60	18.90	17.80	19.00	19.80	17.80	20.40	19.30	20.90	20.00	19.63	1.10
Mean	17.42	15.67	16.61	17.20	17.28	18.07	17.35	17.67	17.91	17.58	17.71	18.27	16.73	17.55	17.63	17.82	16.53	16.22	16.88	17.32	17.77		
Std	2.54	1.47	2.37	1.69	2.08	2.26	2.84	2.65	1.89	2.18	2.59	3.01	1.57	1.99	1.67	2.28	1.79	1.92	1.99	2.40	2.40		

* All data supplied by the Meteorological Office at the DF Malan Airport in Cape Town.

APPENDIX 4.1

OXYGEN ISOTOPE VALUES, EXPRESSED RELATIVE TO THE PDB STANDARD, AND INFERRED SEA SURFACE TEMPERATURES FROM *PATELLA* SHELLS COLLECTED LIVE ALONG THE COAST OF SOUTH AFRICA

Collection site/ species	UCT No.	$\delta^{18}O^{a,b}$ (°/oo,PDB)	t(°C)[c]
Seapoint			
P. granatina	2326	0.44	16.23
	2326	0.72	15.09
	2326	0.59	15.62
	2326	0.78	14.84
	2327	0.62	15.53
	2328	0.42	16.37
	2328	0.71	15.10
	2329	0.57	15.75
	2329	0.45	16.22
	2330	0.49	16.05
	2331	0.69	15.19
	2331	0.82	14.63
	2331	0.65	15.40
	2331	0.83	14.59
P. granularis	2321	0.89	14.33
	2322	0.82	14.63
	2323	1.50	11.77
	2324	1.07	13.58
	2325	1.10	13.46
Buffelsbaai			
P. granatina	2332	0.06	17.98
	2332	0.24	17.15
	2333	0.14	17.62
	2333	0.26	17.05
	2334	0.32	16.79
	2334	0.59	15.63
	2335	0.42	16.37
	2335	0.74	15.00

P. granularis	2336	0.88	14.37
	2337	0.77	14.87
	2338	0.93	14.19
	2339	1.29	12.66
	2339	1.25	12.83
	2340	1.16	13.22
	2341	1.11	13.41
	2341	1.06	13.61
	2342	0.36	16.63
	2342	1.19	13.09
	2342	1.29	12.65
Seapoint			
P. granatina	2358	1.04	13.70
	2358	1.07	13.59
	2358	1.05	13.65
	2358	1.08	13.56
	2358	1.18	13.14
	2351	0.57	15.72
	2352	0.80	14.74
	2353	0.58	15.70
	2354	0.86	14.49
	2354	0.85	14.53
	2356	1.18	13.12
	2356	1.36	12.38
P. granularis	2343	1.49	11.82
	2343	1.65	11.15
	2344	1.08	13.55
	2345	1.31	12.59
	2346	1.23	12.90
	2347	0.77	14.87
	2347	1.04	13.73
	2348	1.72	10.87
	2348	1.84	10.39
	2349	1.49	11.82
Elands Bay			
P. granatina	2489	1.04	13.71
	2490	0.89	14.35
	2491	0.94	14.16
	2519	1.06	13.65
	2520	1.12	13.39
P. granularis	2492	1.42	12.12
	2534	1.42	12.12

South Point			
P. granatina	2493	1.45	12.01
	2494	1.51	11.75
	2495	1.16	13.22
	2521	1.43	12.09
	2522	1.63	11.24
P. granularis	2496	1.70	10.98
	2535	1.85	10.36

[a]Raw data calibrated to PDB using standard laboratory formulae
[b]PDB values corrected to NBS-20 values of -4.14 for $\delta^{18}O$ and -1.06 for $\delta^{13}C$
[c]$\delta^{18}O_w$ = 0.30°/oo

APPENDIX 4.2

$\delta^{18}O$ PROFILE IN A *PATELLA GRANATINA* SHELL COLLECTED NEAR LAMBERTS BAY, WEST COAST IN SEPTEMBER 1989.

Godwin Lab No.	Sample No.	$\delta^{18}O^{a,b}$ (°/oo,PDB)	t^c (°C)
S 91/2516	1	1,46	11,95
S 91/2517	2	1,30	12.60
S 91/2518	3	1,31	12,58
S 91/2519	4	1,44	12,04
S 91/2520	5	1,51	11,75
S 91/2521	6	1,03	13,76
S 91/2522	7	1,01	13,84
S 91/2523	8	0,68	15,25
S 91/2524	9	0,58	15,68
S 91/2525	10	0,84	14,56
S 91/2526	11	0,94	14,14
S 91/2527	12	1,34	12,45
S 91/2528	13	1,26	12,79

[a] Raw data calibrated to PDB using standard laboratory formulae
[b] PDB values corrected to NBS-19
[c] $\delta^{18}O_w$=0.30°/oo

APPENDIX 5.1

RATIOS OF THE WIDTH OF ARAGONITIC AND CALCITIC LAYERS, EXPRESSED AS % LAMELLAR (% ARAGONITE) IN *PATELLA GRANULARIS* SHELLS COLLECTED LIVE ALONG THE COAST OF SOUTH AFRICA

Collection site	Shell length (mm)	% lamellar (aragonite)
DURBAN	7.00	85.00
n=52	8.00	80.00
	8.00	85.00
	8.00	75.00
	9.00	90.00
	9.00	80.00
	9.00	85.00
	10.00	85.00
	10.00	75.00
	10.00	80.00
	10.00	90.00
	10.00	80.00
	10.00	80.00
	10.00	85.00
	11.00	85.00
	11.00	75.00
	11.00	80.00
	11.00	80.00
	11.00	75.00
	11.00	70.00
	11.00	85.00
	11.00	80.00
	13.00	85.00
	14.00	85.00
	14.00	70.00
	15.00	80.00
	16.00	90.00
	16.00	75.00
	17.00	90.00
	18.00	80.00
	18.00	95.00
	18.00	70.00

	19.00	90.00
	21.00	85.00
	21.00	70.00
	21.00	85.00
	22.00	85.00
	22.00	85.00
	23.00	85.00
	25.00	80.00
	25.00	85.00
	25.00	90.00
	25.00	95.00
	26.00	90.00
	28.00	85.00
	28.00	90.00
	28.00	85.00
	29.00	90.00
	29.00	85.00
	29.00	90.00
	31.00	90.00
	33.00	85.00
PORT ELIZABETH	10.00	68.00
n=80	11.00	75.00
	11.00	75.00
	12.00	70.00
	12.00	75.00
	13.00	75.00
	13.00	65.00
	13.00	60.00
	14.00	78.00
	14.00	85.00
	14.00	80.00
	14.00	75.00
	14.00	75.00
	14.00	75.00
	15.00	80.00
	15.00	80.00
	15.00	70.00
	16.00	78.00
	16.00	85.00
	16.00	85.00
	16.00	80.00
	16.00	75.00
	16.00	80.00
	16.00	80.00
	16.00	75.00

16.00	75.00
16.00	80.00
17.00	65.00
17.00	75.00
17.00	82.00
17.00	82.00
17.00	85.00
18.00	78.00
18.00	75.00
18.00	90.00
18.00	75.00
18.00	85.00
19.00	75.00
19.00	78.00
19.00	80.00
19.00	80.00
19.00	85.00
19.00	85.00
19.00	75.00
20.00	83.00
20.00	80.00
20.00	78.00
21.00	78.00
21.00	80.00
21.00	78.00
21.00	75.00
22.00	78.00
22.00	80.00
22.00	80.00
22.00	75.00
23.00	88.00
23.00	70.00
23.00	65.00
23.00	85.00
24.00	85.00
24.00	75.00
26.00	78.00
27.00	80.00
28.00	80.00
28.00	80.00
28.00	88.00
28.00	80.00
29.00	85.00
29.00	78.00
30.00	75.00
31.00	80.00

	31.00	90.00
	31.00	82.00
	31.00	78.00
	31.00	90.00
	32.00	90.00
	33.00	92.00
	33.00	80.00
	34.00	85.00
	38.00	80.00
DALEBROOK	19.20	68.42
n=21	19.60	68.57
	21.90	65.12
	22.60	79.37
	25.40	69.23
	25.90	69.57
	26.60	65.96
	27.40	79.25
	27.80	70.73
	27.80	75.00
	28.00	78.18
	28.10	60.53
	28.90	75.00
	30.60	76.67
	30.70	65.31
	31.60	77.27
	32.00	78.18
	32.20	76.67
	34.60	75.00
	34.80	74.63
	35.90	80.65
EAST LONDON	79.59	
n=28	16.80	63.08
	19.30	64.52
	20.00	83.87
	20.20	52.50
	21.00	55.26
	24.70	75.00
	25.70	63.64
	27.30	71.43
	27.30	66.00
	28.30	73.91
	30.00	79.25
	30.50	69.57
	31.60	70.37

	31.90	77.27
	31.90	76.79
	32.10	77.97
	32.70	82.54
	34.00	72.73
	34.10	73.08
	35.40	74.07
	35.60	79.41
	35.90	77.05
	36.80	79.37
	37.10	81.16
	39.20	77.03
	41.10	81.08
	41.70	85.37
PORT NOLLOTH	17.00	20.00
n=35	21.00	21.00
	22.00	10.00
	22.00	13.00
	28.00	50.00
	30.00	32.00
	31.00	46.00
	31.00	20.00
	31.00	42.00
	31.00	44.00
	32.00	33.00
	33.00	51.00
	34.00	45.00
	35.00	47.00
	36.00	45.00
	36.00	39.00
	37.00	44.00
	37.00	39.00
	37.00	40.00
	38.00	56.00
	39.00	37.00
	39.00	40.00
	41.00	42.00
	41.00	55.00
	41.00	39.00
	42.00	58.00
	43.00	50.00
	43.00	48.00
	43.00	56.00
	44.00	51.00
	45.00	38.00

	45.00	29.00
	46.00	40.00
	46.00	50.00
	47.00	45.00
SEAPOINT	57.95	
n=28	22.00	63.27
	22.50	29.27
	23.50	46.15
	23.90	43.75
	25.10	32.61
	26.20	35.00
	27.80	50.00
	28.00	52.38
	28.10	61.54
	29.50	52.94
	30.30	58.06
	30.80	66.67
	32.60	41.67
	33.70	43.75
	33.90	61.40
	34.00	49.18
	34.80	50.79
	34.90	47.14
	35.90	60.87
	37.50	73.17
	38.00	50.00
	39.20	66.67
	40.40	44.83
	42.60	50.55
	42.80	50.59
	43.60	58.25
	47.90	59.30
PATERNOSTER	14.40	43.59
n=25	16.60	43.33
	20.50	29.27
	22.70	50.00
	22.80	32.61
	25.70	51.11
	25.80	54.00
	28.40	57.45
	29.10	35.42
	32.10	29.58
	32.40	51.43
	33.30	54.55

	34.60	24.66
	34.90	44.83
	36.50	52.94
	36.60	56.82
	37.00	54.79
	37.20	28.40
	37.30	67.47
	38.40	46.15
	40.20	44.44
	41.10	45.00
	43.30	41.18
	44.20	40.91
	45.90	55.65
BUFFELSBAY	15.90	73.33
n=18	16.60	63.64
	17.70	58.97
	18.00	65.85
	20.60	57.14
	21.00	76.09
	21.00	75.00
	23.80	69.77
	24.40	59.32
	26.20	71.70
	27.80	67.80
	28.00	61.40
	30.00	55.81
	30.50	54.10
	31.20	67.57
	31.70	71.43
	32.00	83.33
	43.00	60.78
OUDEKRAAL	15.60	51.28
n=31	17.70	57.50
	20.20	50.00
	22.70	55.56
	24.00	55.81
	24.30	51.79
	25.30	51.02
	27.90	57.63
	29.10	68.12
	30.30	53.52
	31.00	59.21
	31.40	60.27
	32.00	58.82

32.30	50.85
32.40	66.67
32.90	58.21
33.50	64.10
35.90	55.07
36.00	65.91
36.00	54.76
36.50	57.14
37.00	57.33
37.30	46.91
37.80	70.59
38.40	61.86
39.00	63.41
40.80	51.04
41.00	62.96
42.50	57.47
46.60	58.49
48.00	64.80

APPENDIX 5.2

ESTMATED PERCENT ARAGONITE BASED ON X-RAY DIFFRACTION ANALYSES OF WHOLE SHELLS OF *PATELLA GRANULARIS* COLLECTED LIVE FROM THE COAST OF SOUTH AFRICA. THE RELATIVE HEIGHTS OF THE PRINCIPAL PEAKS OF ARAGONITE AND CALCITE WERE CONVERTED TO % ARAGONITE USING A CALIBRATION CURVE (LOWENSTAM 1954).

Collection Site	Shell length (mm)	% aragonite
Oudekraal	15.60	28.00
	17.70	18.00
	20.20	28.00
	24.00	30.00
	24.30	30.00
	27.90	35.00
	32.30	44.00
	35.90	25.00
	37.00	28.00
	40.80	23.00
	41.00	35.00
	42.50	23.00
	46.60	21.00
	48.00	21.00
Dalebrook	15.00	60.00
	24.50	42.00
	24.50	66.00
	28.00	50.00
	28.00	80.00
	29.00	98.00
	31.00	80.00
	31.00	70.00
	31.00	93.00
	31.50	78.00
	33.00	90.00
	34.00	90.00
	35.00	63.00
Buffelsbay	16.40	30.00
	20.87	33.80
	23.80	26.00
	24.10	26.00
	26.20	49.00
	27.80	74.00
	30.00	44.00
	30.50	54.00
	31.20	65.00
	31.70	67.00
	32.00	66.00
	43.00	24.00

Durban	10.10	80.00
	10.90	78.00
	16.30	74.00
	20.58	85.00
	20.70	74.00
	23.70	77.00
	24.60	73.00
	24.80	82.00
	25.50	80.00
	26.50	61.00
	27.60	68.00
	27.90	70.00
	28.00	82.00
	28.80	60.00
	31.00	67.00
	31.40	70.00
Port Elizabeth	11.80	42.00
	15.30	52.00
	17.30	53.00
	18.75	53.00
	20.25	78.00
	22.00	53.00
	22.20	66.00
	23.30	74.00
	27.00	83.00
	27.00	85.00
	29.30	45.00
	32.90	73.00
	37.30	60.00
Seapoint	19.00	15.00
	19.20	10.00
	22.50	10.00
	25.00	10.00
	29.50	8.00
	31.30	12.00
	33.70	7.00
	33.90	38.00
	40.00	7.00
	40.50	13.00
	43.00	13.00
	43.10	5.00
	45.90	10.00
	49.50	27.00
Paternoster	20.00	7.00
	21.00	8.00
	26.00	7.00
	27.60	9.00
	27.90	22.00
	31.00	8.00
	32.60	6.00
	36.20	6.00
	36.50	12.00
	39.00	14.00
	41.50	28.00
	46.60	30.00
	47.10	14.00

	47.50	10.00
	48.00	31.00
	50.30	22.00
	52.50	13.00
East London	16.80	58.00
	19.65	73.00
	24.70	89.00
	27.30	84.00
	27.30	80.00
	31.90	90.00
	31.90	84.00
	34.10	83.00
	35.40	82.00
	35.60	80.00
	41.10	89.00
	41.70	90.00

APPENDIX 6.1

OXYGEN ISOTOPE VALUES EXPRESSED RELATIVE TO THE PDB STANDARD, AND INFERRED SEA SURFACE TEMPERATURES FROM *PATELLA GRANATINA* SHELLS IN WEST COAST MIDDENS

Site/ Midden	UCT No.	$\delta^{18}O^{a,b}$ (°/oo, PDB)	t(°C)[c]
EBC(1)	2498	0.92	14.22
(JOSHUA N'KOMO)	2499	1.12	13.38
	2500	1.13	13.33
	2501	1.10	13.46
	2502	1.50	11.79
DFM(3)	3632	1.47	11.91
	3633	1.58	11.46
	3634	1.66	11.13
DFM(1)	3623	1.63	11.25
	3624	1.39	12.24
	3625	1.56	11.54
EBO	4142	1.55	11.58
	4144	1.19	13.08
	4141	1.39	12.24
	4140	1.25	12.83
EBO	4130	1.40	12.20
	4134	1.11	13.42
	4132	0.83	14.61
	4133	0.87	14.44
DFM2	3628	0.77	14.86
	3629	0.99	13.93
	3630	1.40	12.20
DFM4	3637	1.34	12.45
	3899	1.15	13.25
EBO	4135	1.12	13.38
	4135	1.28	12.70
	4138	0.75	14.95
	4138	0.97	14.01

	4136	1.37	12.33
	4136	1.51	11.75
	4137	1.47	11.91
	4139	1.45	12.00
GRM D(A)	3563	1.31	12.58
	3567	1.11	13.42
GRM D(B)	3557	1.46	11.95
	3643	1.56	11.54
	3901	1.36	12.37
GRM D(C)	3558	1.74	10.80
	3640	1.82	10.47
GRM D(D)	3561	1.06	13.63
	3644	1.17	13.17
GRM B(E)	3562	1.82	10.47
	3642	1.80	10.56
SC (UDF)	3638	1.42	12.12
	3639	1.57	11.50
KBM C(I)	3556	1.68	11.05
	3898	1.43	12.08
	3899	1.65	11.17
EBC(8)	3779	1.49	11.83
(EDDIE BARLOW II)	3781	1.32	12.54
	3782	0.92	14.22
	3783	1.37	12.33
	3784	1.45	12.00
EBC(8)	2362	1.41	12.16
(RHINO)	2363	1.31	12.58
	2466	0.97	14.01
EBC(8)	2528	1.60	11.38
(SHAKA)	2529	1.51	11.75
	2530	1.41	12.16
	2531	1.46	11.95
	2532	1.43	12.08

EBC(11)	2364 1.67	11.09
(MAROON ROBESON)	2365 1.38	12.29
	2468 1.32	12.54
	2515 1.43	12.08
	2516 1.46	11.95
EBC(11)	4214 1.42	12.12
(BURNT ROBESON)	4215 1.35	12.41
	4217 1.65	11.17
EBC(12)	2475 1.57	11.50
(BSBP)	2476 1.75	10.76
	7477 1.45	12.00
	2478 1.32	12.54
	2479 1.57	11.50
EBC(12)	3658 1.52	11.71
(NEPTUNE)	3657 1.21	13.00
	3659 1.30	12.62
	3906 1.62	11.29
	3907 1.43	12.08
	3905 1.74	10.80
	3908 1.84	10.39
EBC(10)	3565 2.09	9.38
(CRAYFISH)	3564 1.82	10.47
	3566 1.95	9.95
	3554 1.60	11.38
EBC(13)	3549 2.01	9.70
(FOAM)	3550 2.03	9.62
EBC(13)	3551 1.95	9.95
(SMOKE)	3653 2.19	8.98
	3553 2.01	9.70
	3651 2.34	8.38
	3652 2.22	8.86
EBC(13)	3570 2.35	8.34
(DUST)	3568 2.18	9.02
	3568 2.08	9.42
	3569 2.11	9.30
	3567 2.11	9.30
	3548 2.13	9.22

EBC(13)	3552	1.83	10.43
(ASHES)	3656	2.04	9.58
	3547	1.99	9.78
	3655	2.08	9.42
EBC(15)	2472	1.74	10.80
(KARL MARX)	2473	1.98	9.82
	2473	1.84	10.39
	3672	1.74	10.80
	3673	1.97	9.86
EBC(16)	2497	1.92	10.07
(GBS)	2523	2.04	9.58
	2524	1.97	9.86
	2525	2.00	9.74
	2526	2.15	9.14

[a] Raw data calibrated to PDB using standard laboratory formulae
[b] pdb values corrected to NBS-20 values of -4.14 for $\delta^{18}O$ and -1.06 for $\delta^{13}C$
[c] $\delta^{18}O_w$=0.30°/oo

DFM=Dunefield Midden;EBC (Crayfish)=Elands Bay Cave, Layer Crayfish; EBO=Elands Bay Open; GRM=Grootrif Midden; KBM=Kreeftebaai Midden; SC=Spring Cave;

APPENDIX 6.2

MEASUREMENTS OF THE WIDTH OF ARAGONITIC (M+1) AND CALCITIC (M+2&3) LAYERS IN *PATELLA GRANULARIS* SHELLS FROM ARCHAEOLOGICAL SITES ON THE WEST COAST OF SOUTH AFRICA. THE LAYER WIDTH RATIO IS EXPRESSED AS % ARAGONITE OR % LAMELLAR.

Site/ midden	Shell length (mm)	M (+1) (mm)	M+ (2&3) (mm)	% lamellar (aragonite)
EBC(1)	30.31	2.07	3.10	39.98
(JOSHUA N'KOMO)	30.32	3.95	2.80	58.52
	30.67	2.75	4.90	35.95
	31.15	3.50	3.10	53.03
	32.45	2.60	3.35	43.70
	34.20	3.25	3.51	48.08
	35.10	3.25	4.60	41.40
	35.10	5.05	3.90	56.42
	35.80	2.20	4.05	35.20
	37.10	3.50	4.40	44.30
	37.20	3.90	5.25	42.62
	38.00	5.10	5.60	47.66
	38.10	2.06	6.10	25.25
	38.34	3.51	5.10	40.77
	39.90	4.70	4.80	49.47
	41.60	5.10	4.70	52.04
	43.20	2.90	5.40	34.94
	43.44	5.60	6.12	47.78
	43.80	4.50	5.10	46.88
	44.60	5.40	5.45	49.77
	45.00	6.30	4.70	57.27
	45.06	4.01	4.20	48.81
	46.12	4.90	5.05	49.25
DFM3	33.00	3.40	4.20	44.74
	33.60	3.70	4.10	47.44
	34.00	3.30	3.00	52.38
	35.00	3.80	3.00	55.88
	35.00	3.60	3.60	50.00
	35.80	3.30	4.20	44.00
	37.00	3.00	3.90	43.48
	37.00	4.00	3.20	55.56

	37.00	3.80	4.30	46.91
	38.00	3.20	4.70	40.51
	39.00	3.70	4.90	43.02
	43.00	4.80	5.70	45.71
DFM1	33.00	2.10	4.00	34.43
	33.70	3.10	4.40	41.33
	34.00	3.30	3.50	48.53
	34.80	3.90	3.00	56.52
	35.60	2.80	3.60	43.75
	36.00	3.30	3.90	45.83
	36.70	1.90	3.40	35.85
	36.80	2.40	4.00	37.50
	37.00	3.50	3.80	47.95
	38.10	3.00	4.00	42.86
	38.40	3.70	3.20	53.62
	38.50	3.50	4.10	46.05
	39.00	3.10	3.00	50.82
	39.30	2.60	4.00	39.39
	39.30	2.60	4.10	38.81
	40.00	2.70	4.20	39.13
	40.20	2.80	4.10	40.58
	41.00	2.90	5.00	36.71
	36.00	2.20	5.50	28.57
EBO	33.00	3.00	3.80	44.12
		3.10	2.40	56.36
	43.20	3.50	4.60	43.21
	32.00	2.40	3.30	42.11
	34.70	2.15	4.00	34.96
	41.50	2.50	5.00	33.33
	37.60	3.40	4.30	44.16
	36.60	3.80	3.60	51.35
	45.00	3.60	5.00	41.86
		3.90	3.80	50.65
		3.50	3.90	47.30
	28.00	2.60	3.30	44.07
		3.20	3.50	47.76
	30.00	2.00	3.30	37.74
	24.40	1.10	3.20	25.58

EBO	40.80	3.50	4.80	42.17
	36.20	3.60	4.10	46.75
	31.50	2.80	3.40	45.16
	32.00	3.80	3.90	49.35
		4.30	4.10	51.19
		2.80	3.90	41.79
		4.00	2.70	59.70
		2.80	3.60	43.75
	41.20	3.60	3.90	48.00
	33.70	2.90	4.10	41.43
		2.90	3.80	43.28
	31.00	2.60	3.50	42.62
	39.00	3.40	4.30	44.16
	36.00	4.50	3.80	54.22
		2.80	4.30	39.44
		4.20	4.50	48.28
DFM2	29.80	2.90	2.80	50.88
	30.00	3.80	3.50	52.05
	30.00	3.00	3.10	49.18
	31.00	4.00	2.90	57.97
	31.10	2.80	3.60	43.75
	34.00	4.00	2.70	59.70
	34.00	3.20	2.90	52.46
	34.00	3.60	3.80	48.65
	34.60	3.70	3.30	52.86
	34.60	3.40	3.60	48.57
	36.00	3.10	3.80	44.93
	37.70	3.20	3.80	45.71
	38.30	4.10	4.80	46.07
	39.50	5.00	4.10	54.95
	42.80	4.20	3.60	53.85
	43.80	4.60	4.20	52.27
EBO	35.20	2.50	5.50	31.25
	21.20	1.90	2.45	43.68
	30.00	2.70	2.90	48.21
	36.00	3.10	3.30	48.44
	36.00	3.50	3.85	47.62
	32.50	3.90	4.10	48.75
	38.40	3.20	5.20	38.10
	39.10	3.70	4.50	45.12
	36.30	3.80	4.00	48.72
	34.40	3.30	3.70	47.14
GRM D(A)	38.30	3.30	4.40	42.86

	36.40	4.50	3.10	59.21
	32.00	2.90	3.50	45.31
	29.00	2.20	3.30	40.00
	18.20	1.80	1.90	48.65
GRM D(B)	32.50	3.60	2.60	58.06
	32.50	2.50	3.10	44.64
	29.70	2.70	2.90	48.21
	29.00	1.80	2.70	40.00
	45.00	6.50	5.75	53.06
GRM D(C)	29.00	4.50	2.00	69.23
	29.50	3.30	3.10	51.56
	31.00	4.00	3.50	53.33
	31.60	2.40	3.70	39.34
	32.00	2.80	3.00	48.28
	33.00	3.10	3.20	49.21
	33.50	3.00	2.20	57.69
	33.60	2.10	4.20	33.33
	34.00	2.20	3.90	36.07
	35.00	2.60	5.60	31.71
	35.00	2.40	3.40	41.38
	36.20	2.60	5.00	34.21
	36.60	3.40	3.20	51.52
	38.00	4.00	3.80	51.28
	38.00	4.10	3.10	56.94
	38.60	2.80	5.00	35.90
	38.70	3.20	2.40	57.14
	44.40	3.20	5.00	39.02
GRM D(D)	23.00	2.70	1.80	60.00
	28.50	3.00	2.40	55.56
	30.40	2.40	4.60	34.29
	31.00	3.00	4.20	41.67
	31.00	4.30	3.20	57.33
	31.00	4.00	2.40	62.50
	31.40	2.70	3.00	47.37
	31.70	3.60	3.50	50.70
	32.00	2.10	2.70	43.75
	32.80	3.00	3.10	49.18
	33.00	2.70	4.30	38.57
	33.70	2.00	3.70	35.09
	34.70	3.60	3.20	52.94
	37.00	3.00	3.90	43.48
	37.00	4.30	4.30	50.00
	39.00	3.90	4.90	44.32

	43.00	3.30	4.20	44.00
	44.00	3.80	4.90	43.68
KBM C(I)	25.00	2.40	2.60	48.00
	27.00	2.00	3.00	40.00
	31.00	2.80	3.00	48.28
	31.00	2.00	4.40	31.25
	31.00	3.40	4.40	43.59
	31.00	2.30	3.20	41.82
	32.00	2.00	3.50	36.36
	34.50	3.10	3.40	47.69
	36.70	3.10	4.00	43.66
	37.00	1.80	5.10	26.09
	42.10	2.30	6.00	27.71
EBC(11)	27.00	3.00	2.00	60.00
(MAROON ROBESON)	32.30	2.00	4.00	33.33
	34.00	3.30	3.10	51.56
	34.00	2.90	2.90	50.00
	36.00	2.00	4.30	31.75
	36.00	3.20	4.30	42.67
	36.70	3.00	3.70	44.78
	37.00	3.40	3.60	48.57
	38.00	3.50	4.40	44.30
	39.00	4.00	2.90	57.97
	39.00	3.60	4.50	44.44
	40.00	4.50	3.60	55.56
	41.30	4.60	4.50	50.55
	41.50	3.80	3.10	55.07
	42.60	4.00	3.40	54.05
	43.00	5.10	3.50	59.30
	43.00	2.30	5.00	31.51
	44.60	6.00	4.30	58.25
EBC(11)	42.10	5.70	4.50	55.88
(NEW ROBESON)	43.50	3.10	5.00	38.27
	45.10	4.10	4.60	47.13
	45.90	6.10	3.40	64.21
	49.30	6.50	6.40	50.39
	44.60	6.00	5.50	52.17
	40.00	5.00	4.20	54.35
	44.00	6.10	4.60	57.01
	47.90	5.00	4.70	51.55
EBC(11)	34.00	2.60	3.90	40.00
(BURNT ROBESON)	34.00	2.30	2.60	46.94

	35.60	3.60	3.50	50.70
	36.50	4.50	2.60	63.38
	36.60	5.00	3.70	57.47
	39.60	3.90	3.90	50.00
	40.00	4.90	3.20	60.49
	42.40	4.90	3.10	61.25
	48.20	4.10	5.90	41.00
	48.50	7.00	4.00	63.64
	49.60	5.80	3.80	60.42
EBC(12) (BSBP)	29.00	1.50	4.00	27.27
	30.00	2.60	3.00	46.43
	30.00	2.30	2.80	45.10
	30.00	2.10	3.80	35.59
	31.00	3.00	2.00	60.00
	31.00	4.00	2.40	62.50
	31.00	3.10	3.00	50.82
	31.00	3.20	3.40	48.48
	31.00	2.20	4.10	34.92
	32.00	2.80	3.00	48.28
	32.00	2.60	4.00	39.39
	35.00	3.40	3.00	53.13
	35.00	3.30	4.00	45.21
	38.00	3.70	3.20	53.62
	39.00	4.30	3.70	53.75
	39.00	3.30	4.30	43.42
	40.00	4.50	4.50	50.00
	40.00	4.50	4.00	52.94
	41.00	4.00	5.40	42.55
	43.00	4.20	5.00	45.65
	46.00	5.40	4.50	54.55
EBC(10) (CRAYFISH)	32.00	2.60	3.00	46.43
	32.60	1.80	2.00	47.37
	32.30	2.30	3.10	42.59
	31.70	2.40	3.40	41.38
	34.40	2.20	5.30	29.33
	31.00	2.40	3.50	40.68
	37.00	3.50	4.90	41.67
	33.00	1.80	3.60	33.33
	32.00	2.10	4.60	31.34
	29.00	2.80	3.30	45.90
	37.00	2.40	4.10	36.92
	32.00	2.60	3.30	44.07
	32.60	3.10	3.60	46.27
	36.80	3.20	4.10	43.84

	34.40	2.80	4.10	40.58
	31.50	2.70	3.00	47.37
	26.80	2.50	3.00	45.45
	31.00	1.80	3.40	34.62
	35.00	3.00	4.30	41.10
EBC(13)	37.50	2.60	5.40	32.50
(ASHES)	39.20	3.80	3.20	54.29
	40.90	4.40	2.80	61.11
	41.50	3.40	4.60	42.50
	41.80	4.30	5.20	45.26
	42.30	4.90	4.20	53.85
	42.80	4.70	4.40	51.65
	43.70	3.30	6.50	33.67
	44.00	3.70	4.60	44.58
	46.90	3.60	6.60	35.29
	47.00	3.90	5.30	42.39
	48.70	5.70	4.50	55.88
	48.90	5.00	5.30	48.54
	49.00	5.40	5.30	50.47
	49.60	6.10	4.00	60.40
	50.60	6.90	5.20	57.02
	38.80	5.50	2.60	67.90
EBC(13)	16.60	1.40	1.60	46.67
(SMOKE)	20.80	1.40	2.60	35.00
	36.60	3.20	5.00	39.02
	38.40	4.30	4.40	49.43
	40.00	2.90	5.50	34.52
	40.00	4.00	5.00	44.44
	41.10	3.70	4.60	44.58
	43.00	3.00	5.10	37.04
	44.00	4.50	4.50	50.00
	44.00	6.00	5.00	54.55
	44.40	3.60	4.40	45.00
	45.50	5.40	4.70	53.47
	46.10	5.40	4.80	52.94
	46.70	4.40	5.20	45.83
	48.80	4.80	4.80	50.00
	49.00	5.90	5.70	50.86
	51.50	5.80	5.50	51.33
	53.10	6.20	5.70	52.10
EBC(13)	29.50	2.60	3.20	44.83
(FOAM)	36.00	3.40	4.00	45.95
	37.20	3.10	3.90	44.29

	38.00	3.60	5.00	41.86
	39.00	3.90	4.20	48.15
	39.30	3.20	4.20	43.24
	39.70	3.40	5.90	36.56
	39.80	4.00	4.10	49.38
	40.00	3.90	4.80	44.83
	40.00	2.60	5.40	32.50
	40.00	3.60	4.90	42.35
	41.00	3.40	4.00	45.95
	41.50	2.50	5.20	32.47
	41.60	4.50	3.50	56.25
	42.00	3.00	5.10	37.04
	42.40	3.80	4.90	43.68
	42.70	3.80	4.80	44.19
	42.80	3.50	4.00	46.67
	42.90	4.30	4.80	47.25
	43.00	3.40	4.90	40.96
	43.00	3.00	5.20	36.59
	43.10	4.40	4.90	47.31
	43.30	4.30	4.30	50.00
	43.60	3.00	4.30	41.10
	43.80	3.80	4.40	46.34
	43.90	3.20	5.30	37.65
	44.20	3.10	5.10	37.80
	44.80	3.90	4.70	45.35
	45.00	3.40	4.10	45.33
	45.00	6.30	4.10	60.58
	45.21	5.10	3.50	59.30
	47.00	3.30	6.20	34.74
	47.10	5.80	5.40	51.79
	47.40	4.70	4.40	51.65
	47.90	5.00	5.10	49.50
	49.00	5.00	5.20	49.02
	49.00	5.20	5.40	49.06
	52.60	4.50	5.50	45.00
EBC(15) (KARL MARX)	33.00	2.20	3.40	39.29
	36.00	3.10	4.40	41.33
	38.00	4.00	4.00	50.00
	39.00	4.00	4.30	48.19
	39.00	3.00	5.00	37.50
	39.00	3.80	4.70	44.71
	40.00	3.20	3.80	45.71
	40.00	3.60	4.70	43.37
	40.00	3.30	5.00	39.76
	41.00	4.40	4.30	50.57

41.60	3.50	4.00	46.67
42.00	2.00	5.00	28.57
43.00	4.40	5.00	46.81
44.00	4.90	4.20	53.85
44.00	3.40	5.00	40.48
44.50	4.00	5.00	44.44
46.00	5.30	4.80	52.48
47.00	4.20	5.40	43.75
47.00	4.50	4.80	48.39
48.00	4.40	5.00	46.81

DFM=Dunefield Midden; EBC(11) (Crayfish)=Elands Bay Cave Spit 11, Layer Crayfish; EBO=Elands Bay Open; GRM D(D)=Grootrif Midden D, Sample D; KBM=Kreeftebaai Midden; SC=Spring Cave.

Appendix 7.1

Oxygen isotope values, expressed relative to the PDB standard, and inferred sea surface temperatures from *Patella tabularis* shell profiles

Site/ Level	UCT No.	Drill hole no.	Ms. No.	$\delta^{18}O^{a,b}$ (°/oo; PDB)	t(°C)[a]
Stillbaai	4769	2	20975	0.02	21.29
		4	20976	0.33	19.88
		5	20943	1.23	15.90
		6	20973	1.73	13.76
		7	20945	1.38	15.25
		8	20946	0.89	17.38
		9	20940	0.81	17.74
		10	20941	0.02	21.29
		11	20947	0.18	20.56
		12	20942	0.11	20.88
		13	20944	0.60	18.67
		14	20948	1.04	16.72
		15	20939	-0.19	22.25
		16	20949	0.15	20.70
		17	20938	0.21	20.42
		18	20974	1.73	13.76
		19	20972	0.69	18.27
Alex	4588	1	18202	0.81	17.74
		2	21301	0.87	17.47
		3	18201	1.36	15.34
		4	21302	1.50	14.74
		5	18200	1.08	16.55
		6	21304	0.13	20.79
		7	21305	0.50	19.12
		9	21306	0.61	18.62
		10	21307	0.94	17.16
		11	18199	0.88	17.43
		12	21309	1.89	13.08
		13	18198	0.59	18.71
		14	21311	0.86	17.52
		15	18197	0.60	18.67
		17	18196	1.33	15.47

E111A2	4671	1	19298	1.27	15.72
		2	19299	0.85	17.56
		3	19296	0.73	18.09
		4	19302	1.01	16.86
		6	19300	0.70	18.22
		8	19301	1.06	16.64
		9	19295	1.21	15.98
		10	19306	0.53	18.98
		11	19304	0.91	17.30
		12	19303	0.96	17.08
		13	19305	0.43	19.43
Bert	4589	2	18954	1.00	16.90
		3	18955	0.34	19.83
		4	18956	0.41	19.52
		5	18957	0.66	18.40
		6	18958	0.80	17.78
		7	18959	1.07	16.59
		8	18976	1.63	14.18
		9	18991	0.90	17.34
		10	18992	0.34	19.83
		11	18993	1.06	16.64
		12	18994	1.22	15.94
		13	18995	1.40	15.16
		14	18996	0.61	18.62
Lucy	4687	4	20007	0.45	19.34
		5	20002	0.26	20.20
		6	20013	0.93	17.21
		7	20008	1.21	15.98
		8	20011	1.03	16.77
		9	20016	1.46	14.91
		10	20012	1.09	16.51
		11	20014	0.59	18.71
		12	20015	0.80	17.78
		13	20006	0.74	18.05
		14	20010	1.30	15.60
		15	20005	1.11	16.42
		16	20004	0.84	17.60
		17	20003	1.01	16.86
		18	20009	0.94	17.16
Mary	4675	2	19412	1.13	16.46
		3	19414	1.61	14.39
		4	19406	1.27	15.85
		5	19410	0.30	20.15

		6	19415	0.80	17.91
		7	19407	1.01	16.99
		9	19409	0.45	19.47
		10	19413	1.35	15.51
		11	19411	1.21	16.11
Reg	4660	1	19196	0.39	19.79
		2	19191	0.55	19.07
		3	19197	1.04	16.90
		4	19195	0.68	18.49
		5	19199	1.31	15.72
		6	19192	1.45	15.12
		7	19200	1.58	14.56
		9	19194	1.06	16.81
		10	19201	0.45	19.52
		11	19198	0.55	19.07
		12	19193	0.83	17.82
		13	19208	1.08	16.72
		14	19213	0.25	20.42
		15	19205	0.55	19.07
		16	19210	0.01	21.52
		17	19211	0.79	18.00
		19	19204	0.83	17.82
		20	19206	1.21	16.16
		21	19209	0.45	19.52
		22	19207	0.44	19.56
Rice A	4676	1	19448	0.12	21.01
		2	19465	0.71	18.36
		3	19466	0.09	21.15
		4	19462	1.18	16.29
		6	19449	0.93	17.38
		7	19463	0.50	19.29
		8	19464	0.82	17.87
		9	19467	0.79	18.00
		10	19450	1.09	16.68
Paul	4597	1	18497	0.15	20.92
		2	18498	0.12	21.06
		3	18499	0.52	19.25
		5	18500	0.06	21.33
		7	18501	0.75	18.22
		9	18502	1.31	15.77
		10	18503	1.16	16.42
		11	18504	1.36	15.55
		13	18505	1.12	16.59

Rice B	4673	1	19337	1.25	16.03
		2	19330	1.63	14.39
		3	19340	0.84	17.82
		4	19338	0.36	19.97
		5	19332	0.85	17.78
		6	19333	1.15	16.46
		7	19334	0.53	19.20
		9	19336	0.46	19.52
		10	19331	0.99	17.16
		11	19335	0.62	18.80
		12	19339	1.00	17.12
Ivan	4672	1	20259	1.14	16.51
		2	20266	-0.04	21.79
		3	20263	0.49	19.38
		4	20264	0.29	20.29
		5	20260	1.07	16.81
		6	20268	1.87	13.38
		7	20269	1.87	13.38
		8	20267	1.68	14.18
		9	20261	1.04	16.94
		10	20262	1.55	14.74
		11	20265	1.00	17.12
Rose	4601	1	19012	1.57	14.65
		3	19013	0.78	18.09
		4	19014	0.44	19.61
		5	19015	0.71	18.40
		6	19016	0.28	20.33
		7	19025	-0.01	21.66
		8	19018	0.45	19.56
		9	19019	0.58	18.98
		10	19020	0.87	17.69
		11	19021	1.10	16.68
		12	19022	1.33	15.68
		13	19023	0.75	18.22
		14	19024	1.26	15.98
Willey	4659	1	19183	0.89	17.74
		2	19177	0.90	17.69
		3	19179	0.13	21.15
		4	19176	0.28	20.47
		5	19182	0.30	20.38
		6	19188	0.52	19.38
		8	19186	0.29	20.42

		9	19181	-0.06	22.02
		10	19187	1.06	16.99
		11	19180	0.64	18.85
		12	19175	-0.16	22.48
Willey	4659	1	20522	1.37	15.64
		2	20525	0.62	18.94
		3	20523	0.38	20.02
		4	20537	0.78	18.22
		5	20538	0.81	18.09
		6	20524	0.19	20.88
		7	20546	0.60	19.03
		8	20527	-0.45	23.84
		9	20528	-0.13	22.35
		10	20545	-0.49	24.02
		12	20535	0.25	20.60
		13	20536	-0.31	23.18
		14	20542	-0.11	22.25
		15	20544	-0.03	21.89
		16	20540	0.27	20.51
		17	20539	0.35	20.15
		18	20534	0.67	18.71
		19	20533	0.43	19.79
		20	20532	0.65	18.80
		21	20547	-0.18	22.58
		22	20543	0.41	19.88
		23	20541	0.82	18.05
		24	20526	0.69	18.62
Rice A	4674	1	19366	0.39	20.06
		2	21013	0.88	17.87
		3	19362	0.84	18.05
		4	19467	0.99	17.38
		5	19368	1.99	13.08
		6	19361	1.42	15.51
		7	19367	0.22	20.83
		8	19364	1.34	15.85
		9	19360	2.07	12.75
		10	21015	0.58	19.20
		11	21016	0.32	20.38
		12	19363	0.92	17.69

Jake	4688	1	19884	1.37	16.68
		2	21004	2.03	13.84
		3	21008	1.86	14.56
		4	21005	0.67	19.79
		4	20018	0.57	20.24
		5	21006	1.85	14.61
		7	21010	2.30	12.70
		8	21011	1.72	15.16
		9	21003	1.76	14.99
		10	21009	1.94	14.22
		11	21007	1.58	15.77
		12	21002	1.45	16.33
		13	19881	0.83	19.07

[a]Raw data calibrated to PDB using standard formulae.
[b]PDB values corrected to NBS-19 values of -2.20 for $\delta^{18}O$, 1.92 for $\delta^{13}C$.
[c]$\delta^{18}O_w$ = 1.00 ‰ (PDB) for samples aged 0 to 3200 yr BP; = 1.03 between 3200 and 4300 yr BP; = 1.04 between 4300 and 5800 yr BP; = 1.08 at 5800 yr BP; = 1.10 at 6246 yr BP; = 1.32 at 8760 yr BP after Fairbanks (1989).

APPENDIX 7.2

RADIOCARBON DATES OBTAINED FROM CHARCOAL* AND SHELLS+ IN NELSON BAY CAVE

Layer	^{14}C Age (yr BP)	Laboratory No.
Alex*	650±50	Pta-3362
E111A2*	2450±60	Pta-2921
Bert*	2925±50	Pta-1485
Lucy*	3270±70	Pta-3097
Reg+	4780±50	Pta-6254
Rice A (Sqr 4)+	4810±60	Pta-6129
Paul*	4520±60	Pta-2916
Rice B+	5190±70	Pta-6127
Ivan+	5340±30	Pta-6186
Rice A (Sqr 5)+	6800±40	Pta-6128
Jake+	9160±45	Pta-6188

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