LATE HOLOCENE CLIMATIC CHANGE: THE LITTLE ICE AGE AND *EL NINO* FROM PLANKTONIC FORAMINIFERA IN SEDIMENTS OFF WALVIS BAY, SOUTH WEST AFRICA

by

RUSSELL S. HERBERT

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ABSTRACT

The variation in abundance of the species *G. bulloides* and *G. pachyderma* with depth in a core of diatomaceous sediment off Walvis Bay, South West Africa, seems to correlate with the Little Ice Age that occurred during the late Holocene. Although similar research, using species and oxygen isotope variations has been completed in similar sediment off northern Venezuela and in the Santa Barbara Basin (Kipp and Towner 1975, Dunbar 1983), these are the first downcore foraminiferal species records of the South West African deposit.

The abundances of some of the minor species, most notably *G. ruber,* show very distinctive peaks at apparently random intervals. It is thought that these sudden and short-lived increases could be linked to major *El-Nino-type* events.

In order to measure accurately all the down-core foraminiferal changes, we had to develop a chemical solution which dissolves diatoms and organic material without damaging the foraminiferal skeletons. It consists of K_2CO_3, $CaCl_2$, $NaOH$ and H_2O_2 in particular concentrations. By using this technique, it is possible to prevent biassing of the foraminiferal signal during extraction of foraminifera from diatomaceous mud.

CONTENTS

TABLE OF FIGURES

CHAPTER 1

INTRODUCTION

This thesis describes the variation in species abundance of planktonic foraminifera in the upper two meters of diatomaceous mud off Walvis Bay, South West Africa. Downcore changes appear to be related to late Holocene climatic fluctuations and sporadic *El-Nino-type* events.

Most notable of the late Holocene climatic fluctuations is the Little Ice Age, a time of marked cooling especially characteristic of certain northern hemisphere regions. It seems to have peaked from 200 to 400 years ago (Lamb 1981, Grove 1979, Eddy 1976 and many others).

In order to detect this event within the foraminiferal record, well-preserved sediment with a high sedimentation rate is needed. Good preservation of carbonate is important, in that dissolution can affect the foraminiferal signal. A high sedimentation rate ensures that a sufficient amount of mud accumulates so that change can be seen from sample to sample.

Such detailed resolution and carbonate preservation can be attained from diatomaceous mud, such as is found on the inner continental shelf off the coast of South West Africa (fig 1.1). As you will see, in this environment a mud core produces a foraminiferal sequence showing perhaps decadal climatic variations. In similar sediment off the coast of northern Venezuela and in the Santa Barbara Basin, Kipp and Towner (1975) and Dunbar (1983) apparently detected the Little Ice Age. Thus far, no research in this field has yet been carried out in sediments elsewhere. Certainly the foraminiferal curves produced here will act as a useful comparison.

Another climatic anomaly that apparently can be detected in the foraminiferal record from this type of sediment is *El Nino*.

El Nino, an equatorial oceanographic anomaly thought to be caused by a change in ocean-atmosphere interaction, reflects itself in an otherwise cold-water coastal environment, as an intrusion of warm water. This is apparently

a frequent event in the Pacific. Recent work (Shannon et al, in press) has shown that warm events similar to *El Nino* also occur in the Atlantic.

Using oxygen isotopes, Dunbar (1983) has detected these warm water intrusions in Santa Barbara Basin sediments. Do *El-Nino-type* events, however, have any effect on species proportions, and if they do, to what extent?

The objectives of this thesis are firstly to produce a series of foraminiferal curves from diatomaceous mud of Walvis Bay, and secondly to compare these curves with what is already known regarding climate change over the same period.

To meet these objectives, the thesis consists of:

1) a literature review, that gives background,
2) a discussion of the collection and preparation of the various samples,
3) the observations of the foraminiferal changes, and
4) an interpretation of the changes.
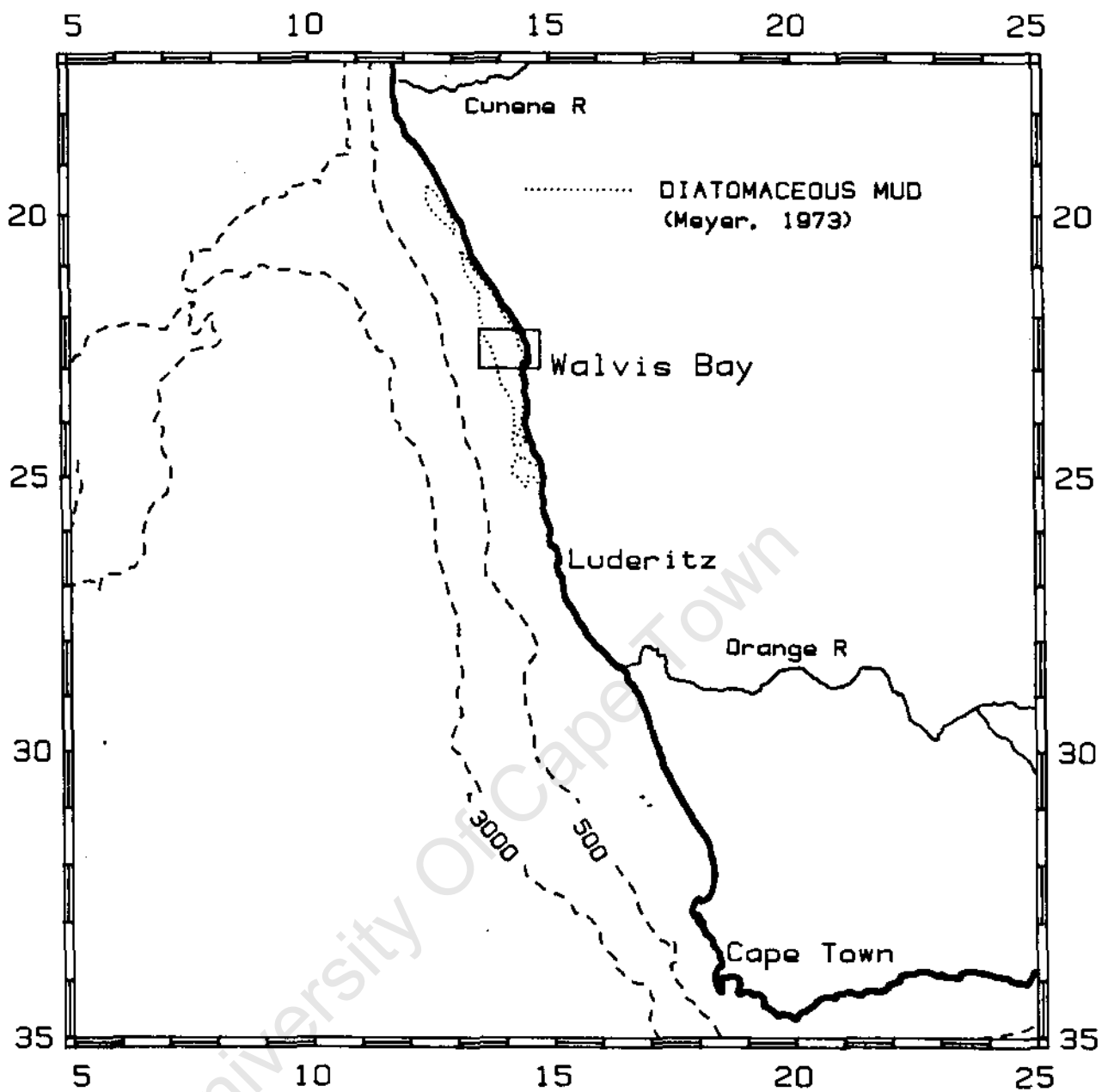
Fig 1.1 Locality map showing diatomaceous mud belt

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

This chapter presents background material. As ultimately the aim of this thesis is to compare the foraminiferal signals to known climatic changes, all the factors that could possibly change must be considered. The objective of this chapter, therefore, is to review these factors by answering the following question&

1) What controls the existence and distribution of the living assemblage, and how has the assemblage responded to these controls?
2) What are the conditions surrounding the sedimentation and subsequent burial of the living assemblage?
3) What type of sediment are the foraminfera buried in. and how will this affect their preservation?

The chapter consists of a review of the following:

1) Climate during the late Holocene, including its relationship with ocean circulation.
2) Ocean circulation off South West Africa.
3) The character of the sediments on the continental shelf off South West Africa.
4) The ecology of the living assemblage.
5) Sedimentation of shells from the living assemblage.
6) The relationship between foaminifera and upwelling and climate.

22 Review of climate during the late Holocene

The Pleistocene is thought to consist of a number of glacial and interglacial episodes, the last one ending with the withdrawal of the Wurm-Wisconsin ice sheets. Subsequent to this, there was a period of gradually rising temperatures, culminating in the climatic optimum at approximately 6000 years BP (Grove 1979, NAS 1975). Since this maximum, there has been a cooling trend, interrupted by three shorter periods of more severe cooling, one of which being the Little Ice Age. Each cold

period was followed by a temperature recovery (NAS 1975).

Many methods have been used to help determine the patterns of climate within this period. They include: glaciology; dendroclimatology; historical records; lake and archeological studies. The pitfalls of these studies include:
1) Glaciology: Plastic deformation within ice sheets causes vertical compression and lateral expansion with depth. (Dansgaard et al 1971). Consequently, dating by stratigraphy is difficult.
2) Historical studies: Although historical data is particularly important in that it deals with short-term climatic fluctuations, it is subject to bias on the part of the writer, who in turn is largely influenced by the particular situation that caused him to write in the first place (Bradley 1985).
3) Dendroclimatology: There are problems in determining whether a specific tree fulfills the basic principle of sensitivity (Hall 1976, Dunwiddie and La Marche 1980).
4) Lake studies: There are problems in dating techniques; beaches become obliterated and driftwood becomes displaced (Clague and Rampton 1981, Andrews and Barnett 1979, Street and Grove 1979).

Bearing these and many other shortcomings in mind, two substantial events have been documented within this time period. They are:
- the Little Ice Age, and
- the Medieval warm epoch.

2.2.1. The Little Ice Age (17th - 19th centuries)

Due to the comparatively recent timing of this event the abundance of historical data *has* resulted in the Little Ice Age being well-documented. Consequently, the Little Ice Age tends to be "best developed" where historical records are most concentrated. Almost all records prior to the 19th century are found in the northern hemisphere (Bradley 1985), while only sparse to non-existent records exist for southern hemisphere regions.

The Little Ice Age was a period of marked cooling that lasted from approximately 1430 to 1850 in the northern hemisphere. It manifested itself in a number of ways, such as:

1) Forest recession (Lamb 1969)
2) Arctic ice pack expansion. The expansion of ice into N. Atlantic waters caused the demise of the Norse colony of S.W. Greenland and the grain crops of Iceland (NAS 1975). The well-established cod fishing industry off S.W. Iceland failed from the period 1615 to 1800 (Lamb 1979), probably due to a significant drop in temperature (Lamb 1969).
3) Glacial expansion in Alaska, Scandinavia, and the Alps (NAS 1975, Grove 1965,1979). Alpine glaciation has been divided into three episodes:
   - the onset of the Little Ice Age - 1580 to 1645
   - the main glacial advancements from the mid 17th to the mid 19th centuries
   - the great recession from the mid 19th century to the present
4) A high frequency of disastrous North Sea floods over the coastal lowlands in the 16th and 17th centuries, with two peaks at 1530 and 1740 (Lamb 1981).
5) The lowest annual rainfall and mean annual temperature recorded in central England, from 1550 to 1700 (Lamb 1965).

In the Southern Hemisphere, the presence of the Little Ice Age has also been noted, although in some cases it seems to have involved a time lag. A Natal dendroclimatological study using the tree species *Postocarpus fakatus* showed that rainfall declined only subsequent to the mid 18th century, with low points at 1755 and 1774 (Hall 1976).

Some climate records indicate that the Little Ice Age was divided into two cold maxima in the 15th and 17th centuries (NAS 1975). This is backed up by research on the variation of incoming solar radiation with time (Eddy 1977).

2.22 The Medieval warm epoch (11th and 12th centuries)

Far less is known about this period (Lamb 1979), and some dissension exists amongst authors over its duration. Whether it lasted from 1100 to 1400 (NAS 1975), from 1000 to 1200 (Lamb 1969), or over some other period does not detract from the fact that it was certainly

not as developed as either the climatic optimum or the warm period during the first half of the 20th century (NAS 1975, Lamb 1969). It did however, develop most of the characteristics that defined the climatic optimum, both in the northern and southern hemispheres (Lamb 1979). These included:

1) Water temperatures in the fiords of SW Greenland reached values 4°C warmer than today.
2) Drift ice rarely appeared near Iceland and Greenland south of 70 N in the 900's, and was apparently absent between 1020 and 1194.
3) There is evidence for greater rainfall in the Mediterranean, Indo-China, Central America and the Sahara.
4) World-wide mean air and ocean temperatures may have been OS - 1°C above 20th century values.
5) Changes in the prevailing temperature and rainfall values over central England amounted to 12-1.4°C and 10% respectively.

The climatic changes that resulted in the development of the Little Ice Age, the Medieval warm epoch and the gradations in between are "small enough to satisfy earlier impressions that there has been no significant change in climate in the last 2500 years, yet large enough to dispute previous meteorological knowledge, and cause grave problems for human economies of those times" (Lamb 1965).

223 Possible causes of the climatic changes

The potential causes for the onset of the Little Ice Age and Medieval maximum are numbered and varied. A few of the more popular theories are (Lamb 1969, Eddy 1977):
   a) variations in the solar energy input
   b) variation and redistribution of the heat stored in the oceans
   c) variations of polar ice extent
   d) variations of the earths surface albedo
   e) global factors such as precession of the equinox.

On the basis of the variation of incoming solar energy, it is thought by some that climate over the last 1000 years has consisted of three episodes (Eddy 1977):
   a) the Maunder minimum 1645 - 1715
   b) the Sporer minimum 1400. 1510
   c) the Medieval maximum 1120 -1280

Both the Maunder and Sporer minimums are present in a curve produced by Suess (1965). In the case of the Maunder minimum, when solar activity dropped off (seen by the drop in sunspot numbers and low solar activity with respect to the 11 year sunspot cycle) climate cooled (in the form of the Little Ice Age). The Maunder and Sporer minimums could also be defining two cold extremes of the Little Ice Age, with the amount of solar reduction being quite critical (Eddy 1976; Eddy 1977; Lamb 1969, Suess 1965). Eddy's (1977) interpretation, however, is controversial (Bradley, 1985 pp69).

23 The relationship **between climate change and changes In ocean circulation**

It seems intuitive that any change occurring within the atmosphere must reflect itself in ocean circulation and, in particular, in coastal upwelling. These changes in turn must influence the prevailing climate through changes in the oceanic heat transfer and moisture input into the atmosphere (Lamb 1979). Certainly if the patterns of oceanic circulation are shifted latitudinally, this will obviously effect the climatic patterns both to north and south of these shifts (Lamb 1969). The Atlantic ocean is more liable to these pole-orientated changes (Lamb 1979):

    1) The approximate N-S alignment of the Atlantic creates currents with predominantly N-S components, and
    2) the Arctic and Antarctic are best connected via the Atlantic.

Since 800 AD there appears to have been large variations in the centers of low and high pressure in the northern hemisphere, suggesting that the upper westerly wind regime weakened and moved equatorwards. This resulted in short wet summers and long severe winters in western Europe and western North America from 1300 to 1600 (NAS 1975, Lamb 1965); ie: changes in atmospheric circulation appear to reflect an equatorward extension of the westerly wave regime and a contraction of the Hadley circulation pattern. This in turn would have influenced ocean circulation (NAS 1975, Bjerknes 1966).

Since 1535 the times of greatest ice in Iceland correspond to the periods of least rainfall in Chile. This implies a more southern position of the subtropical high pressure

system and a southward shift of the "Antarctic depression belt" (Lamb 1969).

2.4 Review of continental shelf circulation

2.4.1 Continental shelf circulation off South West Africa - comparison to other eastern boundary systems

Continental shelf circulation off the coast of South West Africa is quite complex, as it involves the weak to moderate interaction of waters from different sources. These sources can be broadly defined into the South Atlantic subtropical gyre, the subantarctic gyre and the subequatorial gyre.

The eastern margin of the South Atlantic gyre represents itself in the Benguela Current, a sluggish body of water with an average velocity of about 20cm/sec (Shannon 1985, Stander 1964). From Cape Point it moves in a NNW direction parallel to the coastline, moving away from the coast north of 20 S (Venter 1969, Nelson and Hutchings 1983, Shannon 1985). North of this point, however, narrow, secondary longshore branches of the current are thought to flow as far north as 18 S at which point they flow offshore at the Angola front (Shannon 1985). A similar current to the Benguela in the southern hemisphere runs along the western margin of Peru (DeVries and Schrader 1981), while in the northern hemisphere, the California Current is an equivalent. It is southward-flowing and is a mixture of cold, low salinity, nutrient-rich water from the north, and water with opposite qualities that *has* more westward origins (Berger 1970).

Off northern South West Africa, the influence of the southward-flowing Angola current becomes apparent (Shannon 1985). This warm, saline water (Kruger and Boyd 1984) represents the eastern margin of the cyclonic subequatorial gyre (Reid et al 1978).

Most influential to the marine ecology off South West Africa is persistent upwelling, a result of the prevailing southerly winds in the area (Hart and Currie 1960; Stander 1964; Shannon 1985). The cold, nutrient-rich waters that are upwelled along the coast are derived from a mixture of dense subantarctic water and lighter subtropical water (Schell 1970). The upwelled water travels offshore in a WNW direction at approximately 10 cm/sec (Shannon

1985) and becomes progressively warmer, more saline, richer in oxygen and poorer in phosphate, nitrate and silica *as* it moves offshore (Hart and Currie 1960). Two to three active centers of upwelling occur, although measurements recorded during 1982/83 show persistent upwelling along the coast from Luderitz to the Cunene River mouth (Kruger and Boyd 1984). The centers of upwelling are:

a) between the Orange River Mouth and Luderitz, and extending up to Walvis Bay,
b) in the vicinity of the Cunene River Mouth.

The preferential positioning of the plumes is thought to depend largely on bottom topography (Schell 1970).

Upwelling is equally significant off California and Peru and, as with South West Africa, cause arid climates on the adjacent continental borderlands (DeVries and Schrader 1981, Berger 1970)

A plot of summer sea surface temperatures (SST) in the waters off South West Africa can be a good indicator of these various water masses. During my honours year I produced a plot of SST using the South Data Center for Oceanography (SADCO) database (Herbert 1984). Coastal upwelling represents itself as a belt of cold temperatures extending nearly the full length of the South West African coastline. The presence of the warmer waters due to the influence of the South Atlantic and subequatorial gyres elevate the temperatures to the west and north.

2.4.2 *El-Nino* and its effect on the hydrographic setting off South West Africa

The *El-Nino* phenomenon is thought to exist because of longitudinal variations in atmospheric circulation that dominate the tropics, on time scales of weeks or longer (Rasmusson 1985). Normally a persistent trade wind belt within this region causes westward-directed frictional drag on the ocean surface, which in turn results in a raised sea level in the west, with respect to the eastern boundary. The east-west thermocline adopts an opposite gradient, due to the pile-up of mixed, warm water on one side and the absence of it on the other. Any weakening of the trade winds will result in easterly movement of warm equatorial water: the *El-Nino* event (Rasm-

usson 1985, Philander 1986, Shannon in press, Weisberg 1986, Katz et al 1986).

The effect *El Nino* has on the hydrographic setting on the Peruvian and South West African continental margins is to depress the otherwise shallow thermocline, raise the sea temperature, and cause a drastic reduction of the nutrient input into the much-dependant euphotic zone (Hisard et al 1986, Rasmusson 1985).

The Peruvian continental margin is subject to Pacific-generated *El-Nino* events. Off South West Africa the situation is somewhat more complex Here, seasonal warming of Benguela water is a regular occurrence, due to the intrusion of Angola water from further north (Shannon et al, in press). These seasonal events are not regarded as *El Nino's.*

Since the early 1950's, two definite *El-Nino* type events have been recorded off South West Africa: viz in 1963 and 1984. During the 1984 occurrence sea surface temperatures in the area were raised by 2-4°C, and high rainfall resulted in the flooding of Namib desert rivers. Other than the 1963/84 events, evidence also suggests-that an *El Nino* occurred in 1934, when sea temperatures were raised by 2-3°C (Shannon et al 1986). For earlier periods, within the time scale of this thesis, direct observations do not exist.

25 The diatomaceous mud belt off South West **Africa**

2.5.1 General

The diatomaceous mud belt is a post-glacial deposit that runs parallel to the South West African coastline for about 740 km. Its northern limit is Rocky Point (19°S), and it is almost continuous as far south as Silvia Hill (25 S) (see fig 1.1 above). The main Walvis Bay deposit is separated from the smaller patches to the north and south by structural barriers (Bremner 1980). As with the diatomaceous sediment in the Gulf of California (Calvert 1966, Soutar 1971, Baumgartner et al 1985), laminations occur in places (Union Corporation 1972, Meyer 1973, translated by Rogers 1983). The bottom waters of this region are low in oxygen content, due to the depletion of available oxygen by bacterial decomposition (Copenhagen 1954).

The major constituent of the diatomaceous mud is opal (average 54% but can reach 88%), mainly in the form of diatom skeletons (Bremner 1980). Also present are benthic and planktonic foraminifera, decomposed organic matter, terrigenous debris (mainly in the form of wind-driven dust; Whitaker 1984), and phosphorite. The mean water depth on the landward side of the mud belt is 31m, while on the seaward it is 130m Wave action evidently prevents sedimentation of mud in shallower depths (Bremner 1980).

Persistent upwelling within this region results in a high primary productivity. It is thought that the eventual depletion of nutrients in the surface waters prevents more westward deposition at greater water depths (Johnson, It 1985 pen. commun.).

2.5.2 Preservation of Carbonates

Withrn anaerobic environments, it appears that carbonate particles are protected from dissolution (Soutar 1967, Berger and Soutar 1970). This is important, of course, to the objectives of this thesis. Dissolution could alter the foraminiferal distribution, as different species dissolve at varying rates (Berger 1976; see section 2.8).

Dissolution of calcium carbonate occurs because of undersaturation of water in contact with the solid. In the ocean, since there is plenty Cal^+, undersaturation depends on the concentration of carbonate ions. The concentration of carbonate ions, in turn, depends on a number of factors and reactions, including (Breaker 1974):

- aerobic rotting: $C_6 14206 + 602$ $6CO_2 + 61120$

• CO_2 dissolution: $CO_2 + H_2O = H_2CO_3$

• dissociation: $H_2CO_3 = HCO_3 + H^+$

- association: $H^+ + CO_3 = HCO_3$

Under aerobic conditions, the net effect of rotting is to reduce the concentration of carbonate by creating uncommitted hydrogen ions which combine with carbonate to form bicarbonate. Anaerobic conditions, however, do not produce uncommitted hydrogen ions. For example, sulphate reduction generates sulphide ions:

$$C_6{}^{14}{}_{12}O_6 + 35042- = 6 CO_2 + 61120 + 35^{2"}$$
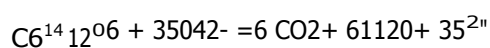
The sulphide ions can use up all the H. from CO_2 dissolution by forming H_2S (Sholkovitz 1973).

2.6 Summary of foraminiferal species encountered

This section gives a brief discussion of the various species that were found and outlines some of the differences between them. The classification of each species is based on that used by Be and Tolderlund (1971) and Rogi and Bolli (1973), although other authors have also been cited in the discussion. Characteristic of the assemblage off Walvis Bay is the low foraminiferal diversity, dominated by the species *G. bulloides* and *G. pachyderma* (Herbert 1984). Photomicrographs of the different species appear in fig 2.1.

2.6.1 *Globigerina pachyderma* (Ehrenberg) and *(Neo)Globiquadrina dutertrei* (d'Orbigny)

G. pachyderm is the best indicator species of polar waters (Be and Tolderlund 1971). Although there are various morphotypes (Kennett 1976), the most easily identifiable individuals have 4-5 coalescing chambers per whorl. An important feature of this species is its coiling direction, as sinistral and dextral individuals have different geographical distributions (Be and Tolderlund 1971, Kennett 1976). *G. pachyderma* is also regarded as a good palaeoclimatic indicator with sinistral individuals characterizing cold water and dextral individuals suggesting wanner-water conditions (Vincent and Berger 1981)

G. dutertrei is a subtropical species that is particularly abundant in gyre margin systems (Kipp 1976), such as off Angola (Be and Tolderlund 1971) and off California, due to its strong affinity to upwelling areas (Berger 1970). Within upwellmg areas, *G. dutertrei* also shows distinctive oxygen isotope values (Dunbar 1983). Controversy surrounds the classification of *G. dutertrei* into either the *Globiquadrina* or *Neoglobiquadrina* genera. The difference between the two is in the position of the aperture and the presence of an aperture! tooth (Rogi and Boll 1973). It has also been suggested that:

  1) there is a nearly continuous genetic gradation from dextral *G. pachyderma* to *G.*

2) *G. pachyderms* and *G. dutertrei* may belong to the same species (Vincent and Berger 1981).

In the California current sediments, small kummerforms of *G. dutertrei* are identified as right-coiling *G. pachyderma* (Berger 1970). In this thesis I have combined *G. dutertrei* and right-coiling *G. pachyderma.*

2.62 *Globigerina quinquiloba* (Natland)

a quinquiloba is a cold water species that predominates in subantarctic and subarctic waters (Be and Tolderlund 1971). It is also a common species within centers of upwelling (Kipp and Towner 1975). Unfortunately this species can be easily confused with *G. pachyderma* (Be and Tolderlund 1971, Kipp 1976). The two species types are best distinguished from each other by different surface textures. *G. quinquiloba* is a spinose species whereas *G. pachyderma* is not *(G. quinquiloba* has a surface texture similar to that of *G. bullaides). G. quinquiloba* is also a small species equivalent in size to juvenile individuals of *G.* pachydenna. The samples discussed below were counted in a size range that tends to exclude its presence. It does, however, appear in the finer size ranges (see section 4.2.1 and fig 2.1).

2.6.3 *Globigerina bulloides* (d'Orbigny)

G. bulloides is a cold-water species typical of subpolar waters and upwelling regions (Be and Tolderlund 1971, Dunbar 1983, Berger 1970). As with *G. dutenrei, G. bulloides* has depleted oxygen isotope values relative to those of the same species in normal deep sea sediments (Dunbar 1983). It does however, also appear in transitional waters, but decreases rapidly in abundance north of the subtropical convergence zone (Kennett 1976). It is spinose and *has* 4 globular chambers in the final whorl and a wide umbilical aperture (Be and Tolderlund 1971, Rog! and Bolli 1973). On the basis of morphological differences of *a bulloides* within sediments of the Guaymas basin, Matoba and Oda (1982) have classified the species into 3 different types: *G.* bulloides *bulloides, G. brdloides quadrilatera,* and *G. bulloides umbilicata.*

The morphological variations in the species I counted seemed quite small. The individuals were certainly all very well preserved and were hence well defined. Most showed a large aperture and stubbly surface texture. There were however, some kummerforms and thicker individuals with constricted apertures, morphotypes indicative of a cold-water environment (Rogl and Bolli 1973).

2.6.4 *Globorotalia Inflate* (d'Orbigny)

G inflate is evidently the only indigenous species of the transitional zone that exists between the subpolar and subtropical waters (Be and Tolderlund 1971, Kipp 1976). Off South West Africa, with distance offshore, the percent abundance of this species increases to measured values of up to 35% (Herbert 1984). Characteristic of this species is a smooth chamber wall, which may show secondary "knobbly" thickening. The chamber shape is more oviform than round (Rogl and Bolli 1973). *G. inflate* has 3-4 chambers in the final whorl, with the last chamber having a characteristically smooth texture.

2.6.5 *Globorotalia truncatulinoides* (d'Orbigny)

G. truncatulinoides characterizes warm to temperate regions, unlike other members of modem globorotalids (Vincent and Berger 1981). Consequently, although it is regarded as being mainly a subtropical species, it is also found in transitional waters of the South Atlantic (Be and Tolderlund 1971). Belonging to the same genus as *G. inflate, G. truncatulinoides* is distinguishable by its angular shape and the presence of a peripheral keel. As with *G. pachyderma, G.*

provinces (Vincent and Berger 1981) that are latitudinally distributed (Be and Tolderlund 1971). Variations are also apparent on a seasonal basis and with time, ie: downcore (Thiede 1971). As the study area is far removed from the presence of warmer water, *G. truncatulinoides* tends to be a rare species.

2.6.6 *Orbulina universe* (d'Orbigny)

0. universe is generally spherical as the final chamber is an all-enclosing one. This is thought to be a feature of reproduction (Berger 1976). It is a cosmopolitan species in that it occupies most water types, but is most common in upwelling regions (Be and

Tolderlund 1971). This can clearly be seen in the results of this thesis where its percent abundance reaches values as high as 40% (see fig 4.6 below). No real consensus has been reached however, on whether *0. universe* should be treated as a single species. The morphology shows many variations (Rogl and BoIli 1973). These include variations in size, wall thickness and degree of roundness (Berger 1976). All these variations occur in the individuals in the samples discussed below. Consequently, I have paid little attention to this species, other than subtract its counts from the totals.

2.6.7 *Globigemoides tuber* (d'Orbigny)

G. tuber is often regarded as the most successful of the warm water species in terms of distribution and abundance, being most abundant in subtropical waters (Be and Tolderlund 1971). Characteristic of this species are three globular chambers per whorl and two apertures. The surface texture is coarse and the walls are thick (Rogl and BoIli 1973). *G. tuber* occurs in both white and pigmented form, where the degree of pigmentation is thought to be related to temperature. The pink/red colour has been found to be more pronounced in warmer months than in colder ones (Vincent and Berger 1981). On average *G. tuber* in this core is rare, but
strongly pigmented individuals suddenly occur in high abundances over short intervals (see section 5.45.1, fig 4.10 and fig 5.6).

2.6.8 *Hastigerina Pelagica* (d'Orbigny)

H. pelagica has a very distinctive shape, as it is large with delicate, transparent walls and long spines which seem to give support to a generally open structure (Rogl and BoIli 1973). Many of the morphological features common to *H. pelagica* are not seen on other species of planktonic foraminifera. This could mean that *H. pelagica* represents a much more advanced stage of development (Spindler et al 1979, Hemleben and Spindler 1983). Due to its fragile shell, *H. pelagica* is rare in marine sediments except where conditions are anoxic and quiet enough to preserve it. In the samples described below, the species is rare, but where it does occur, it tends to be well preserved.

2.7 The ecology of the living assemblage

2.7.1 Species diversity, feeding habits, patchiness and reproduction

Each of the factors discussed in this section could have a significant influence on the distribution of the living assemblage that eventually leaves the surface water, becoming preserved within the sedimentary pile. As ultimately this thesis observes the relationship between a foraminiferal signal based on changing species proportions and a changing oceanographic environment, of key importance is an understanding of species diversity, feeding habits, patchiness and reproduction within the surface waters.

There is a high correlation between the overall distribution of nutrients in the euphotic zone and the biomass of phyto and zooplankton (Berger 1976). The abundance of these key resources is the governing factor in controlling species survival, abundance, distribution and diversity on a local scale (Valiela 1984, Anderson et al 1979 and Spindler et al 1979). However, the domination of one phytoplankton species over- another might not necessarily result in any change in resource abundance for the zooplankton, but would result in a drop in zooplankton diversity due to selective feeding habits (Valiela 1984).

It has been found that different species of planktonic foraminifera have different feeding habits, with individuals being either omnivorous, herbivorous or carnivorous (Anderson et al 1979; Hemleben and Spindler 1983). Species with more versatile feeding habits will have far greater chances of survival than those with more restricted feeding (Anderson et al 1979). In general, non-spinose species tend to be herbivorous, while spinose species are carnivorous (Hemleben and Spindler 1983). However, this generalization is not always true. *G. bulloides* and *G. inflate* both appear to be omnivorous and therefore have a wider ecological range than *G. dutertrei, G. tuber, 0.universa and H. pelagica,* all of whom are either herbivorous or carnivorous (Anderson et al 1979). *H. pelagica* is strictly carnivorous, which will naturally affect its stability in any ecological setting.

Fig 2.1. Photomicrographs of the foraminiferal species that were encountered. The numbers on the photomicrographs correspond to the numbers below. Included for each species except *H. pelagica is* a close up of shell-surface texture.

la-i) *Globigerina pachyderms* (Ehrenberg) and *(Neo)*
        Globiquadrina dutertei (d'Orbigny)
2a-f) Globigerina quinqiloba (Natland)
3a-d) *Globigerina bulloides* (d'Orbigny)
4a-e) Globorotalia inflata (d'Orbigny)
5a-e) *Globigerinoides* mbar (d'Orbigny)
6a-d) *Globorotalia truncatulinoides* (d'Orbigny)
la-e) Hastigerina pelagica (d'Orbigny)
8a-d) *Hastigerinella riedeli* (Rogl and Bolli)
9a-c) Globigerinita uvula (Ehrenberg)
 10) *Globigerinita glutinata* (Egger)
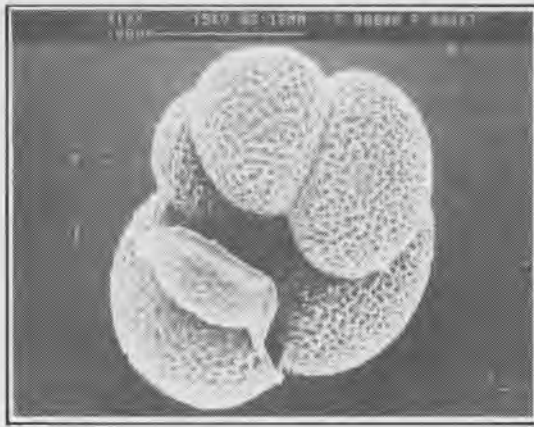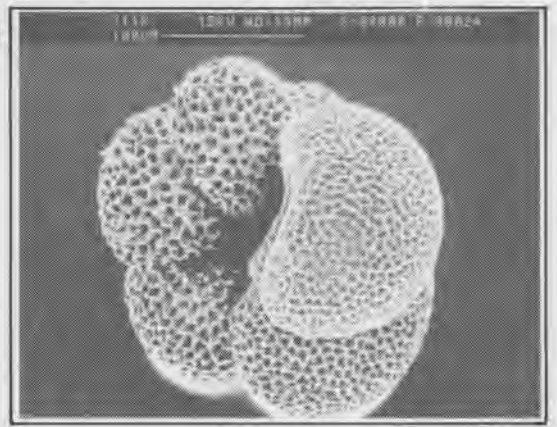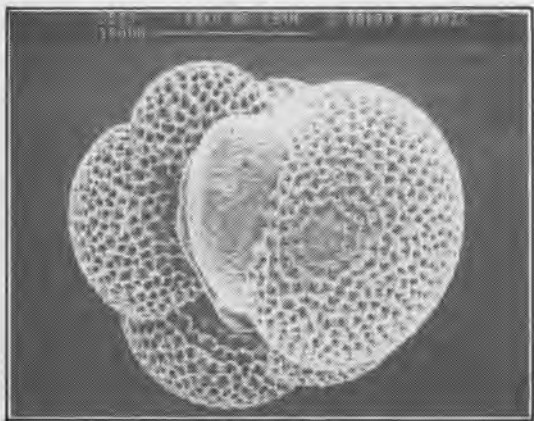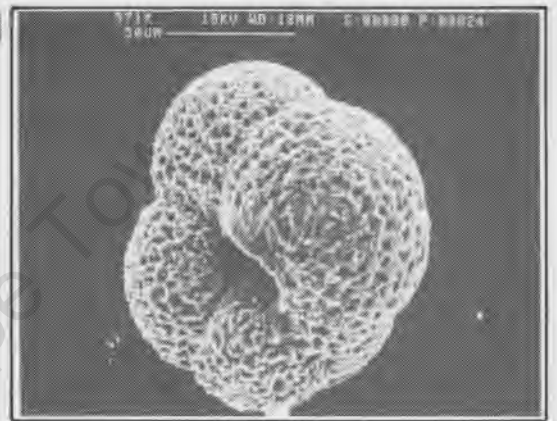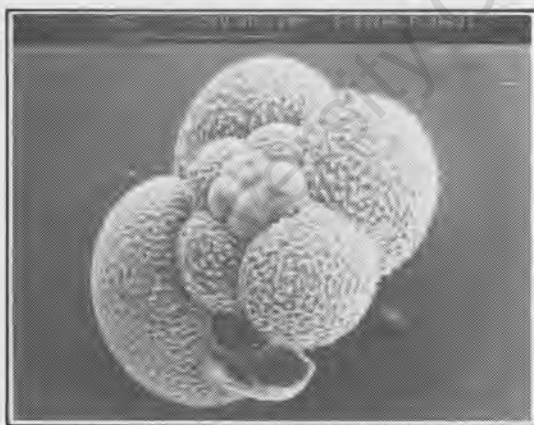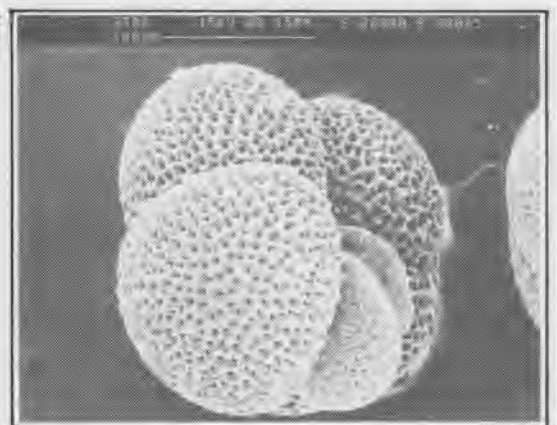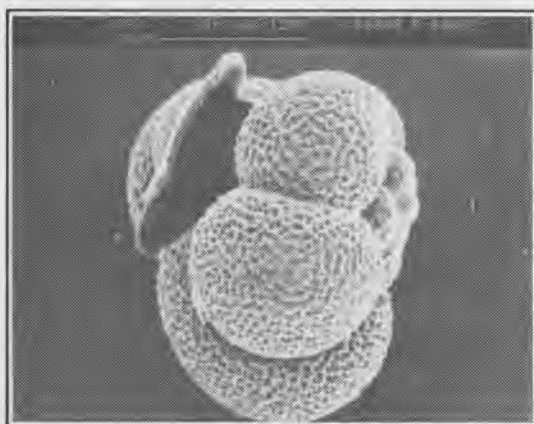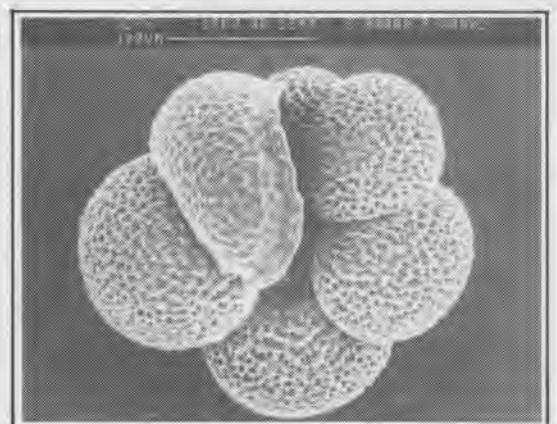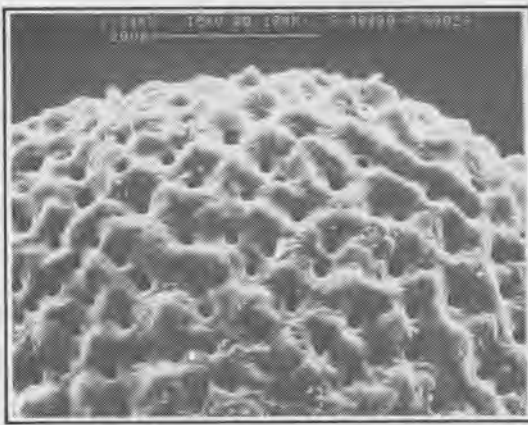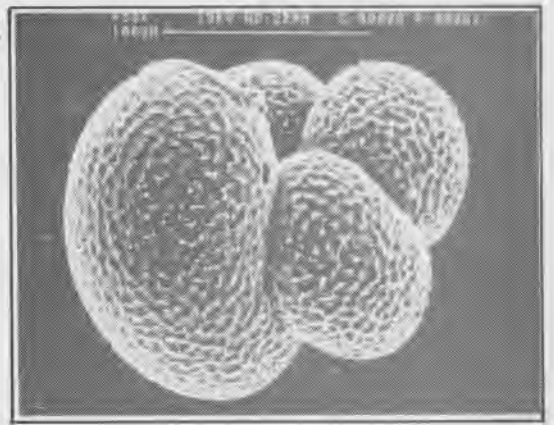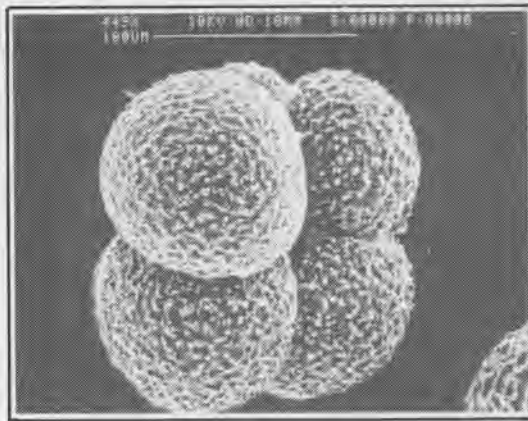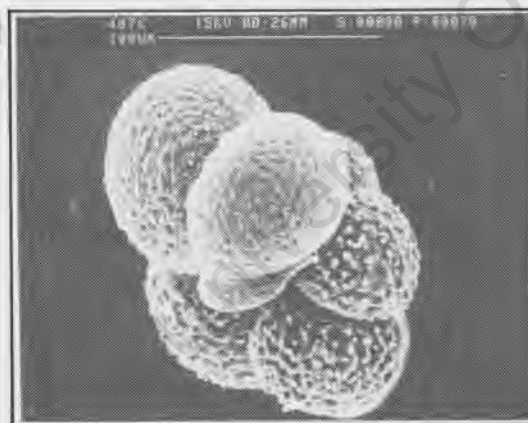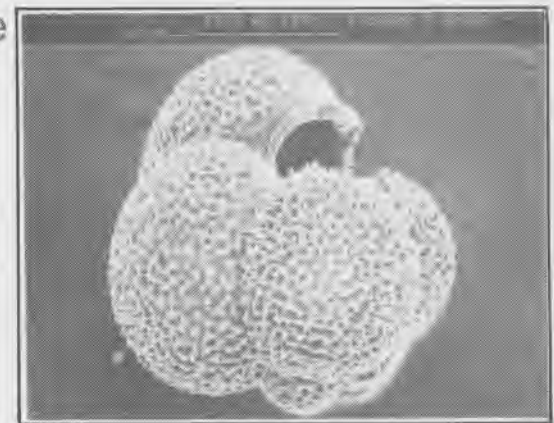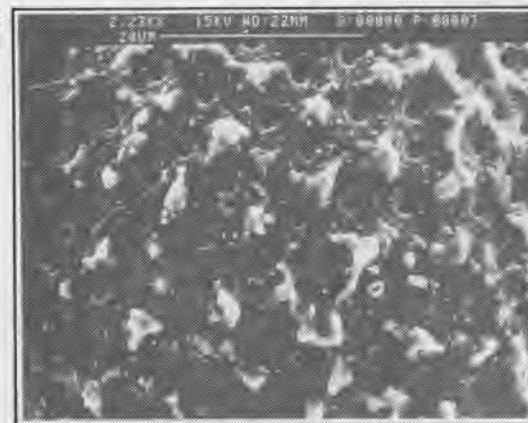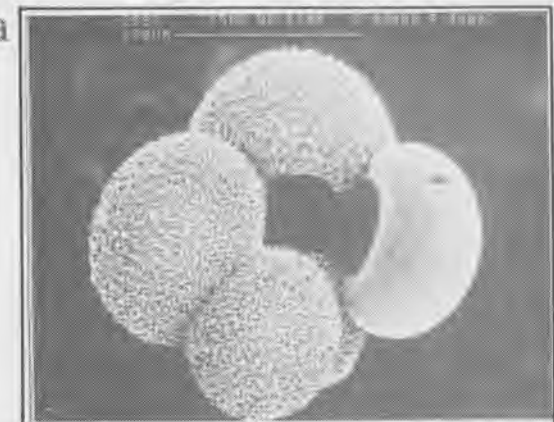
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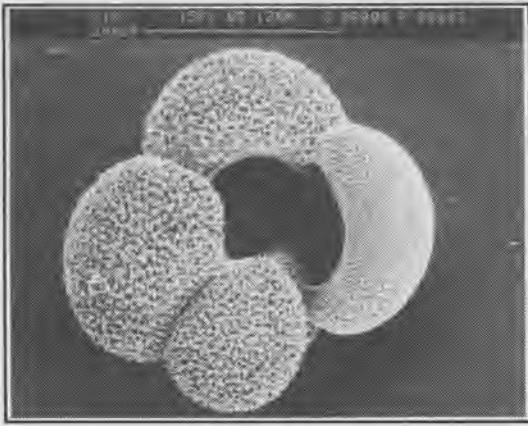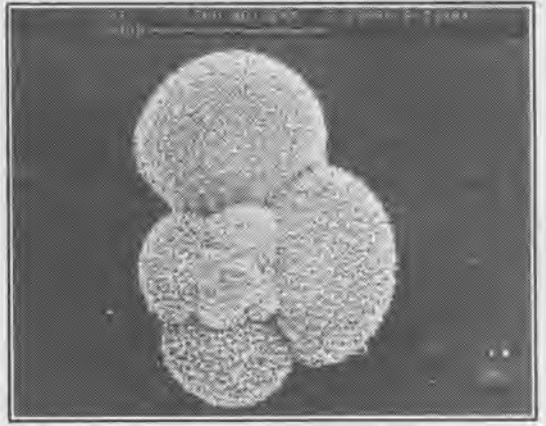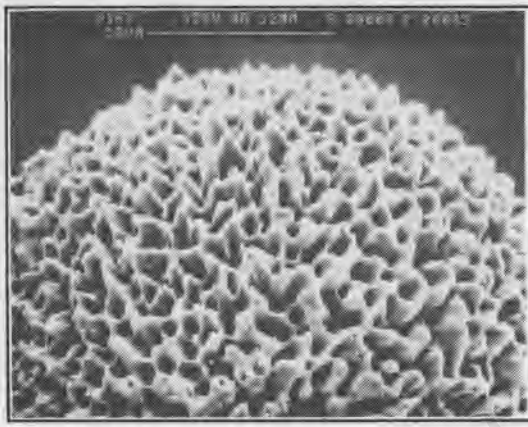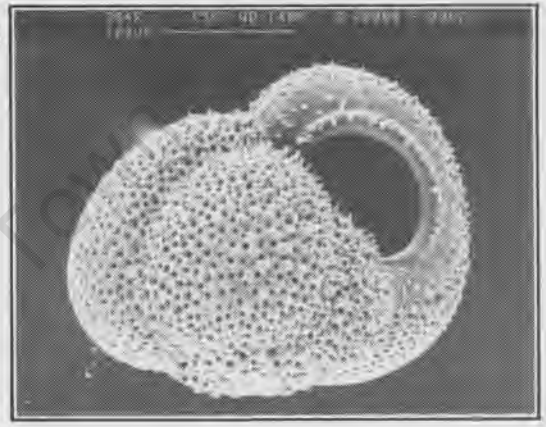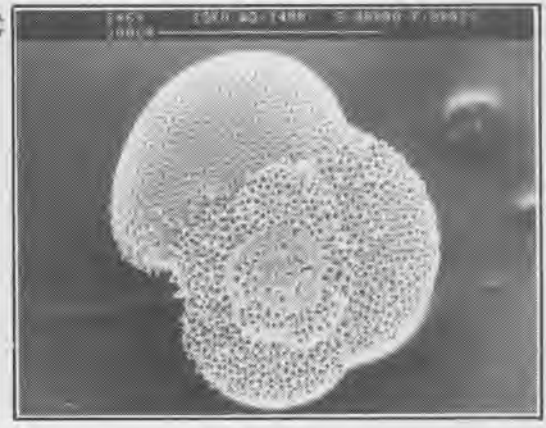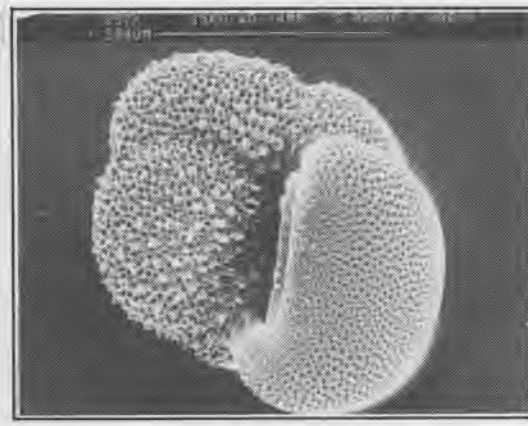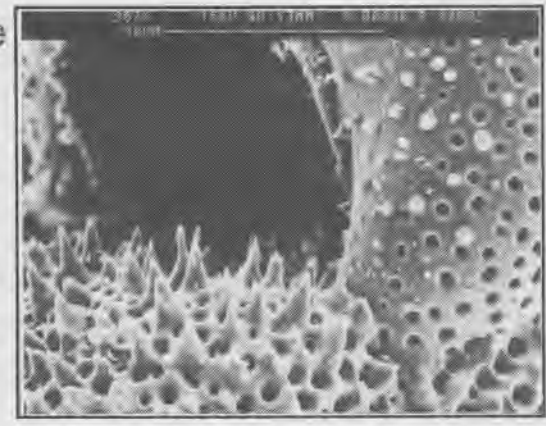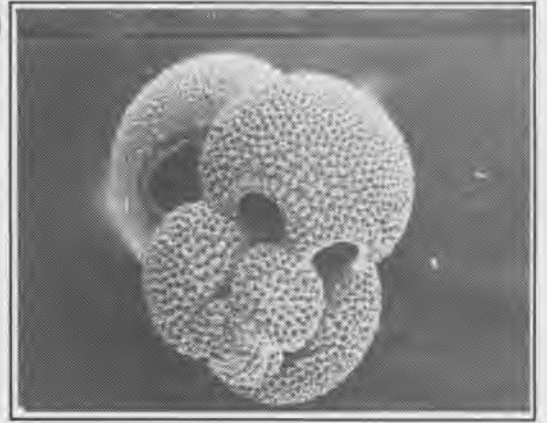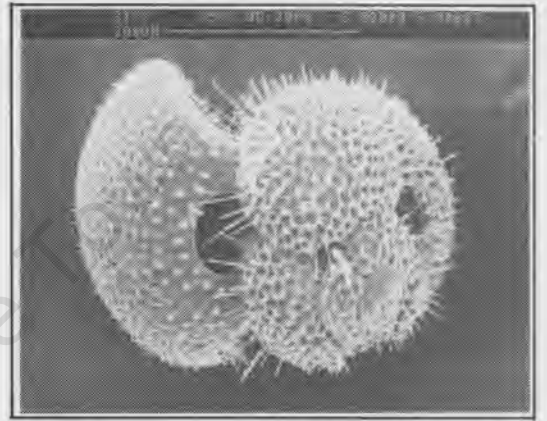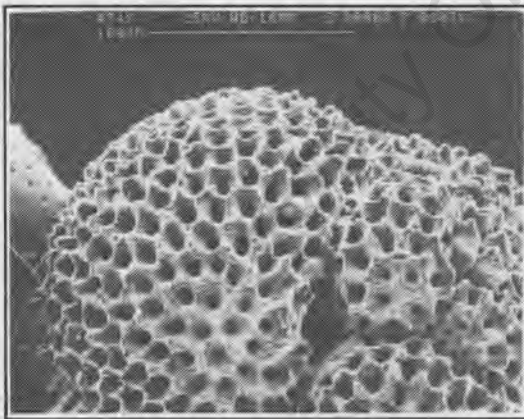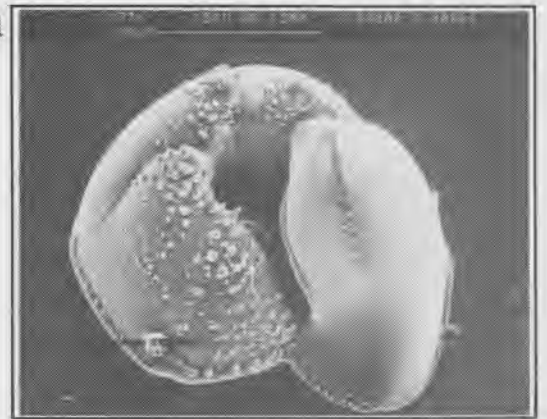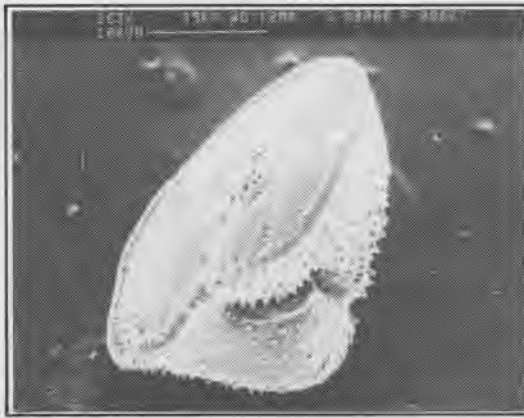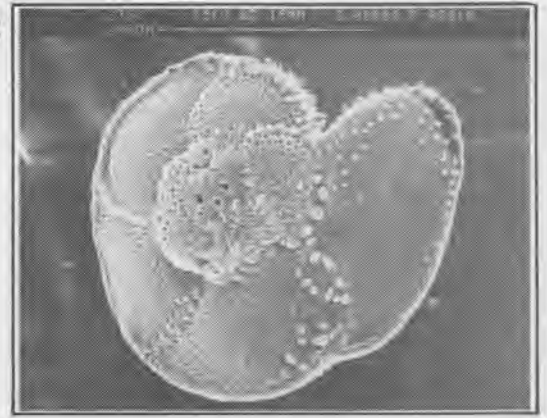
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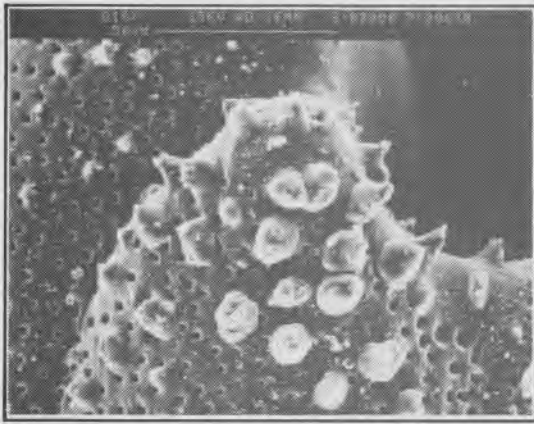
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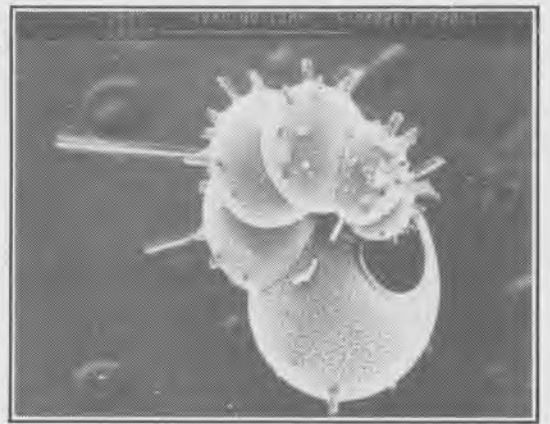
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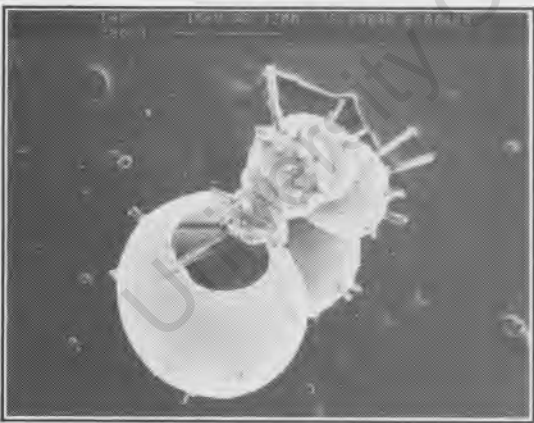
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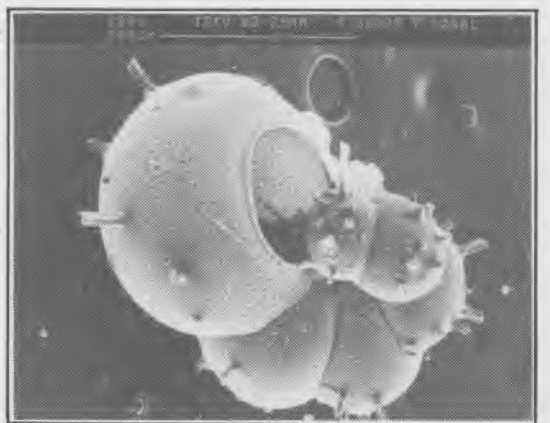
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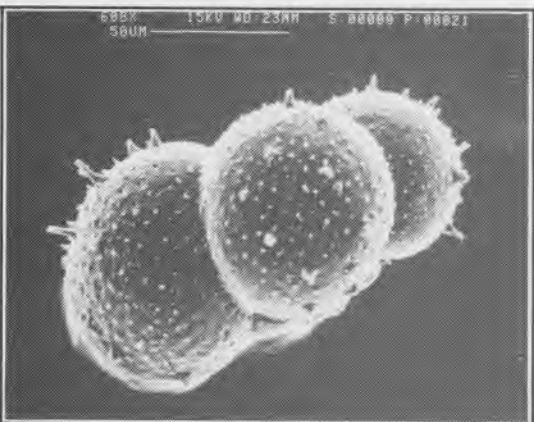
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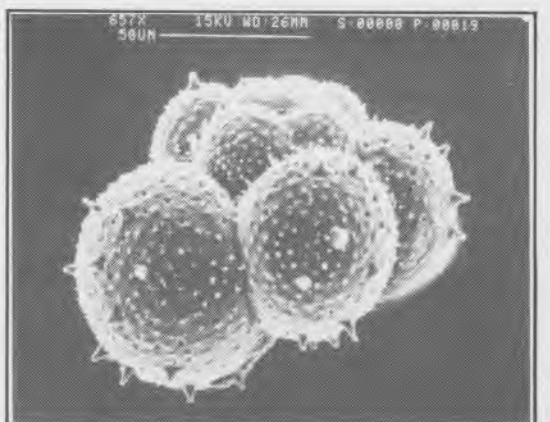
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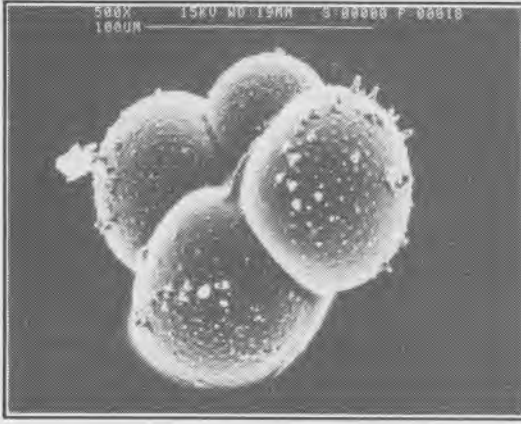
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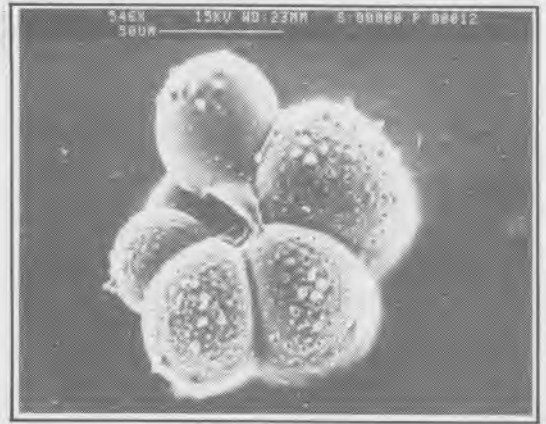
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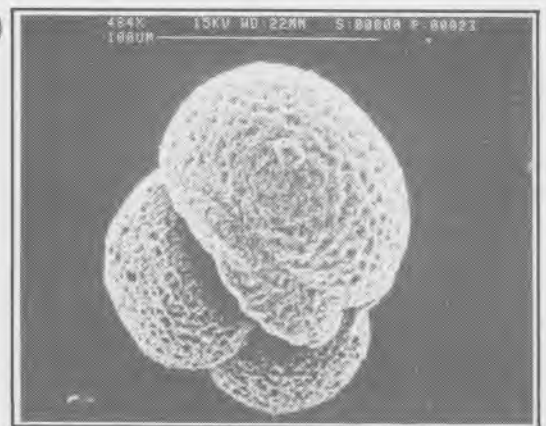
The frequency of feeding is another important factor controlling the foraminifera's life span and final shell size (Hemleben and Spindler 1983). The optimum feeding interval varies between species and results in varying survival times (Anderson et al 1979). A consequence of this could be that in an environment rich in food, species with longer life-spans could dominate over those with a high turnover rates. However, the sediment assemblage could show the reverse: high turnover species could dominate.

Reproduction of foraminifera can influence the presence/absence of a species in the surface waters. This in turn could influence the foraminiferal signal in the sediment *as* the different layers within the water column have different qualities. *H. pelagica* appears to have the most advanced reproductive cycle in that it exhibits a strong lunar periodicity (Hemleben and Spindler 1983; Spindler et al 1979). *H. pelagica* sinks down in the water column during reproduction, due to calcification of its shell during gamete release. This cycle has a period of approximately 30 days and seems to be adopted by most symbiot-bearing spinose planktonic foraminifers. Species such as a *tuber,* a *inflata* and *G. truncatulinoides* do not show this consistent reproductive cycle. *G. inflata* and *G.*

while still calcifying, while *G. tuber* shows a continuously occurring reproductive cycle (Hemleben and Spindler 1983).

The patchiness and type of phytoplankton will greatly influence the surface distribution of the grazing zooplankton. In the Santa Barbara Basin, upwelling-induced phytoplankton blooms favor the production of the fast-growing cold water species, resulting in a sediment that shows a strong cold water aspect (Berger 1971; Herbert 1984).

Because an upwelling center is very active with fairly swift offshore-movement of surface water and corresponding onshore-movement of deeper water to be upwelled, vertical migration could be very important in maintaining a

abundance in its optimum ecological niche.

2.7.2 Spatial distribution of foraminifera in an upwelling area

Seasonal variations of foraminifera in an upwelling environment may be largely controlled by the intensity and timing of nutrient input into the euphotic zone (Valiela 1984). During upwelling months, the distribution of phytoplankton may be quite variable. This in turn would naturally affect the distribution of zooplankton. Phytoplankton volumes measured during the 198283 season off South West Africa show highest values generally between 5-15 miles offshore. The zooplankton distribution tended to be much patchier, but showed greatest abundances on the outer edges of the highest phytoplankton volumes (Kruger and Boyd 1984). Chelton et al (1982) feel that in the case of the California current, upwelling is not nearly as important to the phyto- and zooplankton abundances as is generally believed. Because the highest zooplankton volumes occur much further offshore and with greater offshore extent than seems possible if upwelling was the main driving force, it appears that large-scale variations in the flow of the California current are paramount in controlling the plankton biomass.

2.8 Sedimentation of planktonic foraminffera

The path from the living surface water *assemblage* to the collection of foraminifera that are extracted from a preserved mud layer can be divided into four stages (Berger 1971, Dunbar and Berger 1981, Berger and Piper 1972, Berger and Soutar 1970).
   I) removal of foraminifera from the euphotic zone,
   2) settling to the sea floor,
   3) dissolution, and
   4) redeposition
The influence of each of these four stages will vary for different environments and species. The result of this is that the initial death assemblage on the sea floor might or might not represent the original life assemblage, while the preserved, buried assemblage might differ even more.

One cannot generalize the sedimentation of foraminifera out of the complexly-controlled living assemblage in the euphotic zone into a simple process equal for all species types. Not only do the life spans of individual species vary, but their time of existence in

the euphotic zone is governed by a number of factors, each one different for different species types.

Once the foraminifera have been removed from the surface waters by whatever method, drfferent settling rates will result in a death assemblage different from the equivalent life assemblage (Berger 1971). Dissolution of individuals during settling can also be important, although off South West Africa, dissolution and lateral transport during settling is probably negligible, based on the settling velocities of Berger and Piper (1972). Fragile species with low settling velocities such as H. *pelagica,* could still be affected enough, perhaps, to alter the death assemblage.

The death assemblage and subsequent preserved assemblage differ by the amount of bottom dissolution, resuspension and redeposition that takes place (Berger 1971). Dissolution leads to an enrichment of resistant species over easily soluble ones. Winnowing leads to a residual assemblage made up of rapidly-settling foraminifera, while subsequent redeposition in quieter areas concentrates the slower-settling individuals (Berger and Piper 1972).

Off South West Africa, conditions seem to favor the preservation of the death assemblage:
  1) Shallow water (approx. 100m) results in negligible settling problems, save for possible resuspension of the organic matter, diatoms and smaller foraminifera.
  2) The low concentration of oxygen in the bottom water (Copenhagen 1954) result in excellent preservation of the foraminiferal assemblage. This is seen by the presence of spines on spined foraminifera, and the presence of *H. pelagica.*
  3) Generally fairly quiet bottom water conditions are indicated by the presence of the diatomaceous mud in the first place.
  4) Rapid mud accumulation rates (1-2mm/yr) results in quick burial and preservation.

2.9 The relationship planktonic foraminifers have with upwelling and climate

One of the objectives of this thesis is to interpret the foraminiferal trends in terms of climate change. This immediately raises the following question. What is the present-day relationship between species distribution and upwelling and climate?

The strong correlation that different foraminiferal species have with temperature has been both known for a long time and well-documented (Be and Tolderlund 1971, Kipp 1976 and others). It has also been shown that the various oceanographic gyres represent the principle marine biological provinces, with a certain degree of faunal mixing occurring where the gyres come into contact with each other (Reid et al 1978). Research has been carried out on the influence that coastal upwelling has on foraminiferal populations (Gansen and Samthein 1983, Dunbar 1983, Kipp and Towner 1975, Thiede 1975). Upwelling on the continental shelf off northern Venezuela is most intense from January to July, when phytoplankton blooms are followed by blooms of *G. bulloides* (Kipp and Towner 1975). Off South West Africa, the spatial distribution of selected species appears related to summer sea surface temperature (Herbert 1984). *G. pachyderma* tends to be most abundant in centers of upwelling, decreasing in abundance offshore, to the advantage of the more transitional species *G. inflata.* Off the coast of North West -Africa, the distribution of foraminifera has been studied by Thiede (1975). In his research, he found:

  4) A high concentration of *G. bulloides* coincided with the cool, southward-flowing Canary current, and
  2) *G. quinqiloba, G. dutertrei* and *G. inflata* predominating in the cold, upwelled waters.

Research similar to that contained in this thesis has been done on sediments off Peru, northern Venezuela and in the Santa Barbara Basin off California (Dunbar 1983; Wefer et al 1983; DeVries and Schrader 1981; Kipp and Towner 1975). On the continental shelf off Peru, it has been found that although the Holocene was characterized by tropical diatom species, the period 200 - 400 years BP (corresponding to the Little Ice Age) sometimes showed a greater abundance of subtropical species. However, during the height of this period, tropical species dominated as warm-water incursions seem to have disrupted the upwelling zone (DeVries and Schrader 1981). These frequent warm-water incursions, which could either have originated from the tropics

or from intensified offshore counter-currents, are also detected in oxygen isotope studies (Wefer et al 1983).

In the Santa Barbara Basin, both isotope and carbonate studies suggest that both upwelling rates and surface productivity were greater during the Little Ice Age (Dunbar 1983).

The laminated muds in the basin show a foraminiferal assemblage characterized by a dominant right-coiling *G. pachyderma, with G.* i
Towner 1975). During the Little Ice Age, a colder assemblage formed, where a *quinquiloba* dominated over right-coiling *G. pachyderm*. This assemblage gradually increased during the early part of the Little Ice Age, to become consistently dominant during the second half of the period. It was subsequently replaced by a wanner-water assemblage approximately 100 years ago. During most recent times, the assemblage has been more mixed, implying warmer temperatures and decreased upwelling. Off northern Venezuela, the Little Ice Age saw a drop in the usually dominant species a *Inloides (Kipp and Towner 1975).*

2.9 Summary of literature review

As has been mentioned in the introduction, the objectives of this thesis are to produce a series of foraminiferal records showing species variations, and to interpret them in light of what is known regarding climate change, the foraminiferal life cycle and their subsequent sedimentation in diatomaceous mud.

Climate change over the last 1000 years *has* been affected by two events: the Little Ice Age (17-19th century) and the Medieval warm epoch (11-12th century). Both events appear to have been best-developed in the northern hemisphere, altering rainfall, land and sea temperatures, the extent of onland ice and human settlement patterns. Direct observations are not readily available for the study of climate change in southern hemisphere regions, especially those that affect the area of study. However, indirect approaches such as South African dendroclimatological and Antarctic ice core studies show similarities with northern hemisphere records.

Ocean circulation off South West Africa appears to be influenced by the following:

1) the Benguela current
2) the Angola current
3) persistent upwelling.

Of the three, upwelling is of greatest importance *as* it provides a source of nutrients into the surface waters upon which the phytoplankton grow. Without this, there would be no diatomaceous mud belt. Another important influence to this region is sporadic i type events. These phenomenon introduce warm, tropical water into an otherwise cold environment. They can have devastating effects on the resident marine ecosystem.

The diatomaceous mud belt on the inner continental shelf runs from Rocky Point (19°S) to Silvia Hill (25 S), and consists mainly of opal in the form of diatom skeletons. Due to persistent upwelling, primary productivity is very high. The bottom waters are low in oxygen, which results in excellent sediment preservation.

In the area of study within the mud belt at least 11 species of planktonic foraminifera have been found. Included are polar and subtropical species, and the fragile species *H. pelagica.*

Implicit to the interpretation of the species curves is an understanding of the ecology of the living assemblage, its subsequent sedimentation and later burial. In each of these three stages, a number of factors can lead to the final buried assemblage having the species distribution quite different from the original living assemblage. However, off South West Africa, the shallow water depths, the low oxygen content of the bottom waters and the rapid sedimentation rate seem to favor a buried assemblage closely resembling the original death assemblage.

11

CHAPTER 3

SAMPLES AND SAMPLE PREPARATION

3.1 Introduction

This chapter discusses the collection of samples and sample methods used.

The biggest disadvantage in working with the diatomaceous mud off South West Africa are the low planktonic foraminiferal concentrations. For example, data presented below show that the average for Core 3 is 44.5 foraminifera >212 microns per gramme wet sediment. To generate representative foraminiferal curves, we need:

1) large amounts of undisturbed mud, and
2) **some method to extract all the** foraminifera per unit interval.

If the samples that are counted are not representative of what was preserved in the mud, then any changes in the species curves could easily be artifacts. This is particularly important for the rarer (warmer water) species, as their signal could be quite crucial in a search for *El-Nino-type* events.

The positions of the grab samples and cores used and a brief outline of the procedure surrounding the collection of a giant box core have been included in this chapter. Mostly, though, this chapter is an outline of the development of a chemical method of foraminiferal extraction that attempts to minimize damage to foraminiferal shells, while at the same time ensuring that all the individuals are extracted from the samples.

3.2 Sample locations

Fig 3.1 shows the locations of samples used. Most of the sediment comes from TB Davie Cruise 474, which lasted from 15-27 November 085. I have used 12 grab samples and one core from this cruise. I have also used material from vibracores SF-7 and SF-14. Core SF-7 and SF-14 come from R.V. Benguela cruise 186 during August 1983 (Bremner et al 1983).

Core 3 was taken with University of Cape Town's newly-developed giant box corer, a device that can recover cores up to 4 m in length and 30x30cm in width (Johnson, 1985; Johnson, in prep). Core 3 was extruded on board into polyurethane boxes, each one accommodating a section of the core 20 cm deep. It was extruded in such a way to prevent any disturbance of the material (see fig 32 below). Two sections of Core 3 were scrambled during extrusion. The result of this is that my downcore counts have two 20cm gaps.

33 Sampling In the laboratory

33.1 Core SF-7

Two downcore sections of core SF-7 were initially photographed and were then cut into samples of equal depth interval (and therefore of equal volume). One section was cut into 5cm layers while the other was cut into 1cm3 layers. Layer volumes were 50cm^3 and 10cms respectively (the width of the core was 10cm and the sections were 1cm thick).

Gravity separation and sieving was used to separate out the foraminifera in the size range 212-300 microns (see section 3.4). Once the foraminifera had been counted, two problems were encountered:

1) The concentration of foraminifera was very low. Although the 5cm slices contained sufficient individuals for meaningful counts to be made (ie: where confidence limits were good enough to prevent masking of any real changes), samples from the 1cm slices sometimes had no foraminifera in 'them at all.
2) *Where* the concentration of foraminifera reached low values, summed' results over 5cm intervals did- not match up to *he* ults of the equivalent intent hi °the' adjacent slice. This lack of correlation Suggested problems with' the gravity' method of extraction $\quad$ gravity method

33.2 Core 3

For Core 3, the polyurethane sample boxes were cut into 2cm-thick vertical slabs. Each slab was then resealed using hard, clear plastic (Johnson, in prep). For this thesis, slab num-

Fig 3.1 Sample positions within the diatbmaceous mud belt.

Legend:
- ● Grab
- ■ Box core
- ▲ Vibracore

Labels on map: SF-7, 1&2&10, 4, 5, 6, 7, 8, 9, 11, 19, Core 3, 12, SF-14, Swakopmund, Walvis Bay, 150m, 100m, 50m

Coordinate labels (top): 30', 45', 14, 15', 30', 45'
Coordinate labels (left): 15', 30', 45', 23
Coordinate labels (bottom): 30', 45', 14, 15', 30', 45'
Coordinate labels (right): 15', 30', 45', 23
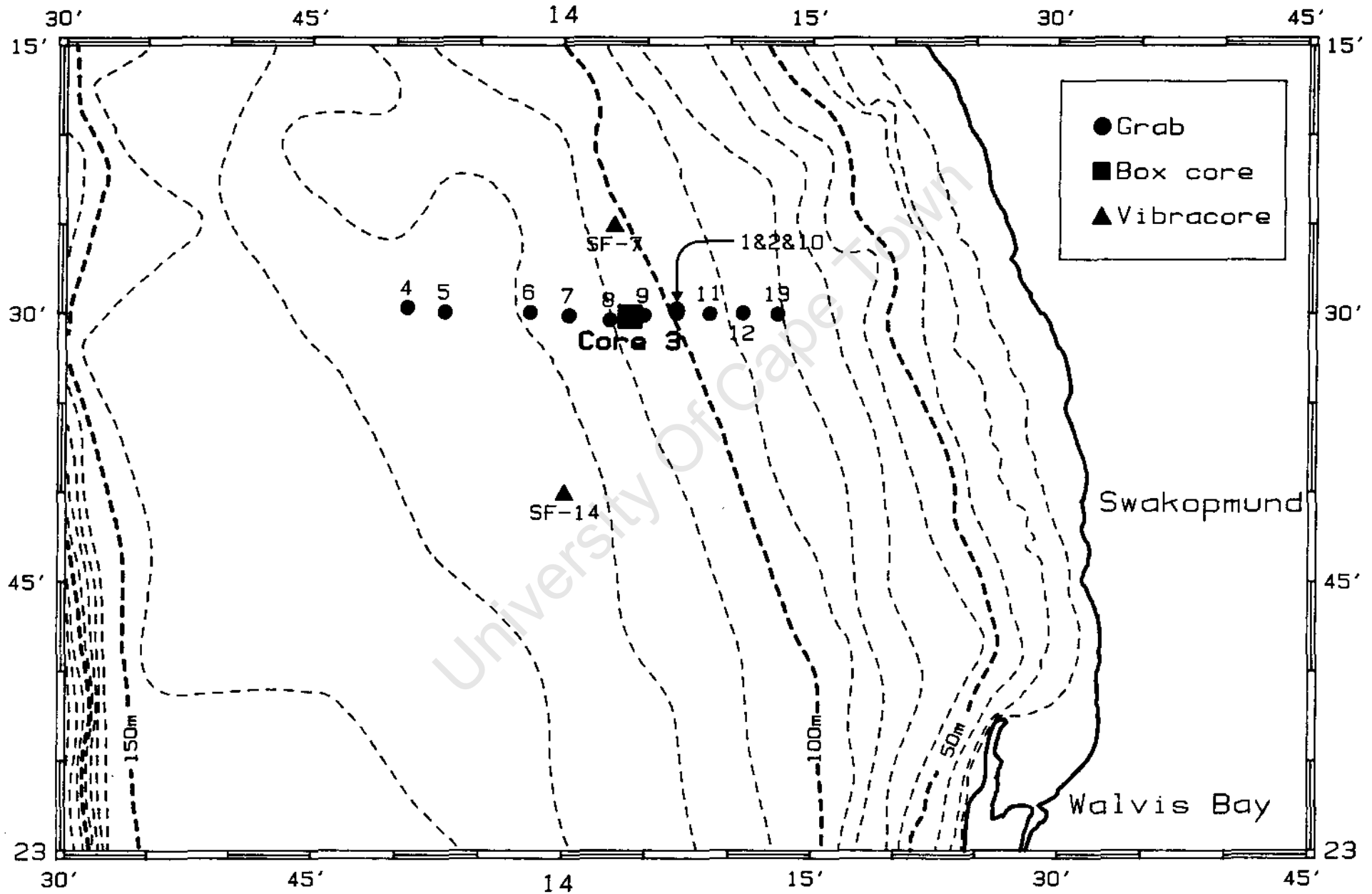
ber 2 (the penultimate slice to one of the wall-slabs), was used. The reason for this choice was:

    a) the wall-slabs had been affected by drag effects along the sides of the core;
    b) mud near the middle of the core appeared to have slumped a bit; and
    c) other people needed the more central slabs.

Ⅰ photographed each slab in black and white and colour (including a grey scale in the colour photographs). Then, using the enlarged black and white photographs, Ⅰ traced out on overhead transparency all the well-defined strata (fig 3.2). These were then subdivided, such that the resultant samples were approximately 1 cm deep. The distance of each end of the drawn lines from the top of the polyurethane box were measured. The average of the two values plus the depth to the top of the polyurethane box became depth-in-core.

I then opened each slice in turn and, using a sharp, thin knife, cut along each of the drawn Ernes. Over the entire length of the core, the mud had jelly-like consistency and held its form. Consequently, the mud cut cleanly.
After cutting, I weighed each sample.

3.4 Existing **methods of foramaminiferal extraction**

Various methods are used by different authors to extract foraminifera from diatomaceous sediment. For sediment from the Guaymas Basin, Matoba and Oda (1982) adopted the following method:

    1) disaggregate with a warm hydrogen peroxide solution
    2) sieve, dry and then dissolve the diatoms in a concentrated solution of sodium hydroxide. Section 35 below shows that a solution containing only NaOH damages the foraminifera.

Another method of foraminiferal extraction was used by Dunbar (1983) and Wefer et al (1983) in similar sediment in the Santa Barbara Basin and off the coast of Peru respectively:

    1) ultrasonify sample in a buffered calgon solution.
    2) dry and sieve through a 63 micron screen.

For my honours thesis (Herbert 1984), I used gravity separation:

    1) The sample was washed with single-distilled water.
    2) If necessary, some of the samples were disaggregated using a small quantity of dilute H_2O_2 and NaOH.
    3) The sample was separated into two size fractions: 75 - 150 microns and 150 - 300 microns.
    4) Each size fraction was gravity-separated in distilled water to remove the bulk of diatoms and organic matter.
    5) Where necessary, the nearly-pure calcareous sample was placed in a solution the same as in 2), heated and left to stand overnight so that some of the remaining diatoms and organic matter could dissolve.
    6) Finally, the sample was washed and dried.

Disadvantages of this method were:

    1) it was very time-consuming, as the tedious procedure had to be carried out step-by-step for one sample at a time.
    2) biassing of species abundances occurred. Spinose species that still had spines, juveniles (and other small individuals), thin-walled individuals and individuals of the species *H. pelagica* were caught up in the slowly-sinking diatoms and diatom girdles and discarded. To prove this, I took a sample, gravity-separated it, and counted the foraminifera in the residue and in the discarded solution. Ⅰ discovered only 1 (damaged) *H. pelagica in* the residue, but 6 of them in the discard. Also, the individuals caught in the discard did not represent a random scattering of species - most were spinose *G. bulloides.*
    3) When the concentration of foraminifera was low, any foraminifera left in the discard severely altered the relative species abundance in the residue.
    4) Putting foraminifera in H_2O_2 and NaOH is damaging (see below). Certainly any *H. pelagica* would have been destroyed. During my honours study, Ⅰ spotted no individuals of *H.pelagica* (Herbert 1984).

3.5 The development **of a chemical method of extraction**

The major constituent of diatomaceous sediment is amorphous silica, reaching values of 88%

Fig 3.2. Core 3, Slab 2, photographic sequence and layer defi-
nition. Core box numbers appear in the central column. The
right-hand column shows the positions at which individual
samples were cut. Average depth-in-core is displayed on the
extreme right As a result of minor distortion and compression
incurred during the various stages of extraction, the total
depth-in-core measurement is 12cm less than the true core
length.

		Average depth in core cm.
	Top Box Foram lag deposit in 5th sample	0 —10
	3.2.1 Coarsely banded	—20 —30
	3.2.2 Coarsely banded. Middle section disturbed	—40 —50
	3.2.3 Middle section very disturbed. Not sampled	—60 —70
	Missing Box	—80 —90
	3.2.5 Coarsely banded	—100 —110
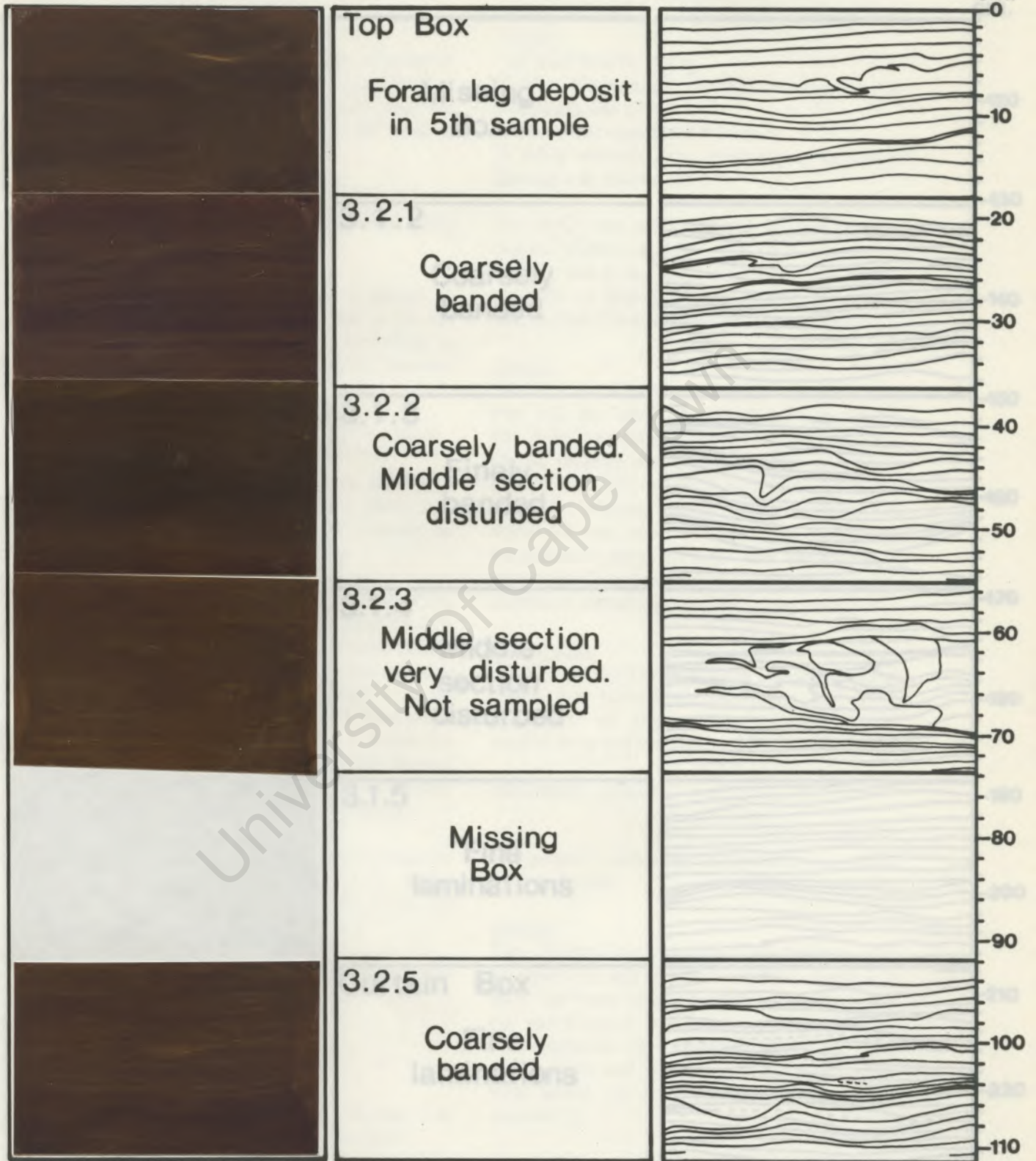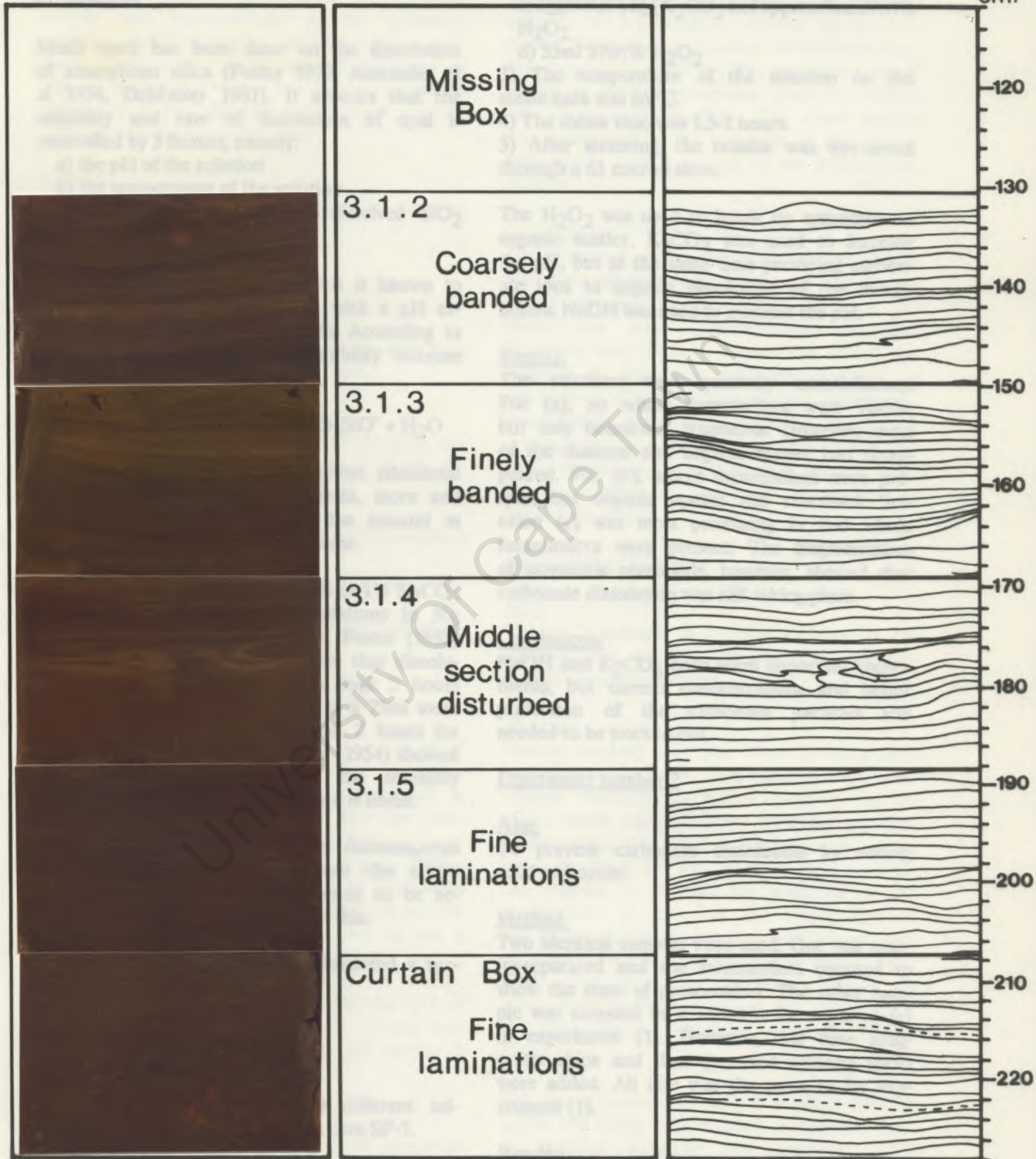
Average
depth
in core
cm.

—120

—130

Missing
Box

3.1.2

Coarsely
banded

—140

—150

3.1.3

Finely
banded

—160

3.1.4

Middle
section
disturbed

—170

—180

3.1.5

—190

Fine
laminations

—200

Curtain Box

—210

Fine
laminations

—220

(Bremner 1980). If a chemical procedure is used to dissolve this silica, then it must not dissolve, break-up or otherwise affect the foraminifera.

Much work has been done on the dissolution of amorphous silica (Foster 1953, Alexander et at 1954, DeMaster 1981). It appears that the solubility and rate of dissolution of opal is controlled by 3 factors, namely:
    a) the pH of the solution
    b) the temperature of the solution
    c) the concentration of the dissolved SiO_2 in the solution

The solubility of amorphous silica is known to increase in an alkaline solution with a pH acceding 9 (Alexander et at 1954). According to Alexander et at (1954), the solubility increase can be explained by the equation:

$$Si(OH)_4(dissolved) + OW = HO_3SiO'' + H_2O$$

The formation of (HO_3SiO^-) allows additional silica to dissolve. As pH increases, more and more SiO_2 goes into the ion; the amount as ($Si(OH)_4$) more or less stays the same.

DeMaster (1981) used a 50m1 bath of 1% $NaCO_3$ solution at 85 C, to dissolve diatoms in 30g of sediment in two hours or less. Foster (1953) showed in a series of experiments that dissolution of opal was asymptotic. It took 2 hours to dissolve 94% of 400g of opal in a 75ml weak NaOH solution and an additional 2 hours for the remaining 6%. Alexander et al (1954) showed that the relationship between the solubility of amorphous silica and temperature is linear.

For foraminiferal extraction from diatomaceous mud, dissolution of silica is not the entire problem. Organic matter also needs to be removed. I used 11202 to accomplish this.

To find the best procedure, I completed a succession of experiments:

Experiment number 1

ARM
To test the effectiveness of 4 different solutions on diatomaceous mud from core SF-7.

Method:
 1) In each case 20g of homogenized SF-7 mud went into 200m1 of solution.

2) The 4 solutions contained:
    a) 2M NaOH and approx. 5m1 37wt% H202
    b) 2M K_2CO_3 and approx. 5m1 11202
    c) 2M NaOH, 2M K_2CO_3 and approx. 5ml 37wt% 11202
    d) 35m1 37wt% H202
3) The temperature of the solution on the steam bath was 66 C.
4) The steam time was 15-2 hours.
5) After steaming, the residue was wet-sieved through a 63 micron sieve.

The H202 was used to break up aggregates of organic matter. K_2CO_3 was used to increase the pH, but at the same time providing carbonate ions to impede dissolution of the foraminifera. NaOH was used to increase the pH.

Results.
The solutions were generally unsatisfactory. For (a), no whole foraminifera were visible, but only occasional fragments. However, most of the diatoms and organic matter had disappeared. For (b), whole foraminifera were present, but organic matter still remained. Solution (c) was most promising in that whole foraminifera were present. The fragmentation of aragonitic pteropods, however, showed that carbonate dissolution was still taking place.

Conclusions:
NaOH and K_2CO_3 both seem important constituents, but correct concentrations and better protection of the carbonate particles still needed to be worked out.

Experiment number 2

Aim:
To prevent carbonate dissolution by adding solid carbonate.

Method:
Two identical samples were used. One was gravity-separated and the foraminifera counted to show the state of preservation. The other sample was steamed in a solution the same as (c) in experiment (1). However, this time aragonitic chips and dust (crushed abalone shell) were added. All else was the same as for experiment (1).

Results:
I counted 766 foraminifera in the gravity-separated sample. Minor dissolution was evident (perhaps in situ, see section 2.42), but for-

aminiferal fragments were absent. Many of the *G. bulloides* shells showed spines. Foraminifera with translucent shells were also present. I found 1 specimen of *H. pelagica*. The steamed sample was unsatisfactory as the aragonite particles made counting the foraminifera difficult. Once again, there was no evidence of organic matter and only a few diatoms remained. However, a few diatom girdles were causing foraminifera to cement together.

Conclusions:
The solid carbonate made foraminiferal counting difficult.

Experiment number 3

To prevent carbonate dissolution by saturating the solution with Ca^{2+} and $003^{2'}$ ions.

Method:
1) I thoroughly mixed a tub of SF-14 mud and took 3 identical subsamples from it. 3 different 200ml solutions were made up:

a) 1M K2CO3; 10ml 37wt% H202; 0.5 teaspoons of aragonite powder.
b) 1M K2CO3; 4mM CaCl2 0.4M Na0H; 10ml 37wt% H202 (pH=12)
c) 1M K2CO3; 10ml 37wt% H202, sea water (pH=11)

2) 30g of sample was used in each case.
3) Steam time was 2.5 hrs.

Theory:
An alternative to solid CaCO3(aragonite) is CaCl2 and K2CO3. It is known that the solubility of CaC12 at 80°C exceeds that of aragonite by a factor of 10^6 (Perry and Chilton 1973). To prevent the dissolution of CaCO3 in 200ml of water, at least 0.4mM CaCl2 is needed (Perry and Chilton 1973). I decided to use a concentration 10 times as large, as this is still beneath the saturation level of CaCl2. For K2CO3, at its saturation point, the pH of the solution is approximately 12. (Perry and Chilton 1973). To increase the pH further I used NaOH in small quantities.

Results:
In the case of sample 1, once again aragonite made counting difficult. However, I was still able to count the sample (see fig.4.1 below). For sample (2), 1 saw very few fragments alth-

ough there was some dissolution of the fragile pteropod shells. I also counted 8 complete *H. pelagica* shells in the >300 micron size range. There was a problem, however, with cementing together of foraminifers. Diatom girdles entwined themselves in amongst the foraminifera. For sample (3), when K2CO3 was added to sea water, a dense precipitate formed, making the solution cloudy-white. The dried sample was dominated by the presence of this precipitate which made counting of the foraminifera difficult.

Conclusions:
There appears to be no major differences in the state of preservation between the foraminifera extracted by the chemical solution and those that were gravitationally separated. However, due to poor circulation within the beakers, it appeared that the solution at the bottom of the beakers became rapidly saturated with respect to dissolved silica, preventing further diatom dissolution. More efficient circulation, therefore, was needed within the beakers to speed up dissolution of the diatom girdles.

Experiment number 4

Aim:
To test a method of heating to improve circulation, and to test robustness of foraminifera to prolonged heating.

Method:
Narrow masking tape was wound around each beaker at a set level. The beakers were then lowered through the widest holes in the lid of the steam bath, with the masking tape preventing them from falling right through. Adjusting the level of the masking tape enabled the beakers to rest on the waterline in the steam bath. In this way, the temperature of the water within the beaker was raised from $66°C$ to the temperature of the steam bath, $84°C$. Also, as half of the beaker was in the open draft above the lid of the steam bath, the temperature difference improved natural convection.

For this experiment I took 4 identical samples in the size range >212 microns and placed them in identical solutions that contained 0.5M K2CO3; 4mM CaCl2;025M NaOH and 6ml 37wt% H202. The solutions showed a pH of 13.2 at

25oC. Every half hour one of the samples was removed, washed and dried.

Results:
The most obvious result of this method of heating was that the diatom girdles that had plagued previous experiments had completely dissolved. However, with increasing steam time, fish scales started to take on a sugary surface texture. The foraminifera seemed unaffected by the long steam times (fig 33) although after two hours, individuals of *H. pelagica* showed definite signs of dissolution. Organic matter disaggregated in the first half hour but the silica took up to two hours to dissolve.

Conclusions:
Convection increases the rate of dissolution of diatoms. Heating time should not exceed 2 hours.

Experiment number 5

Aim:
To determine the relative importance of each of the constituents of the chemical solution chosen from experiment number 3.

Method:
8 identical samples of 25g of unwashed sediment from Grab 2 were each placed in 200ml of solution, with each solution missing one of the constituents. The solutions consisted of:

1) 05M K_2CO_3; 10ml 37wt% H_2O_2; 4mM $CaCl_2$; 0.25M NaOH. (pH 25°C: 13.3).
2) 05M K_2CO_3. (pH 25°C: 11.5).
3) 0.5M K_2CO_3; 10ml 37wt% H_2O_2. (pH 25°C: 11.4).
4) 0.5M K_2CO_3; 4mM $CaCl_2$. (pH 25°C: 11.5).
5) 055A K_2CO_3; 0.25M NaOH. (pH 25°C: 13.4).
6) 0_5M K_2CO_3; 4mM $CaCl_2$; 10ml 37wt% H_2O_2. (pH 25°C: 11.3).
7) 0.5M K_2CO_3; 4mM $CaCl_2$; 0.25M NaOH. (pH 25°C: 13.4).
8) 0.5M K_2CO_3; 10ml 37wt% H_2O_2; 0.25M NaOH. (pH 25°C: 133).

Each sample was first wet sieved through a 106 micron sieve.
Samples were steamed on the steam bath waterline for 1 hour.
The temperature of the solutions were 84°C.

Results:
What follows are abbreviated descriptions of the samples after treatment. Included are values on a scale of 1-10 of the amount of organic and diatom remains that stuck to the watch glasses once the dried foraminifera in the size range >212 microns had been removed (fig 3.4). A bar graph of the species distribution appears in fig 3.3.

Sample 1
Foraminifera very clean. No cementing together of individuals. Slight etching visible, but does not cause fragmentation; could be dissolution in situ. Any partial dissolution seems confined to *H. pelagica.*

Sample 2
Dissolution more prominent than for (1). Silica strands evident. Cementing together of foraminifera by diatom girdles make counting a selective size range difficult. Whole diatoms still present. Many foraminifera still caked in organic matter.

Sample 3
A cleaner sample than (2), but still many diatoms and much organic matter. *H. pelagica* very fragmented. Cementing together of foraminifera still evident.

Sample
A fairly clean sample. Negligible dissolution of the foraminifera. Organics and diatoms still remain, hampering counting.

Sample 5
A clean sample. However, fragments and dissolution of foraminifera evident Fragmentation of *H. pelagica* and small clam shells serious.

Sample
Sample dominated by organic matter making counting difficult.

Foraminifera clean showing little dissolution except for *H. pelagica.* The fragments count due mainly to two broken individuals of *0. universe.* Remaining organic material tends to cement together some of the foraminifera.

Sample 8
A clean sample. No cementing of foraminifera. However, get partial dissolution and fragmen-
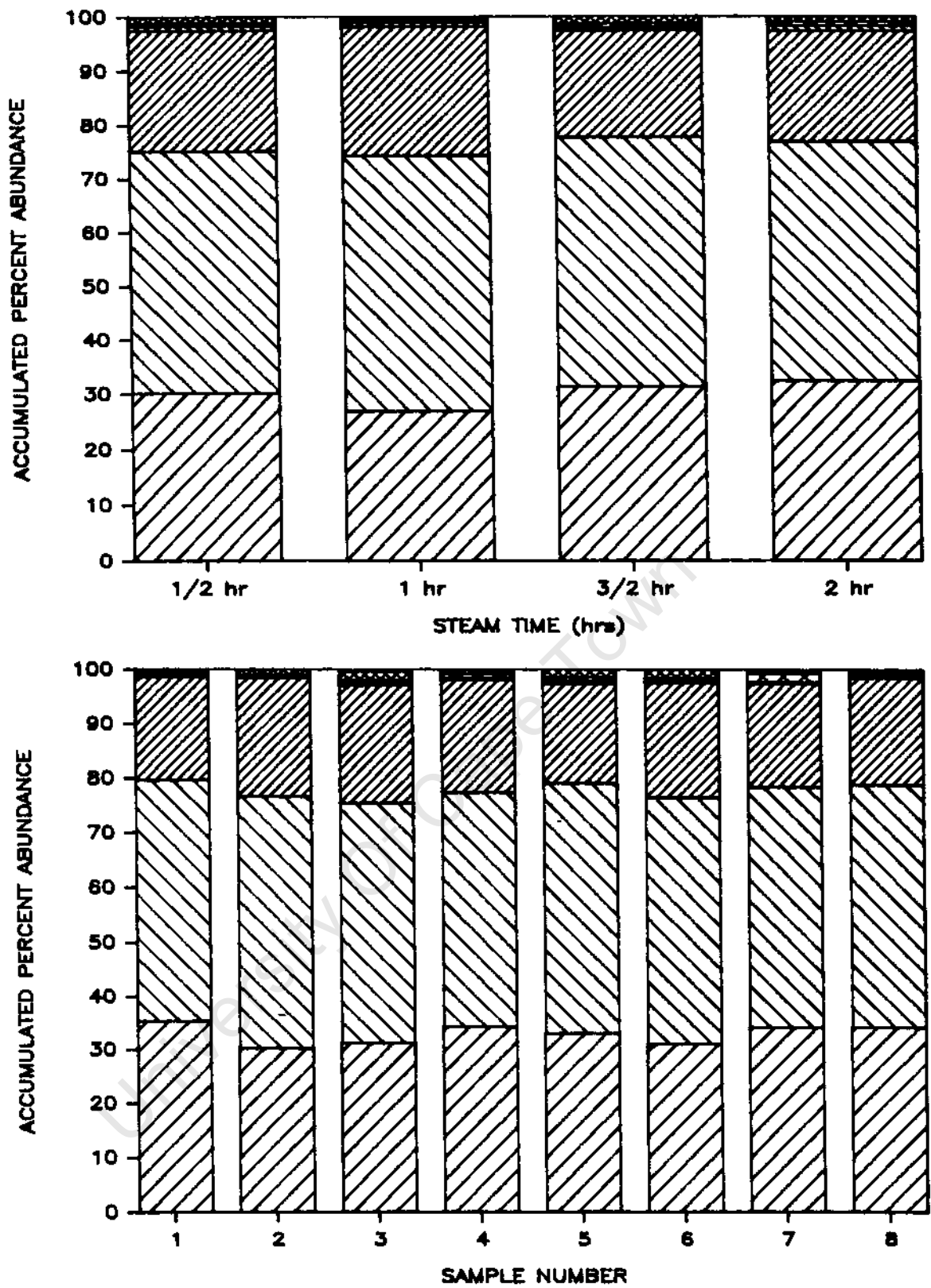
Fig 3.3. Upper graph: experiment 4: species distribution to test the robustness of foraminifers to prolonged steam times. Lower graph: experiment 5: species distribution for differing chemical solutions. Key for both graphs:

▨	*G. pachyderma*	▧	*H. pelagica*
◩	*G. bulloides*	▨	*G. inflata & G.ruber*
▨	*O. universa*	▨	*fragments*

Fig 3.4. Experiment 5 residues. Each photograph represents the amount of organic material left on the watch-glasses after the dried foraminifers in the 212-71Q micron size fraction had been removed. This gives some indication as to the effectiveness of each solution.

talon. Fragments count due mainly to two broken individuals of *If pelagica.*

Conclusions:
It seemed that the best solution was that used in (1).

After all this trial and error, the final
method of extraction was:

Prepare a solution of 0.5M K2CO3; 0.25M NaOH; CaCl2 and 6ml 37wt% H202 in a 200m1 beaker. Wet-sieved the sample at 212 microns. Place in solution and heat on the waterline of a steam bath for 30 minutes. Then wet-sieve again, put into a fresh solution and heat for an additional 15-2 hours. Then sieve and dry.

3.6 Foraminiferal counting

After each sample was chemically prepared and dried, it was brushed into a labeled vial. In some cases a few diatoms and diatom fragments remained. However, as the foraminifera were brushed off the watch glasses, the diatoms tended to stick to the glass surface.

The samples were dry-sieved to ensure that the foramaminifera were totally disaggregated from one another and only represented the size fraction >212 microns. To check that a combination of wet and dry sieving was giving representative samples, I subjected 4 identical mud samples to the full extraction procedure. The results of this experiment can be seen in fig. 35.

If the volume of foraminifera was too large for counting, I split them down into smaller subsamples with a microsplitter. For each sample approximately 1000 individuals were counted. Any piece of foraminifera less than half the original size was counted as a fragment.

3.7 **Summary**

Most of the foraminiferal counts for this thesis come from Core 3, taken in November 1985 with the newly-developed giant box core.
Once the core had been cut up into 2cm-thick downcore vertical slabs, one slab was subdivided into approximately 1cm-deep samples. The foraminifera from each sample were then extracted from the mud.

The various pitfalls of the method of gravitational separation led to the development of a chemical method of extraction. The chemical solution has a high pH that dissolves the diatoms. Saturating the solution with Cal$^+$ and CO_3^{2-} ions prevents the dissolution of the foraminifera. The constituents were: 0.5M K2CO3, 4mM CaCl2 6m1 37wt% 11202 and 0.25M NaOH. The samples were heated in 200m1 of this solution for half an hour, then wet sieved, placed in a fresh solution and heated for a further 2.5 hours.

It was found that the dissolution of the diatoms was more complete if the beakers were lowered through the lid of the steam bath so that the base of the beaker sat on the waterline. This raised the temperature of the solution by almost 20°C, resulting in much better convection.

OBSERVATIONS

4.1 Introduction

This chapter presents counts of planktonic-foraminifera from three sources:

4.2 Core SF-7.
4.3 Grab samples 1-13, excluding Grab 3.
4.4 Core 3.

The counts appear in three separate sections of the chapter. The data that has been presented for Core SF-7 represents that sampled at 5cm intervals. Although gravity separation was still being used, there was still enough material to enable some comparisons to be made with the grab and Core 3 data. I have not included the SF-7 samples extracted at 1cm intervals due to the ineffectiveness of gravity separation on samples of this size.

42 Foraminiferal counting

4.11 Size fraction choice

For core SF-7, for the grab samples and for Core 3, an average of 990 individuals were counted per sample interval. Because of this high count, the random counting error became significantly less than the amplitude of many of the downcore changes.

The chosen count size fraction was generally >212 and <710 microns. The reasons for this choice were:

a) The size range only contains the coarser foraminiferal assemblage which, in the event of minor winnowing, would be the best indicator of the death assemblage
b) This size range is easier to count than a finer one.
c) By choosing a coarser size range, the concentrations of the rarer foraminiferal species, such *as G. inflate, G. ruber* and *H. pelagica* are amplified.
d) Most of the foraminifera pass through the 710 micron sieve. Most fish scales and bones do not.

Many other researchers choose a slightly finer size fraction, >149 microns (Kipp 1976 for example). How would such a size fraction have affected my counts?

When Experiment 3 (Core SF-7) was carried out (see section 3.5), the results were divided into 2 size fractions:
1) 150-300 microns, and
2) 300-710 microns.
The results were plotted as accumulated species percent for each sample and size range (fig 4.1). As can be seen, within the coarser size range, although the percent abundance of *G. bulloides* remains roughly the same, the percent abundance of *G. pachyderma* drops while that of *0. universe* and *H. pelagica* increases. The downcore signal of *H. pelagica* is important for reasons explained below, while the percent abundance of *G. pachyderma*, although low at the surface, shows an interesting trend further downcore (see below).

Within the finer size ranges, viz, 150-212 microns and 63-149 microns, of the missing box 3-1-1 (treated as a grab), the following species have been identified: *G. pachyderma, G. quinquiloba, H. reideli, G. uvula* and *G. glutinata* (see fig 2.1). Because the last four of these species are so small and I am using a fairly coarse count size range, they do not appear in the downcore counts.

4.2.2 Confidence interval calculations

Where the number of individuals of any particular species type exceeded 5, then the confidence limits were calculated (Dixon and Massey, 1969 pp193).

The choice of a count size of 1000 as opposed to the customary 300 hardly affects the confidence limits of the major species types. However, for most of the minor species, a large count size results in their curves becoming statistically meaningful. For species count sizes less than 5, as the standard equation for confidence limits cannot be used (Dixon and Massey 1969 pp194), another method was adopted which involved assigning calculated
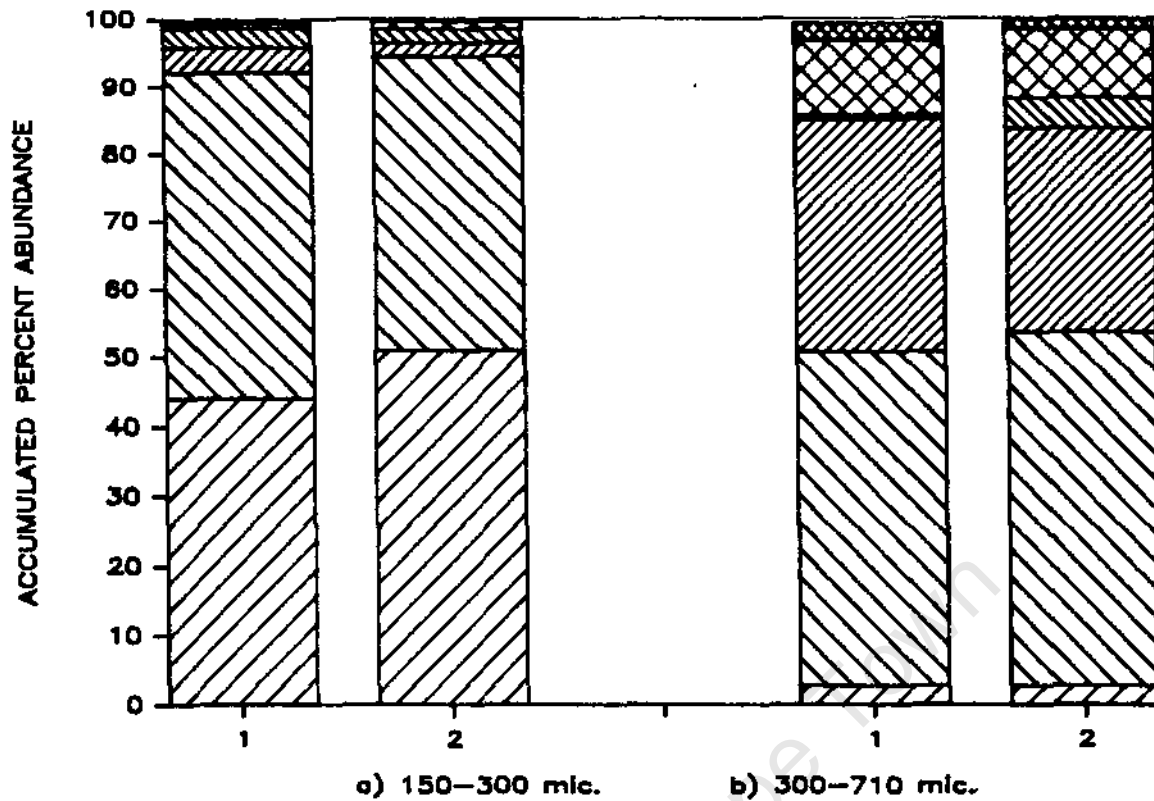
Fig 4.1 Species distribution in different size fractions (from experiment 3). Two samples of SF-14 were counted in the size fractions 150-300 microns, and 300-710 microns. Key to the graph:

▨	*G. pachyderma*	▨	*H. pelagica*
▨	*G. bulloides*	▨	*G. inflata*
▨	*O. universa*	▨	*G. ruber*
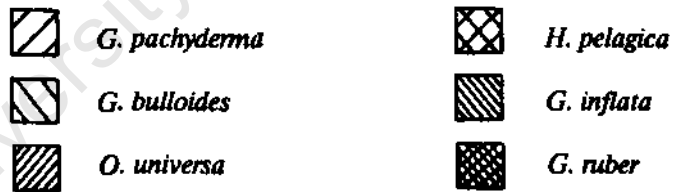
limits for species counts of 5, 4, 3, 2, 1 and 0 respectively, based on the F-distribution (Sachs 1978).

43 Core SF-7

Some of the details relating to Core SF-7 are in section 33.1.

The count size range was 212 - 300 microns. Consequently the abundance of *0. =Versa* is much lower than that for Core 3. The distribution of different species with depth appears as a bar chart in fig 4.2. *G. bulloides* is the dominant species, followed by both forms of *G. pachyderms.* Other species include *G. inflata* and *0. universa.* The abundance of *G. inflata* is low, while *G. truncatulinoides* is virtually non-existent. *H. pelagica* is completely absent probably because of gravity separation (see section 3.4). Core SF-7 is positioned in between grab's 8 and 9.

4.4 Grab samples 1-13

These were the first set of samples to be subjected to the chemical method of extraction. The size range was 212 - 710 microns. Fig 4.2 shows the counts of each grab, arranged in west to east order. Most notable in these observations is the appearance of *H. pelagica* and *a universa.* The percentage of *H. pelagica* peaks in Grab's 5. 6 and 7 where it reaches values of up to 1.6%. Its presence is a clear reflection of the success of the chemical method of extraction. Although this size interval (212-710 microns) allows counting of *H. pelagica,* it also contains a high percentage of *0. universa,* a confusing species (see section 2.6.6). To prevent this species from distorting the observations, fig 4.2 has been calculated without it.

Fig 4.1 shows the following:
  a) *G. bulloides* is the dominant species throughout, although the summed percent of left- and right-coiling *G. pachyderms* reaches up to 50% in places.
  b) Grabs 6, 10 and 11 all have very high percentages of *G. bulloides.*
  c) 3 samples were taken at longitude 14 06'E (grab's 1, 2 and 10). They don't, however all show the same species distribution.
  d) West of 13 58'E (grab 6), there is an apparent increase of the transitional species *G. inflata.*

4.5 Core 3

The foraminiferal counts for Core 3, expressed as percent abundance, appear in figs 43 - 4.10. Depth in core is the summed depth readings taken during sampling (see section 3.3.2).
The relative abundances of the major species appear as both 3 and 10-point running averages. The reason for subjecting the results to these filters is:
  1) 3-point miming averages help to smooth out small layer-by-layer irregularities. Also, by applying a 3-point running average, foraminifersl counts of 1000 become an effective 3000. This in turn improves the confidence limits by the square root of one third.
  2) 10-point running averages show only the longer term changes down-core.

A full listing of the counts is in the appendix. Fig 4.11 represents the distribution of the major species *(G. bulloides,* left- and right-coiling *G. pachyderms,* a *universa)* plotted downcore as 3 and 10-pt. running averages respectively. The missing sections in the curves represent the two missing core boxes (see section 33.2). The 10-point running averages presumably enhance the longer-term trends, while a 3-point running average show shorter-term changes.

The high concentration of *0. universa* confuses the plots somewhat. To correct for this, fig 4.12 shows percent abundances ignoring this species.

Some of the most obvious features of figs 4.11 and 4.12 are:

  1) a steady decrease in the abundance of *G. bulloides* downcore to the apparent advantage of right-coiling a *pachyderms* and *G. dutertrei,*
  2) major peaking of left-and right-coiling *G. pachyderms* in the top half and in the middle of the core,
  3) very little change in major species abundances in the last quarter of the core sequence,

The distribution of the minor foraminiferal species *(G. rubel; G. inflates,* a *truncatulinoides* and *H. pelagica) has* been plotted in figs 4.7 - 4.10. Due to the high total

19
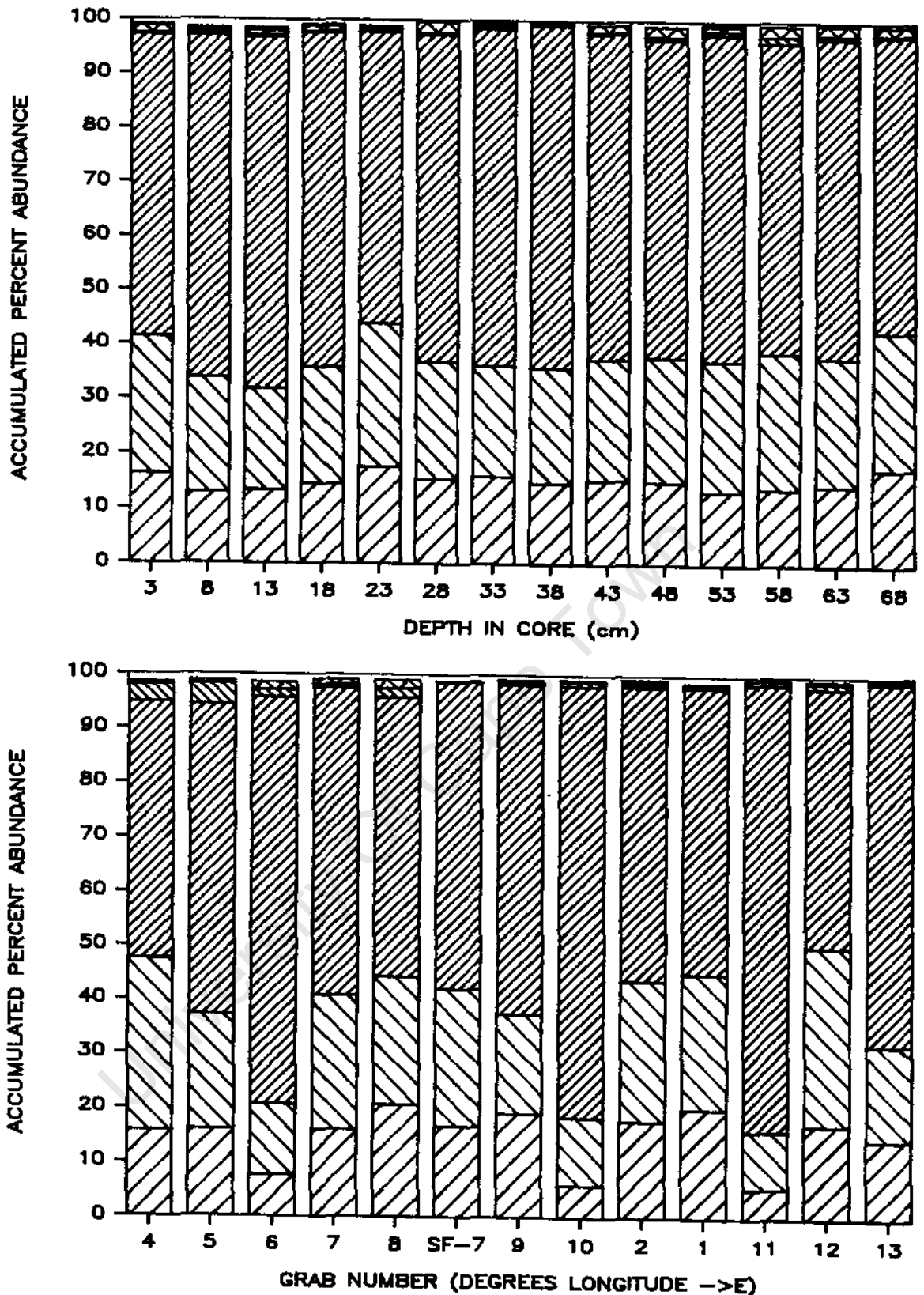
Fig 4.2. Upper graph: Species distribution with depth in Core SF-7. Sampling interval was 5cm, size range 212-300 microns. Lower graph: Species distribution with respect to grab sample number and longitude (SF-7 included). Count size range 212-710 microns. a *universa* not included.

Key for both graphs:

G. pachyderma (l.coiling)   G.bulloides

G. pachyderma (r.coiling)   G.inflata

lower graph: *H.pelagica*
Upper graph: *O. universa*
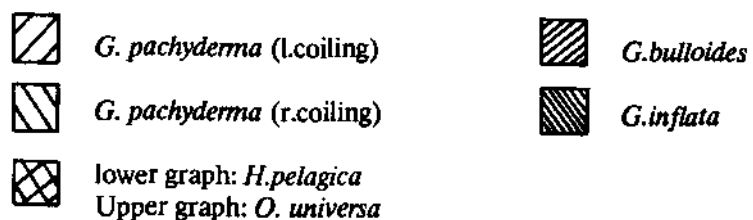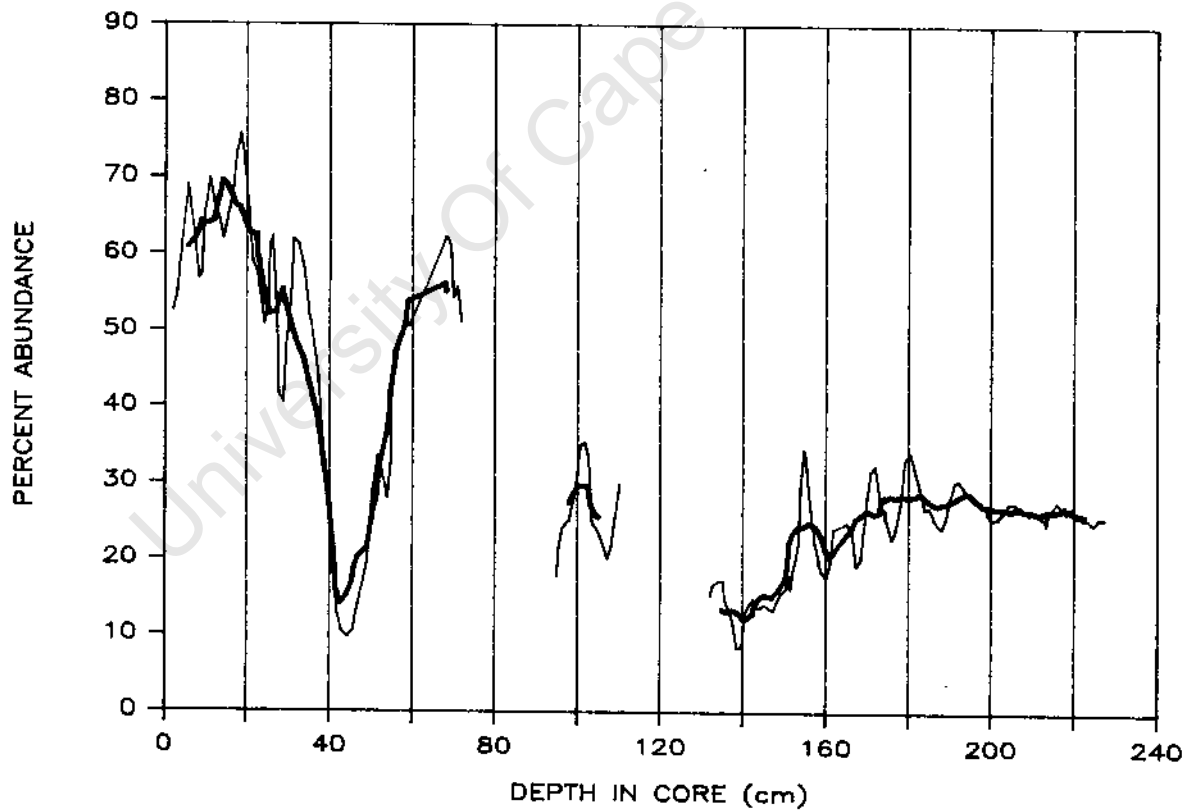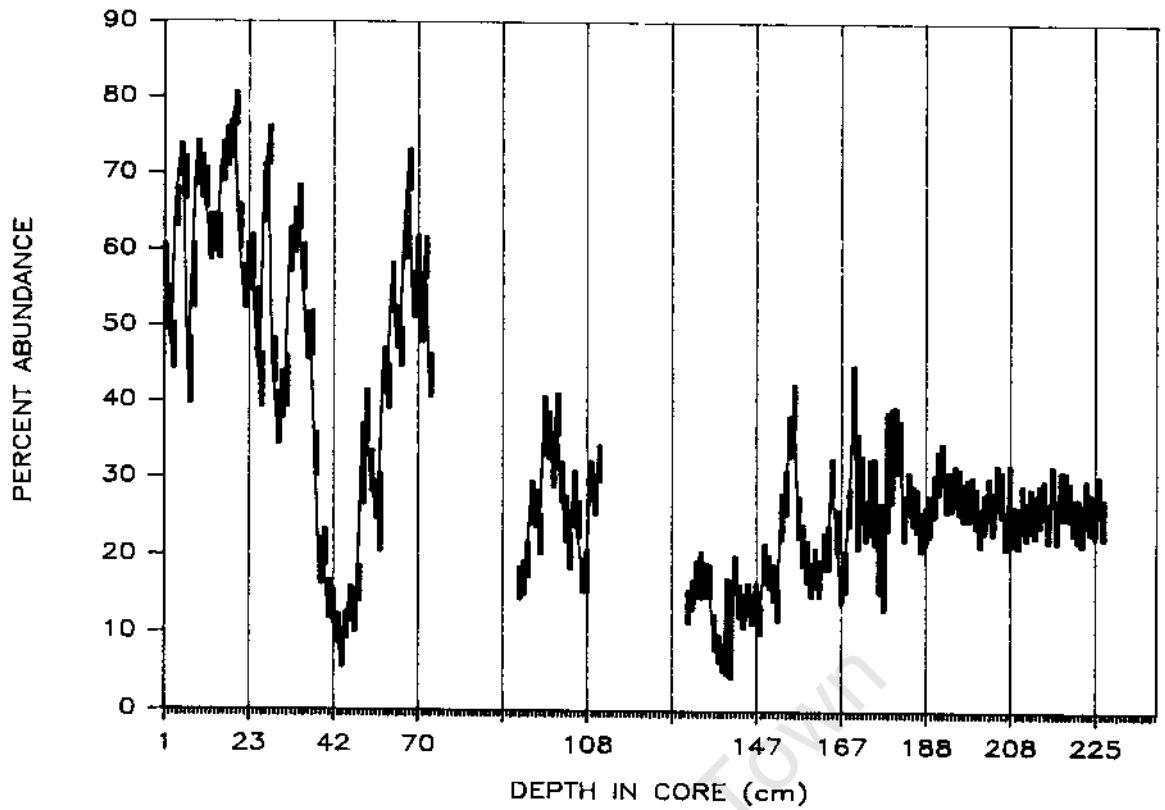
Fig 4.3. Relative abundance of *G. bulloides.* The upper graph
shows the observations with 95% confidence bars. The lower
graph show 3-point (thin curve) and 10-point (thick
curve) running averages of the observations.
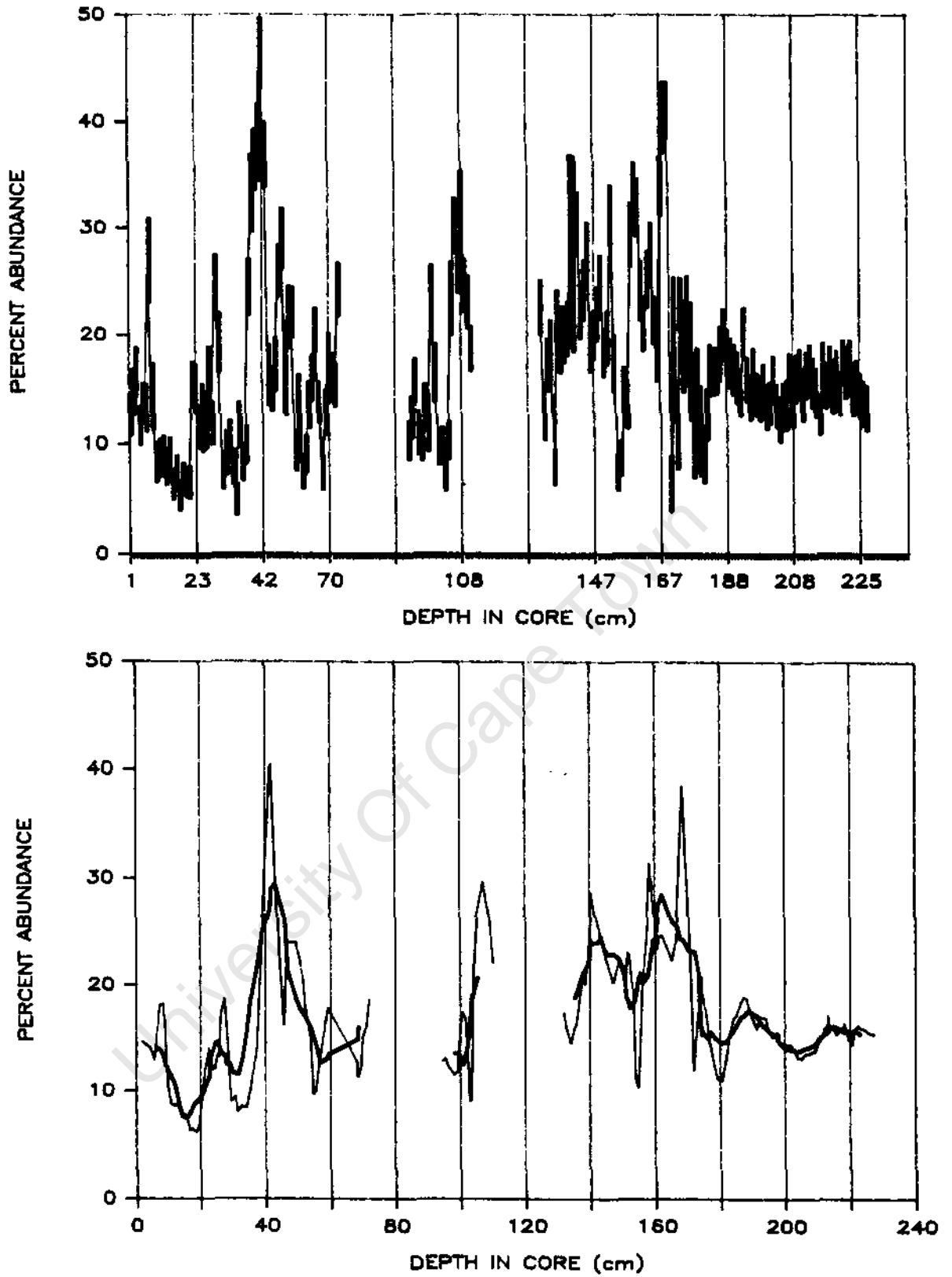
Fig 4.4. Relative abundance of left-coiling *G. pachyderma.*
The upper graph shows the observations with 95% confidence
bark The lower graph show 3-point (thin curve) and 10•point
(thick curve) running averages of the observations.
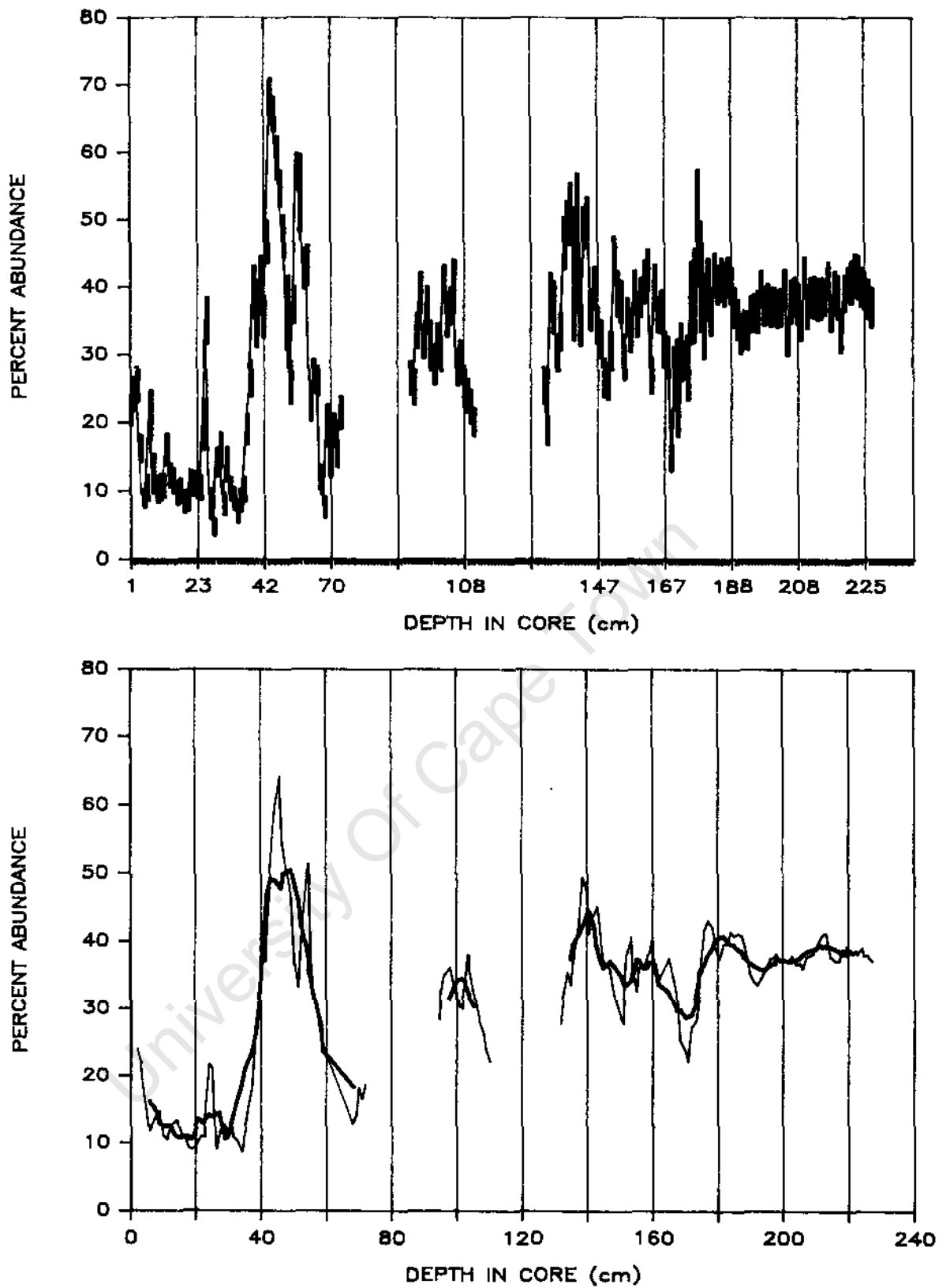
Fig 4.5. Relative abundance of right-coiling *G. pachyderma.*
The upper graph shows the observations with 95% confidence
ars. The lower graph show 3-point (thin curve) and 10-point
(thick curve) running averages of the observations.
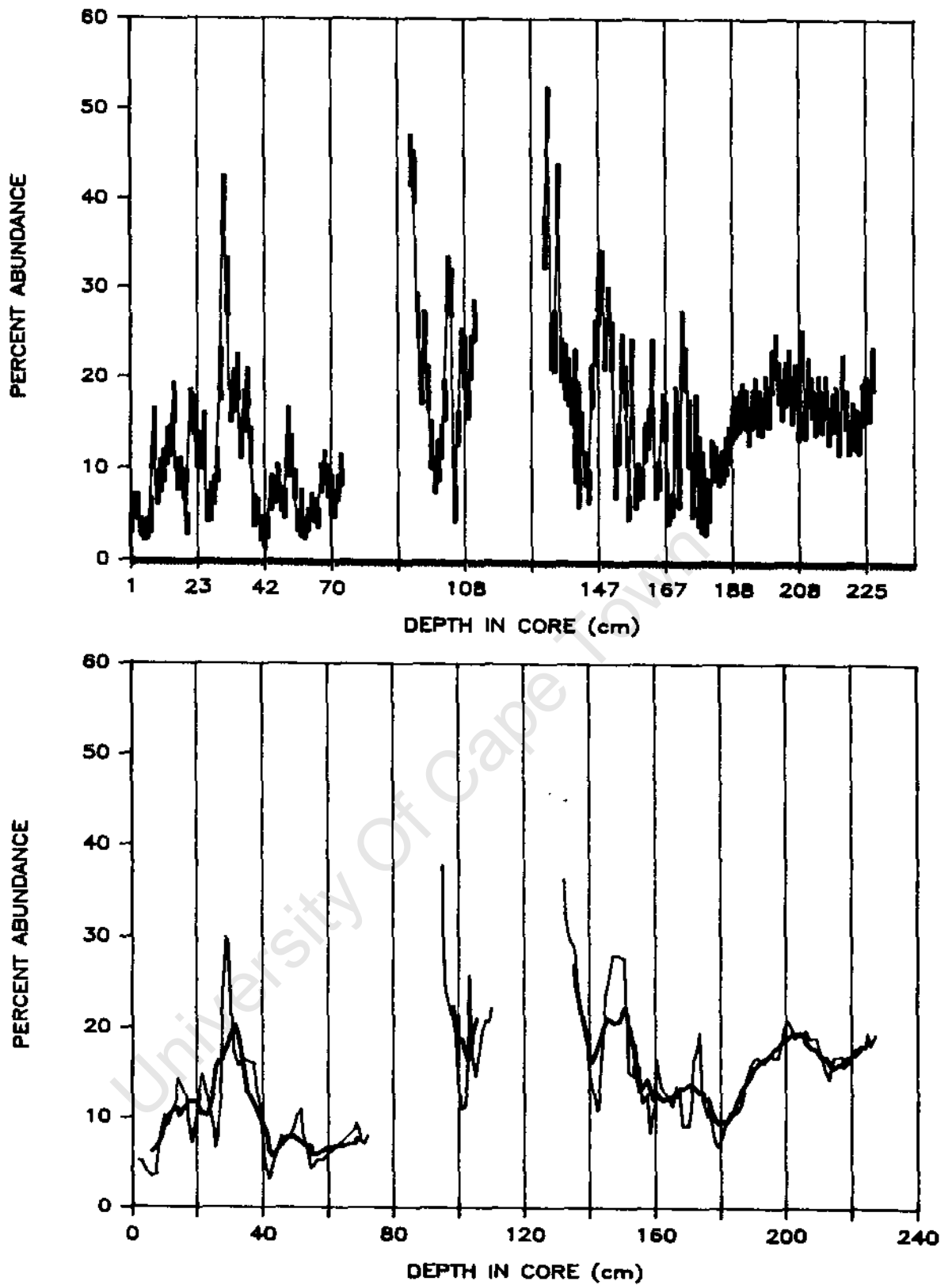
Fig 4.6. Relative abundance of *0. universe.* The upper graph.
shows the observations with 95% confidence bars. The lower
graph show 3-point (thin curve) and 10-point (thick curve)
running averages of the observations
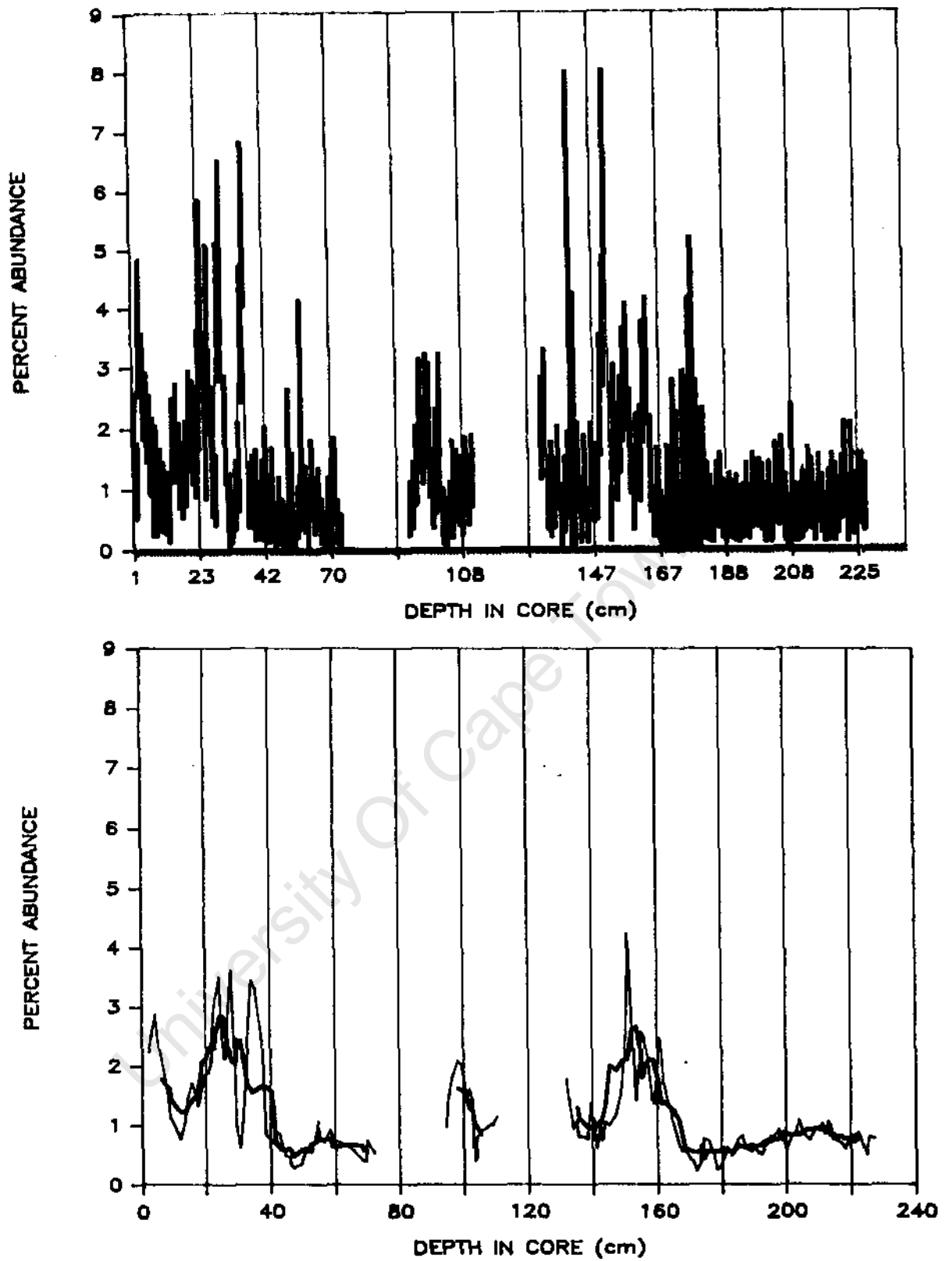
Fig 4.7. Relative abundance of *G. input* The upper graph shows the observations with 95% confidence bars. The lower graph show 3-point (thin curve) and 10-point (thick curve) running averages of the observations.
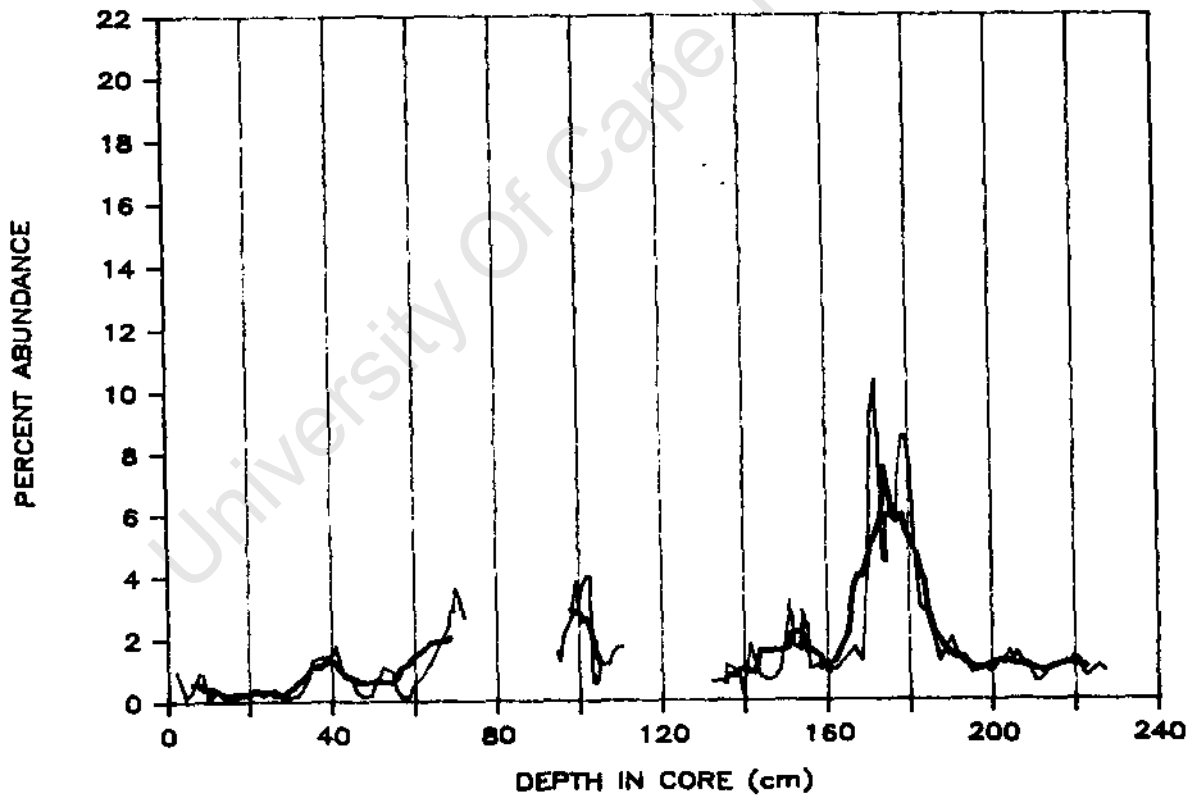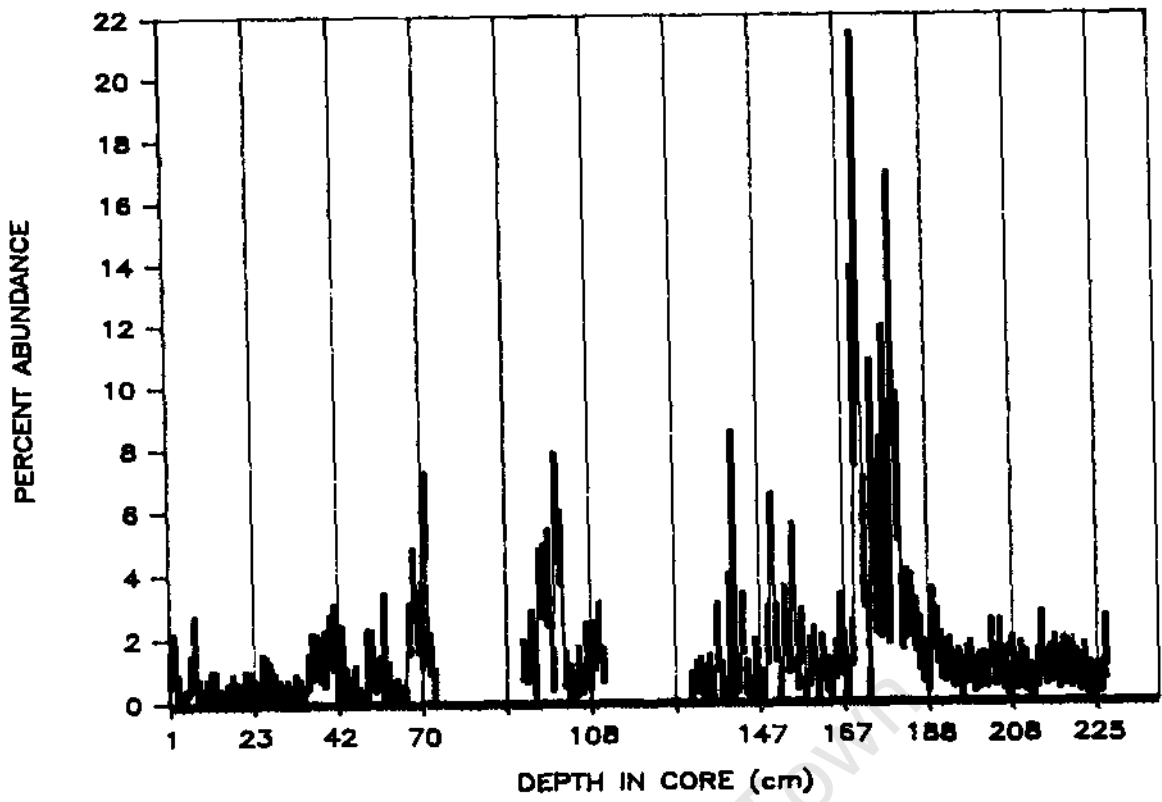
Fig 4.8. Relative abundance of *G. pelagica.* The upper graph
shows the observations with 95% confidence bars. The lower
graph show 3-point (thin curve) and 10-point (thick curve)
running averages of the observations.
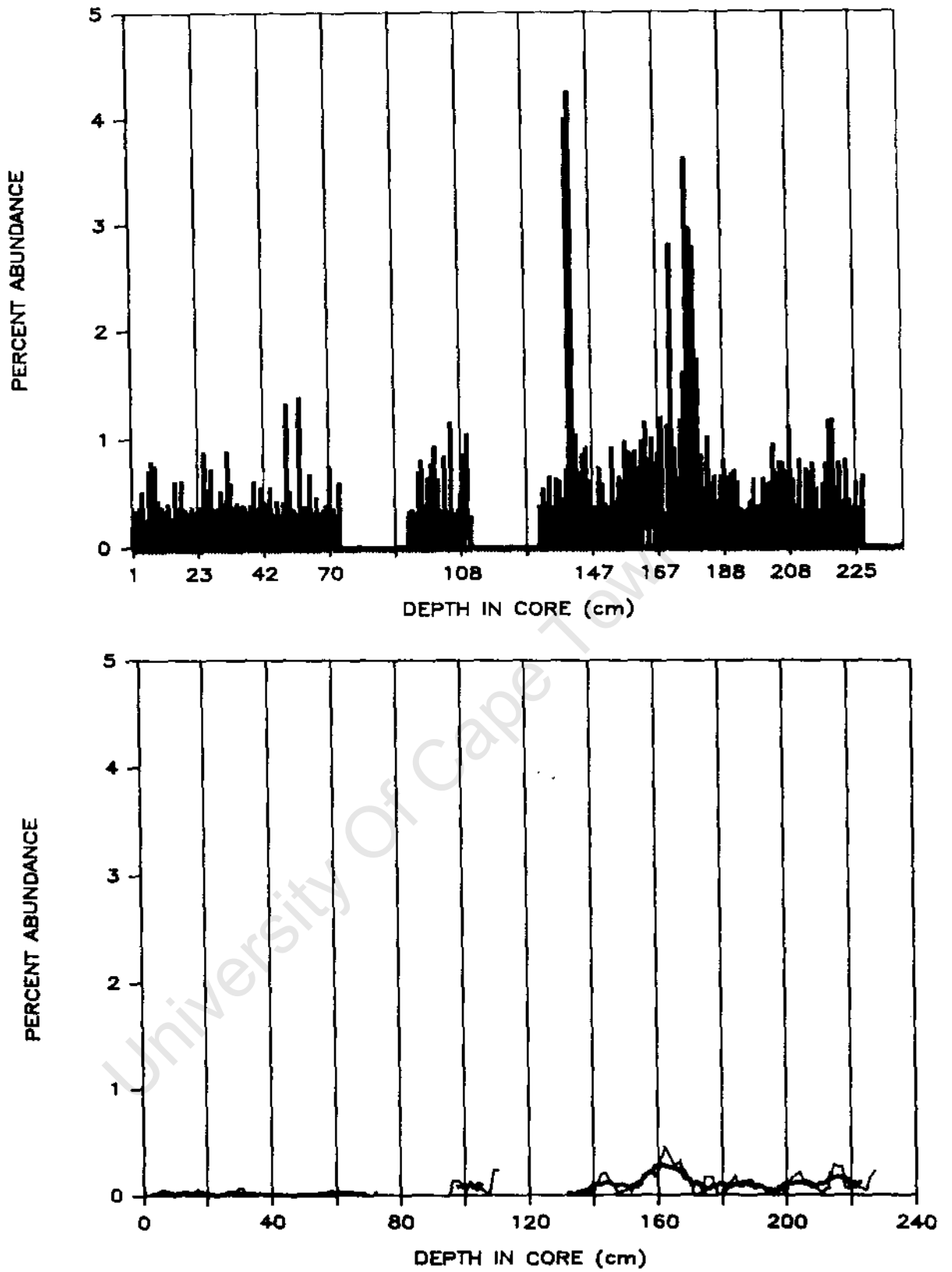
Fig 4.9. Relative abundance of G. truncarulinoides. The upper
graph shows the observations with 95% confidence ban. The
lower graph show 3-point (thin curve) and 10-point (thick
curve) running averages of the observations
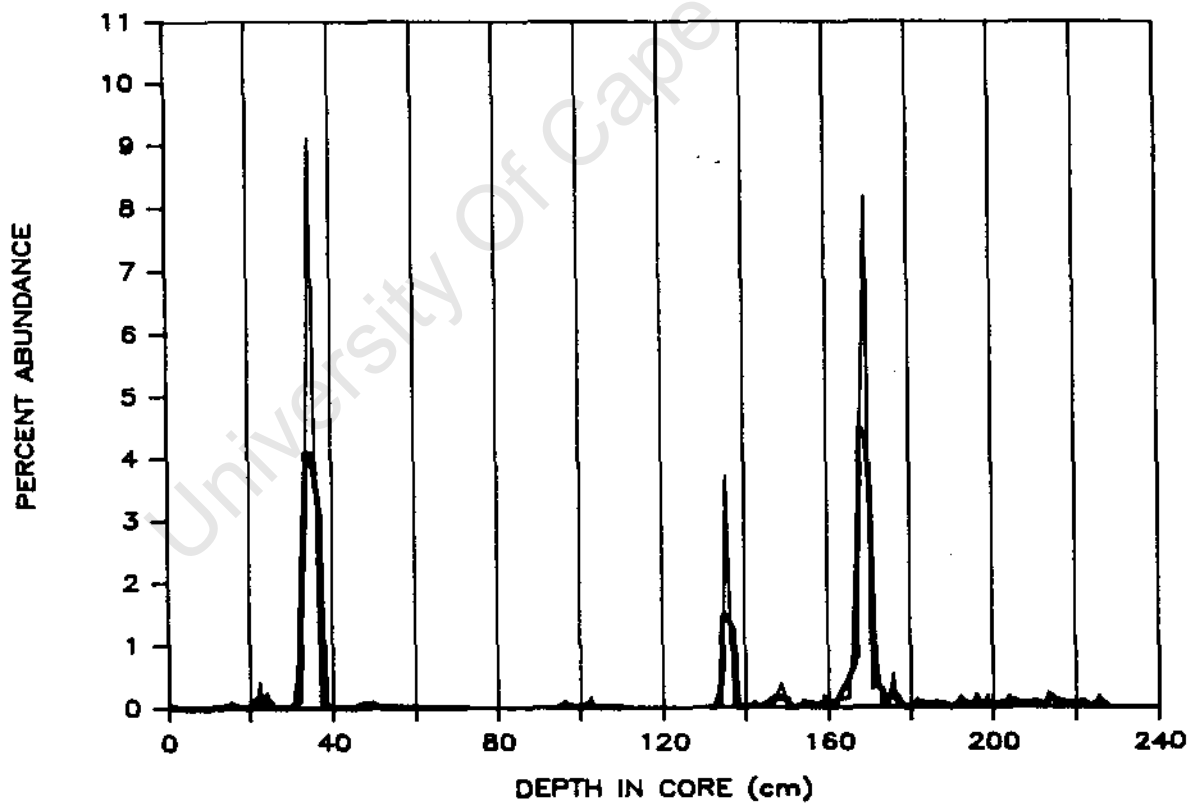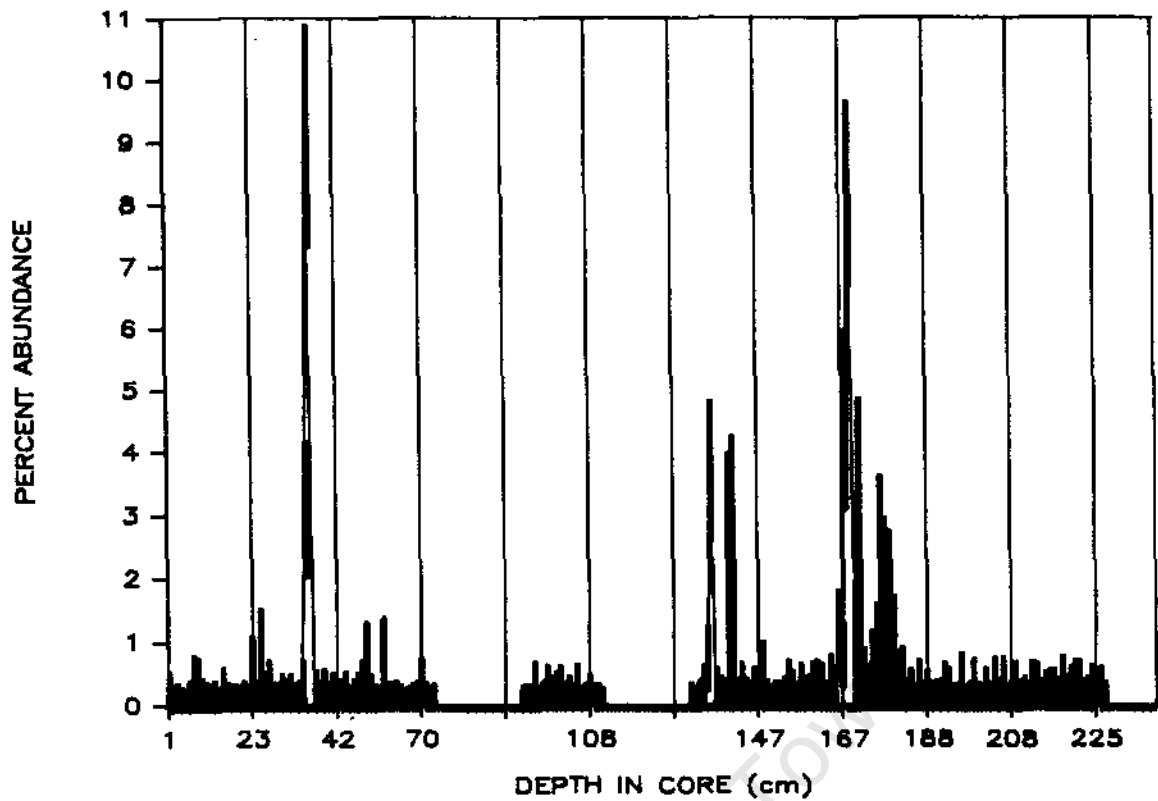
Fig 4.10. Relative abundance of *G. fuller*. The upper graph shows the observations with 95% confidence bars. The lower graph shows an unadjusted (thin curve) and a 3-point (thick curve) running average of the observations
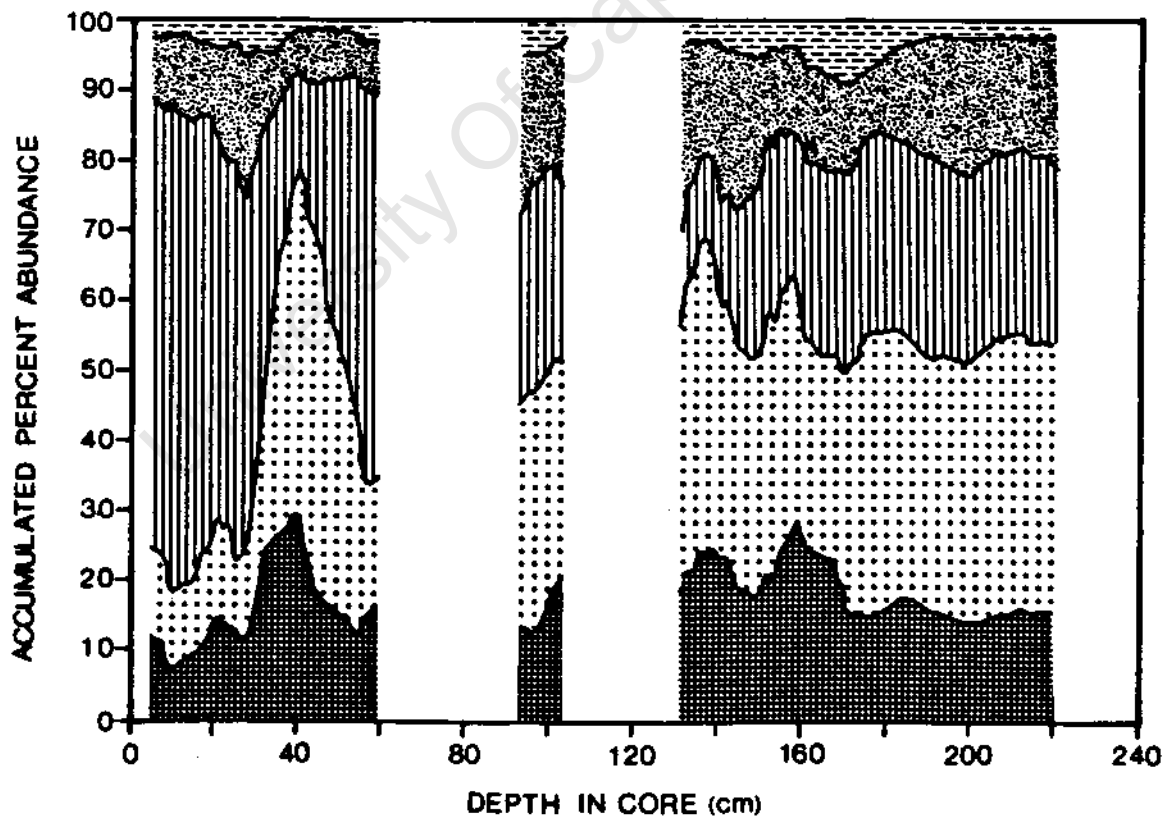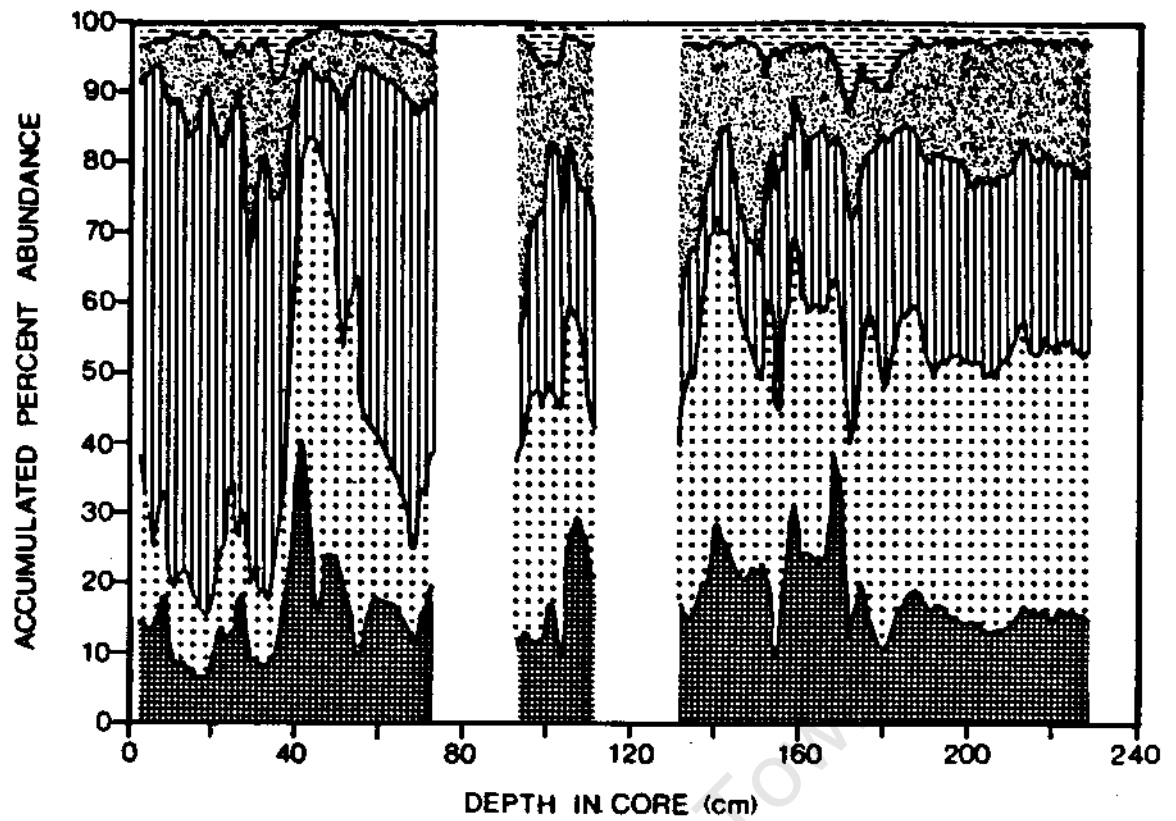
Fig 4.11. Accumulated abundances of *G. bulloides*, a *pachy-derma, 0. universe* and others with depth in Core 3. The upper and lower graphs represent 3- and 10-point running averages of the observations respectively. Key for both graphs:

- *G. pachyderma* (l. coiling)
- *G. pachyderma* (r. coiling)
- *G. bulloides*
- *O. universa*
- Other
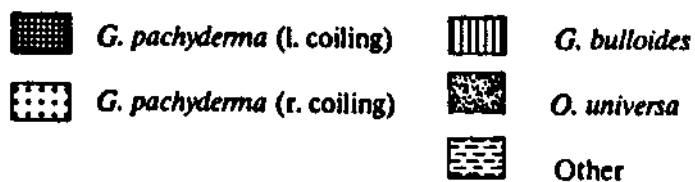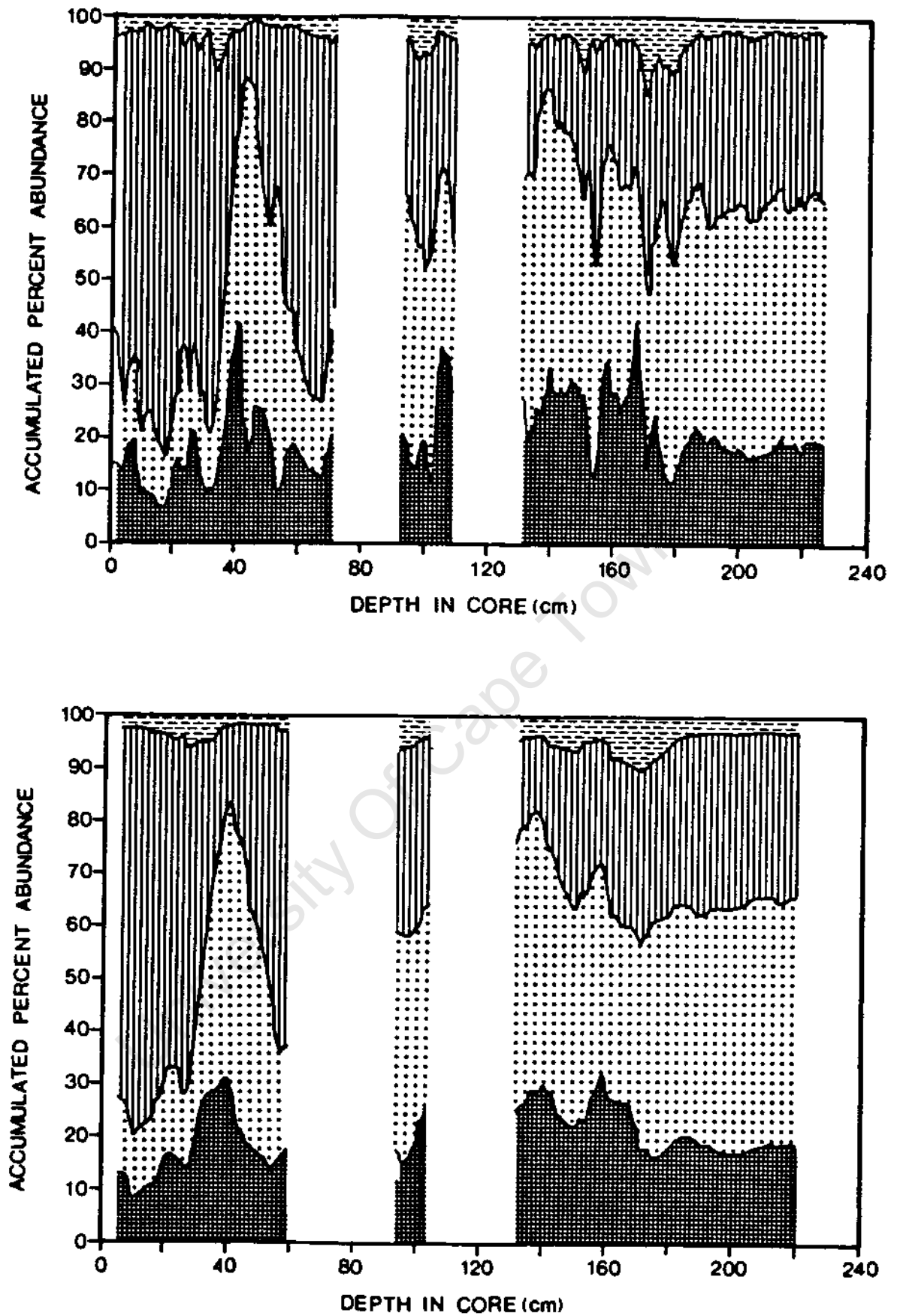
Fig 4.12. Accumulated abundance of *G. bulloides, C. pachyderma*
and others with depth in Core 3. *O. universa* is not included
in the count. The upper and lower graphs represent 3- and

Key for both graphs:

▓	*G. pachyderma* (l. coiling)	▥	*G. bulloides*
▦	*G. pachyderma* (r. coiling)	▧	Other
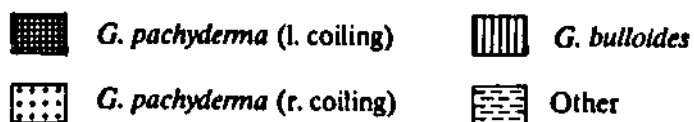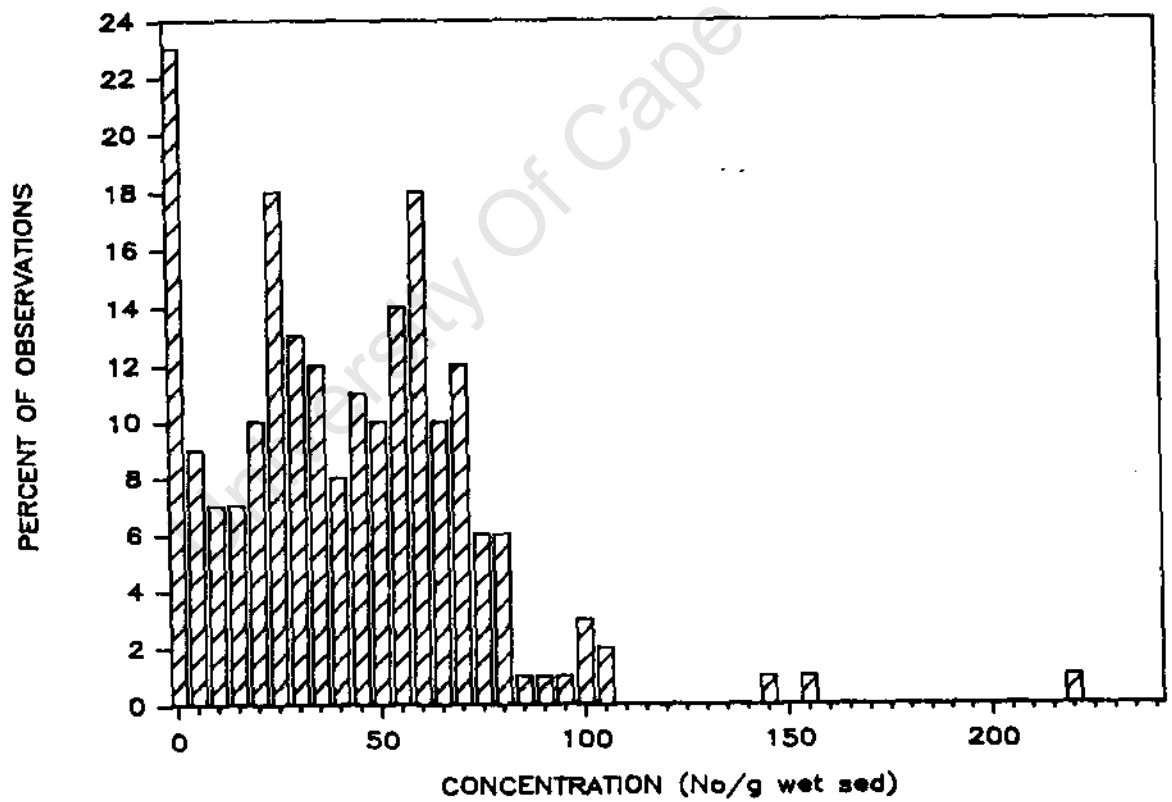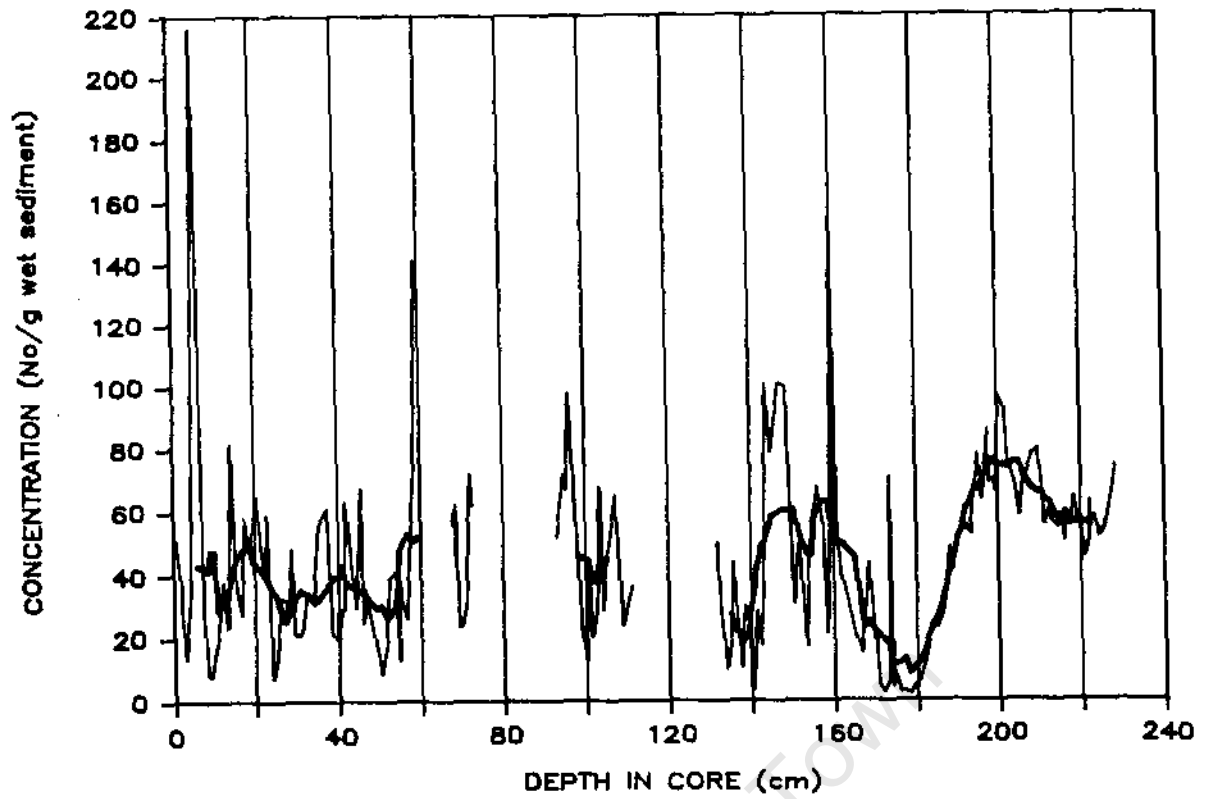
Fig 4.13. The concentration (number per gramme wet sediment) of foraminifera with depth in Core 3. The upper graph shows the observations (thin curve) and a 10-point (thick curve) running average of the observations. The lower graph is a histogram of concentration

counts, many of the peaks and valleys in these curves have statistical significance.

Concentration of foraminifera per gramme wet sediment appears in fig. 4.13. The heavy curve represents a 10-point running average. Included is a histogram of this concentration.

4.6 Regression between species

Regression lines between left- and right-coiling *G. pachyderma* and *G. bulloides* appear in figs 4.14 and 4.15. The y-intercept, slope of regression and correlation co-efficient of the lines also appear in the figures. The formula for the slope and correlation co-efficient is in Dixon and Massey (1969).

A comparison between the *G. bulloides/left-coiling G.* pachyderma regressions of core SF-7, Grabs 1-13 and Core 3 shows a strong similarity between all the Mopes and y-intercepts. This however, could mean one of two things:

1) *G. bulloides* and *G. pachyderm°* belong to different ecological niches. When the abundance of *G. bulloides* increases, that of *G. pachyderma* decreases at a proportionate rate.

2) The abundance of *G. bulloides;* left- and right-coiling *G. pachyderma* together make up to 90% of this coarse size fraction. Consequently, the percent abundance of left-coiling *G. pachyderms* may simply be fluctuating in accordance with the changes in the percent abundance of the dominant species *G. bulloides* (these values are with respect to the total foraminiferal count as opposed to being foraminiferal fluxes or concentrations). The trends may be real however, as the relationships between other sets of species do not show good correlations (eg: the relationship of left-coiling *G. pachyderma* to its right-coiling counterpart, which presumably includes *G. &word,* has a correlation co-efficient of only 027; see fig 4.15).
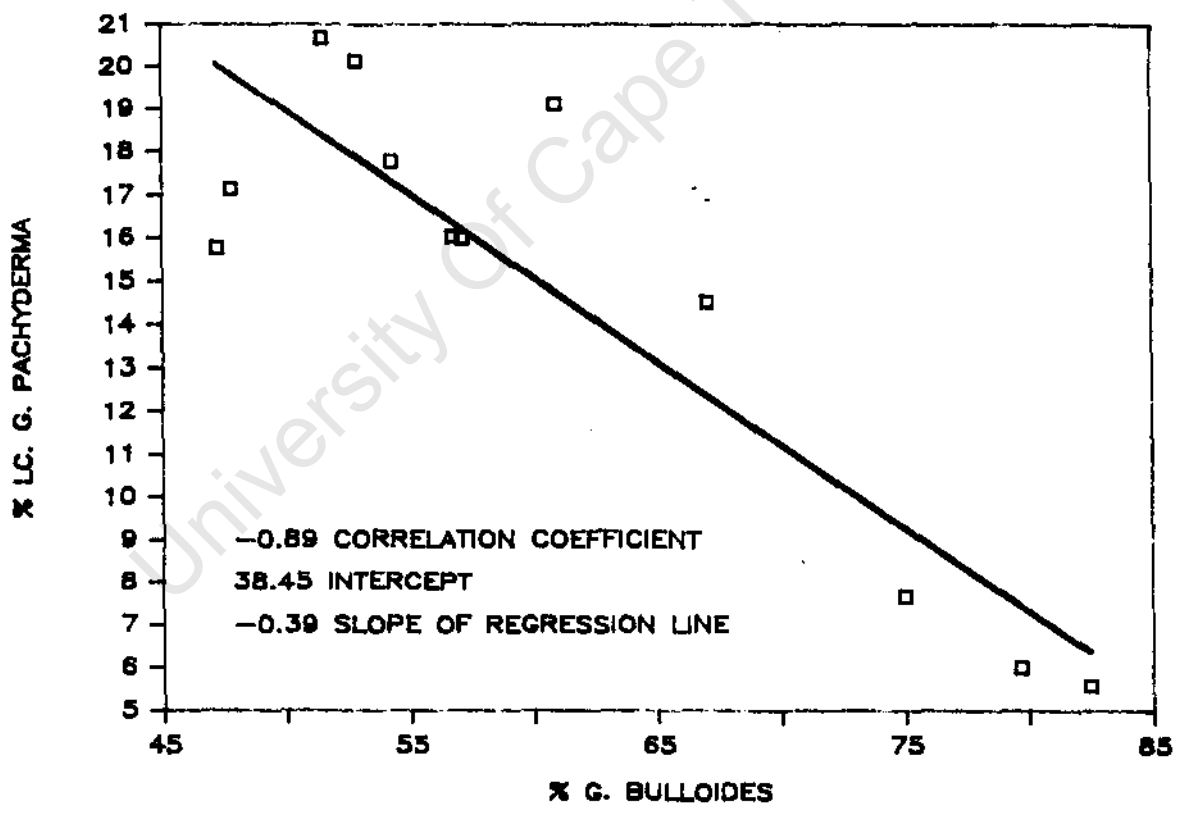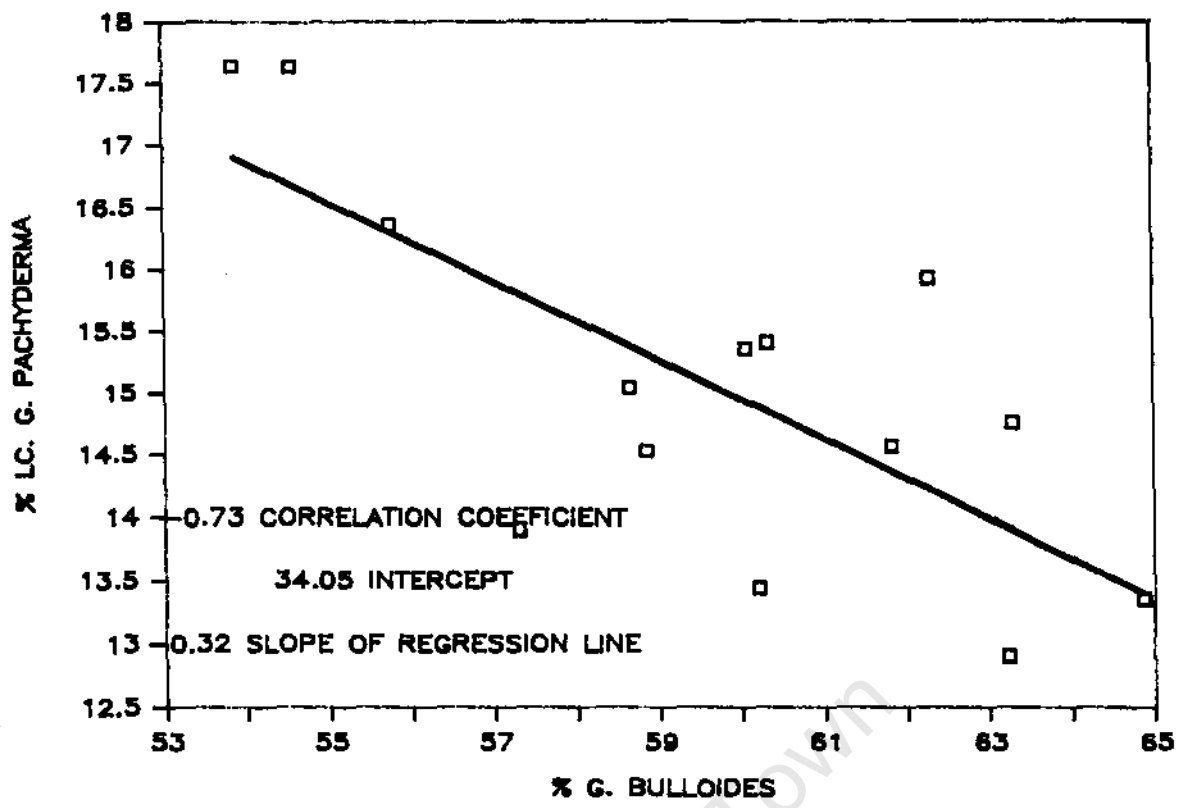
Fig 4.14. Regression lines of *G. bulloides versus* left-coiling *G. pachyderma.* The upper curve represents Core SF-7. The lower curve represents Grab samples 1-13, corrected for *O. universa.*
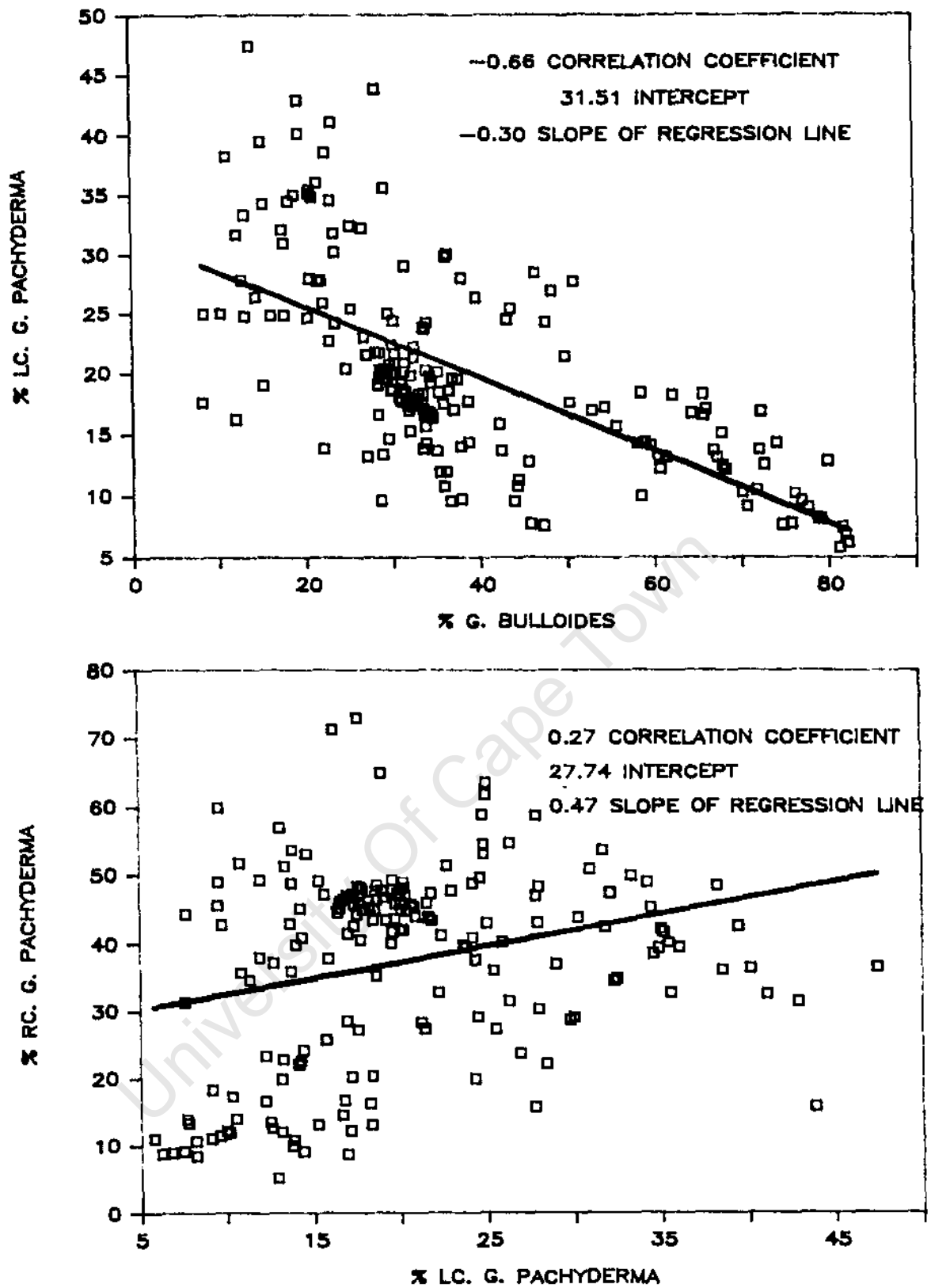
Fig 4.15. Regression lines for Core 3. The upper graph represents *a bulloides* versus left-coiling *G. pachyderma*. The lower graph represents left-coiling- versus right-coiling *G. pachyderma*. Both graphs have been corrected for 0. *universe*.

CHAPTER 5

INTERPRETATION

5.1 Introduction

This chapter attempts to explain the observed dovmcore changes in terms of climate change and its influence on circulation. One cannot, however, simply presuppose that the curves either directly or indirectly reflect climate change, as fluctuations in them could conceivably result from a number of causes.

Before proceeding to the dovmcore counts in Core 3, this chapter first briefly discusses the results of the grab samples and Core SF7.

52 Grabs 1-13 (excluding 3)

The following can be said for fig. 4.2:

1) The persistently high concentrations of *G. bulloides* and left- and right-coiling *G. pachyderma* is to be expected, considering the grab's positions within the plume of Walvis Bay upwelled water (see section 2.4). Unlike the trend shown by Herbert (1984), the abundance of *G. pachydenna* does not increase in an easterly direction. Two explanations for this could be:

The grabs were taken along an east-west line that cuts obliquely across the plume of upwelling as opposed to running down the length of it. Consequently, Grab 13 (eastern edge) does not really represent much colder conditions than for Grab 4 (western edge).
- The size range of foraminifera counted for the grab samples of this thesis was 212-710 microns, as opposed to a range of only 150-300 microns used in the earlier research. As a result the relative abundances of different species is not the same (see section 4.2). Grabs 1-13 have much higher *G. percen*—
tages than the earlier (Herbert 1984). Consequently any variation of species abundances in the smaller size range will be suppressed for the grab samples of this thesis.

2) The abundance of *G. inflata* is small in all the grabs. However, it does show an apparent increase in the three samples west of 13 58'E (Grabs 4, 5, 6). This compares well with earlier research (Herbert 1984), and is possibly due to both the availability of food favored by this transitional species and the influence of warmer water further offshore.

3) *H. pelagica* remains a minor species in all the grab samples, even though the chosen size range is suitable and the chemical method of extraction does not seem to damage them. Its seems obvious, therefore, that this region is not suited to such a warm water species. The virtual absence of *H. pelagica* **is** characteristic of most of Core 3 as well.

53 Core SF-7

The average abundance of the major foraminiferal species at the top of the analyzed section of Core SF-7 compares well to that of grabs 8 and 9 (fig 4.2). The section of core analyzed did not however, represent the sediment-water interface (the uppermost section has a soupy consistency). One possible reason for the good correlation is that the grabs samples may have overpenetrated. Comparison of Core SF-7 data to that of Core 3 is difficult due to possible overpenetration of Core 3. The bottom 40cm of Core SF-7 may correspond with the first 40cm of Core 3. However, within this region. Core 3 shows a much higher *G. bulloides* abundance than that for Core SF-7. It must be remembered though, that:
  1) gravity separation was used for foraminiferal extraction, and
  2) the count size range was 212-300 microns for Core SF-7 and 212-710 microns for Core3.

Both of these factors cause a drop in the relative abundance of *G. bulloides.*

The high abundance of the wanner species *G. bulloides* relative to the cold-water species *G. pachydenna* is possibly indicative of the modern climatic optimum (Eddy 1977).

5.4 Core 3

As mentioned, the observations central to this thesis come from Core 3. To interpret this core, we will look at major species separately

from the minor species. The reasons for this will become clear shortly.

Essential to understanding the downcore change is a time scale. Before considering the species variations, we will first consider the problem of converting depth-in-core to time.

5.4.1 Converting from depth-in-core to time

Few measurements have been made of the sedimentation rate in the diatomaceous mud belt off South West Africa. Also, whatever dates have been produced need to be treated with caution, as it is not certain *as* to exactly what they represent:
  1) Are the carbonate dates influenced by older carbon respired from the mud column?
  2) Has the organic matter used in dating been winnowed and redeposited?

In regions of the mud belt where the depth of water and concentration of calcium carbonate most closely approximates that of the Core 3 location, average sedimentation rates of 1mm/year have been found (Veeh et al 1974).

Another estimate of sedimentation rate can be made as follows (Bremner 1980). The thickness of the mud belt at the Core 3 site is approximately 6m (R Johnson, 1986 pers commun). Assuming, at latest, that within this near-shore site, silica and carbonate accumulation began at 6000 years BP, then the accumulation rate is 1mm/year (see Bremner 1980).

On the other hand, within the upper 30cm of a core taken in the vicinity of Core 3, on the basis of ^{210}Pb dates, DeMaster (1981) *has* produced an accumulation rate of 8mm/year.

For the purposes of this thesis, I initially assumed an average accumulation rate of 2mm/year. Ideally, the curves should be interpreted in terms of a changing accumulation rate. However, for this to be possible, a number of reliable dates are needed downcore.

When Core 3 was taken, the surface of the core definitely penetrated past the sediment-water interface. This complicates matters somewhat. After examining the consistency of the mud at the top of the core and accounting for other conditions at the time of collection, I decided that at least one box's worth of mud was lost at the top. On the basis of the very fluid nature of the mud at the surface, I have assumed a starting date for the core of 1900 AD. Using this as a starting date and a sedimentation rate of 2mm/year, a time axis has been added to the curves.

Another problem is how to adjust the measured depth in order to correct for the effects of winnowing and redeposition. It is important to create some hypothesis, as erosion/redeposition will both alter the length of any section of the core and dilute or concentrate the foraminiferal signal. This can happen by:

  1) complete removal of a mud and foram layer
  2) addition of foram-depleted mud to an existing layer
  3) erosion of mud only, to leave a foram lag deposit.

I have addressed the problem in this way:

Assume that foraminifera are neither winnowed nor redeposited from upslope. Then the original mud thickness is:

$$To = (C/C0) \times T$$

where:
  T0 = the original mud thickness without erosion or redeposition
  T = the measured thickness, changed by erosion or redeposition
  Co = the foraminiferal concentration without erosion or redeposition
  C = the measured foraminiferal concentration

I have assumed that Co has the value of a 10-point running average and C has the value of a 3-point running average. Although obviously in many instances, fluctuations in the 3-point curve relative to the 10-point curve are probably not due to either erosion or redeposition, this method effectively accounts for the scattered foraminiferal lag deposits. As it turned out, this procedure did not change the shape of the down-core plots very much.

5.4.2 Major species distribution

5.42.1 General

The best way of presenting the species changes would be as a flux of foraminifera (number per unit area per unit time). if foraminifera are

not winnowed or redeposited, then flux changes must correspond to ecological changes. However, as I do not have any real dates to work with, measuring fluxes is not possible.

An alternative to foraminiferal flux is to ratio two species together. The change in the concentration of one species is always viewed relative to the change in concentration of the other. In this way, assuming that the two species have similar settling times, winnowing and redeposition have no effect (ie: if species A increases in concentration by a factor x and species B increases by a factor xy, by ratioing the two species together, real change can be plotted).

Ratioing on its own is not really suitable, however, as the curve becomes compressed vertically when the value of the species in the denominator exceeds that of the species in the numerator. Logging the ratio is one way of solving this Alternatively, another method would be to use the ratio:

$$speciesB/(speciesB + speciesA)$$

The ratio can only equal zero when species B equals zero. This kind of foraminiferal index has been used in the curves seen in fig 5.1.

5.422 Interpretation of the curves

As can be seen in figs 4.3 - 4.5, substantial changes in the relative abundance of *G. bulloides* and *G. pachydenna* exist downcore. The confidence limits of *G. bulloides* and left-coiling *G. pachyderma* show that these changes are statistically significant at the 95% confidence level in terms of counting error (fig 4.3 and 4.4). These changes could be influenced by a number of factors, including:

1) A change in the oceanographic setting could influence the positioning of the faunal provinces.
2) An increase/decrease in bottom activity could lead to winnowing and redeposition. Winnowing could conceivably increase the concentration of *G. bulloides* and other large and hence rapidly-settling species. In the case of the species found off South West Africa, this would enhance the warm-water aspect of the sediment.
3) Any increase in bottom dissolution of the foraminiferal assemblage would lead to

the preferential dissolution of the more fragile species over the thicker-walled ones. In the case of the major species, *G. bulloides* tends to be a finer-walled individual than *G. pachyderma*. Consequently the assemblage would take on a colder-water aspect.
4) Any change in the intensity of upwelling could effect both the quantity of nutrients entering the euphotic zone and the temperature of the water reaching the Core 3 location. As the type and distribution of phytoplankton and other food sources depends on the distribution of the upwelled nutrients, if the intensity of upwelled water is varied, so the species distribution of grazing foraminifera will change (Berger and Soutar 1971) Upwelling in turn is controlled by the winds in the area. Any change in intensity of upwelling, therefore, can probably be linked to a change in the prevailing winds.

(1) and (4) are interlinked. Upwelling off South West Africa dominates the oceanographic environment in the nearshore zone. Further offshore, the distribution and diversity of foraminiferal species will be influenced more by the presence of the wanner waters of the Benguela and Angola currents (Shannon et al, in press, Herbert 1984). Any change in the intensity of upwelling would presumably result in a changing interaction of the various water masses.

5.4.3 Temperature and wind stress versus species abundance

On the assumption that the species distribution in the vicinity of Core 3 varies in accordance with a changing intensity of upwelling (which in turn will affect sea surface temperature), a relationship between species abundance and temperature should exist. Also, changing upwelling intensity must be due to a changing prevailing wind strength. Ultimately therefore, a relationship between the distribution of foraminiferal species and wind speed should also exist.

The relationship between species abundance and sea surface temperature was estimated in the following way:

Using the *G. bulloides* and left-coiling *G. pachydama* abundances from the earlier grab samples, the SADCO summer sea surface tem-
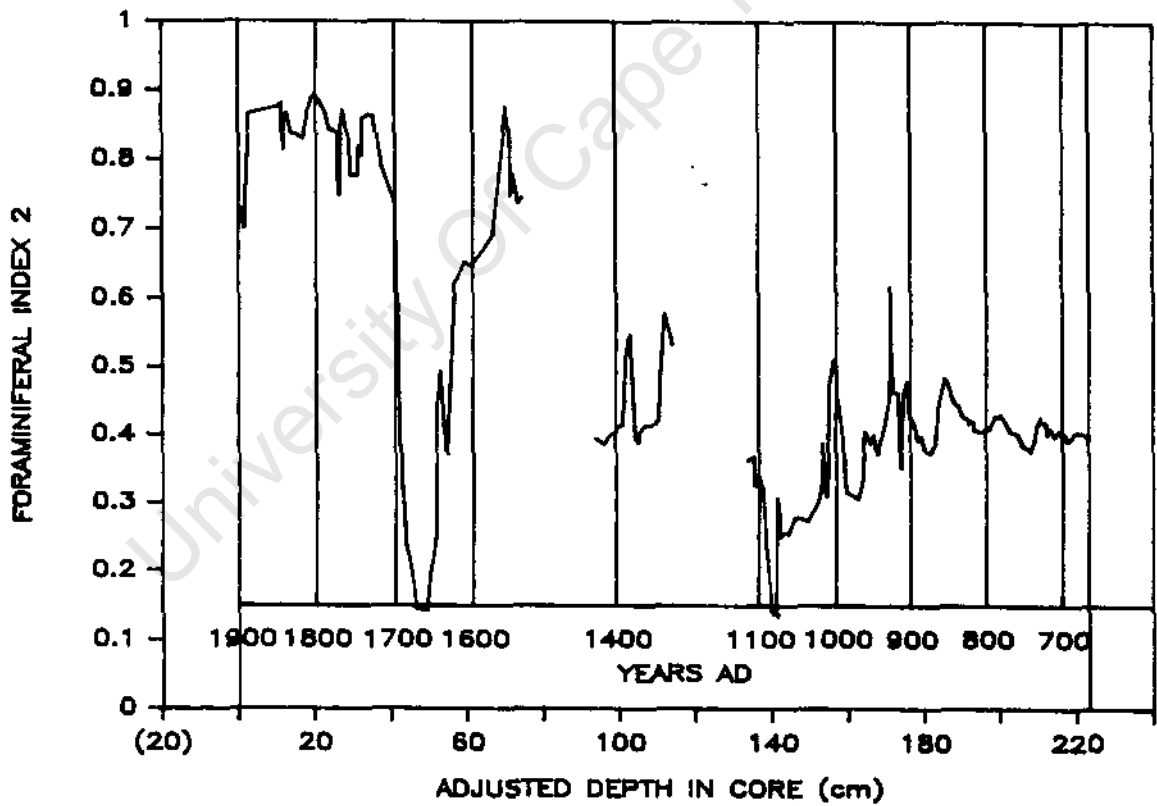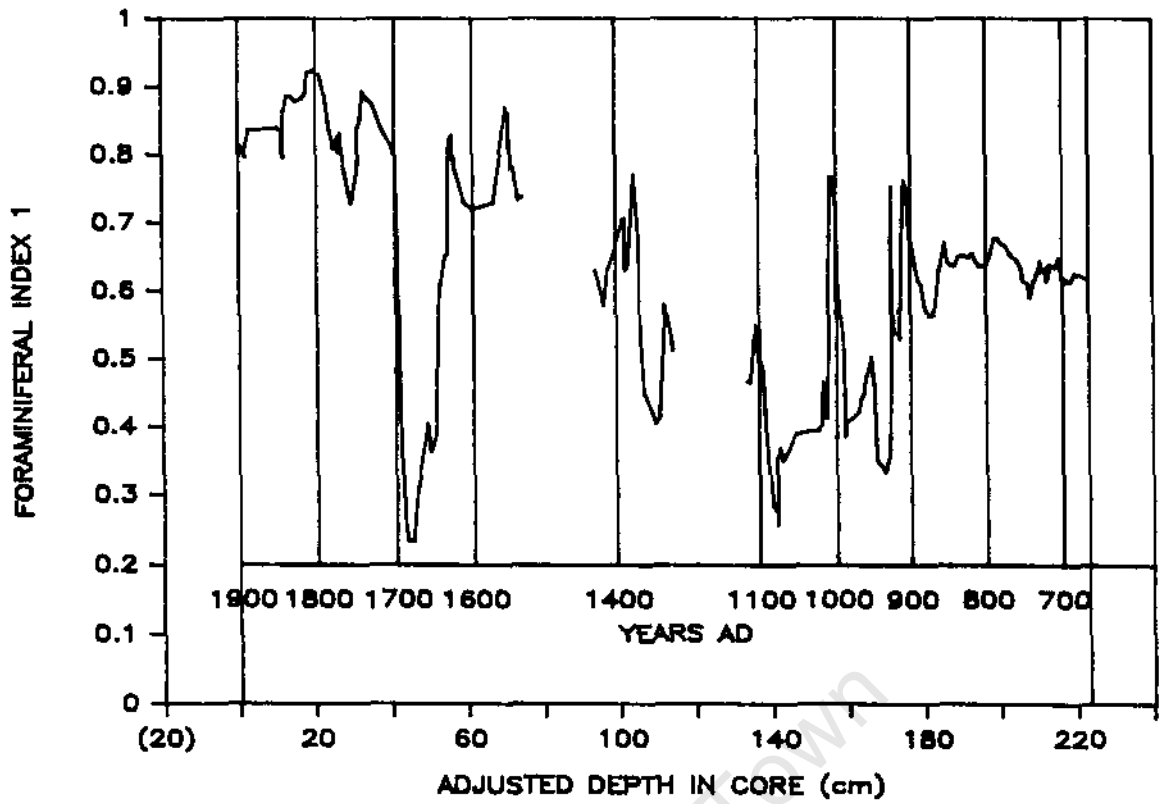
Fig 5.1. Foraminiferal index versus adjusted depth and time
in Core 3. In the upper graph the foraminiferal index
represents the ratio of *G. bulloides/(G.bulloides+left*
a *pachyderma),* while in the lower graph it represents *G.
ballades/ (G. builoides+right-coiling G. pachyderma).*

perature plot (Herbert 1984) and the sea surface temperature plot from Shannon (1985), a scatter diagram with an associated regression line was plotted (fig 5.2). Although the correlation coefficient for this line is fairly good, it hinges on one cold-water sample (Grab 3567: 24.7 S, 14.5 E). This point lies near the Luderitz upwelling plume. If it is removed from the scatter plot, the correlation coefficient and slope would change. Any lack of correlation could be due to:

a) the scarcity of sample points and their uneven distribution

b) the non-linear relationship that *G. bulloides* has with temperature (Herbert 1984).

c) the lack of relationship between temperature and the foraminiferal temperature index.

The regression line can be expressed as:

$$T^\circ C = 9.05^\circ \text{ (foraminiferal index)} + 8.64$$

Using this equation, a temperature curve for Core 3 can be constructed (fig 5.2). As the only difference between this curve and the foraminiferal curve is in the value of the two constants, the curves have the same shape and differ only with respect to the y-axis.

Although this curve does not necessarily represent real conditions, it suggests that during the little Ice Age the sea surface temperature in the vicinity of Core 3 dropped to 10-11 C, the present-day temperature of Luderitz upwelling. Also, sea surface temperature in recent years appears to have been the warmest within the period of the study.

The relationship of temperature to wind stress was estimated in the following manner:

Summer wind stress values were extracted for every degree latitude along the South West African coastline, from Luderitz to the Cunene River mouth, using a plot from Shannon (1985). Wind stress is represented by a scale from 1-12. At each latitude, using the same sea surface temperature sources that were used in the previous model, summer sea surface temperature values (in the line of upwelled water at successive positions approximately 05 degrees longitude offshore, equal to the offshore distance of Core 3) were determined (fig 53).

Once again the wind curve differs from the foraminiferal curve only in the raids scale and the fact that the curve is inverted.

Some of the wind speed changes it postulates (eg: 40-55cm) are unlikely. One possible explanation for this error in scale could be in the regression between sea surface temperature and species distribution (fig 5.2). If the single sample point that controls the slope of the regression was removed, or if other sample points could be added, the slope might alter significantly. This in turn would change the scale on both the temperature and wind stress curves. Even though the scale of the wind stress curve is possibly incorrect, it at least indicates significant changes.

5.4.4 Comparison with existing climate records

A number of referenced curves have been included in this section. This enables comparison between the foraminiferal index curve of this thesis and what is already known about climate change over the last 1000 years (see section 2.2 and fig 5.4). Five curves have been used. They are:

Curve B: a foraminiferal index curve from core Y71-10-117P that was taken from diatomaceous mud in the Santa Barbara Basin, California. Varve counts yielded a sedimentation rate of 0.8mm per year (Kipp and Towner 1975).

Curve C: a foraminiferal index curve, from core V12-99 that was taken from laminated sediment in the Cariaco trench off northern Venezuela. A ^{14}C date yielded an average sedimentation rate of 40cm per 1000 years (Kipp and Towner 1975).

Curve D: a mean annual temperature curve for central England as 50-year averages back to 900 AD (Lamb 1965).

Curve E: a ^{14}C curve from fossil radiocarbon in tree rings (Eddy 1977).

Curve F: a curve of the deuterium/hydrogen ratio in a bristlecone pine from White mountains, California, plotted as 40-year averages of 10-year intervals. The trees rings were used for age dating (Epstein and Yapp 1976).

The curves presented in fig 5.4 have all been plotted according to the various dates that have been assigned to them. Of the 5 referenced curves, D, E and F are the most reliably dated. No attempt has been made to shift

0.92 CORRELATION COEFICIENT

8.64 INTERCEPT

9.05 SLOPE OF REGRESSION LINE

SUMMER SST. DEGREES C.

19
18
17
16
15
14
13

0.5   0.6   0.7   0.8   0.9   1

FORAMINIFERAL INDEX 1

SST. DEGREES C.

18
17
16
15
14
13
12
11
10
9
8
7
6

1900 1800 1700 1600   1400   1100 1000 900 800 700

YEARS AD

(20)   20   60   100   140   180   220

ADJUSTED DEPTH IN CORE (cm)
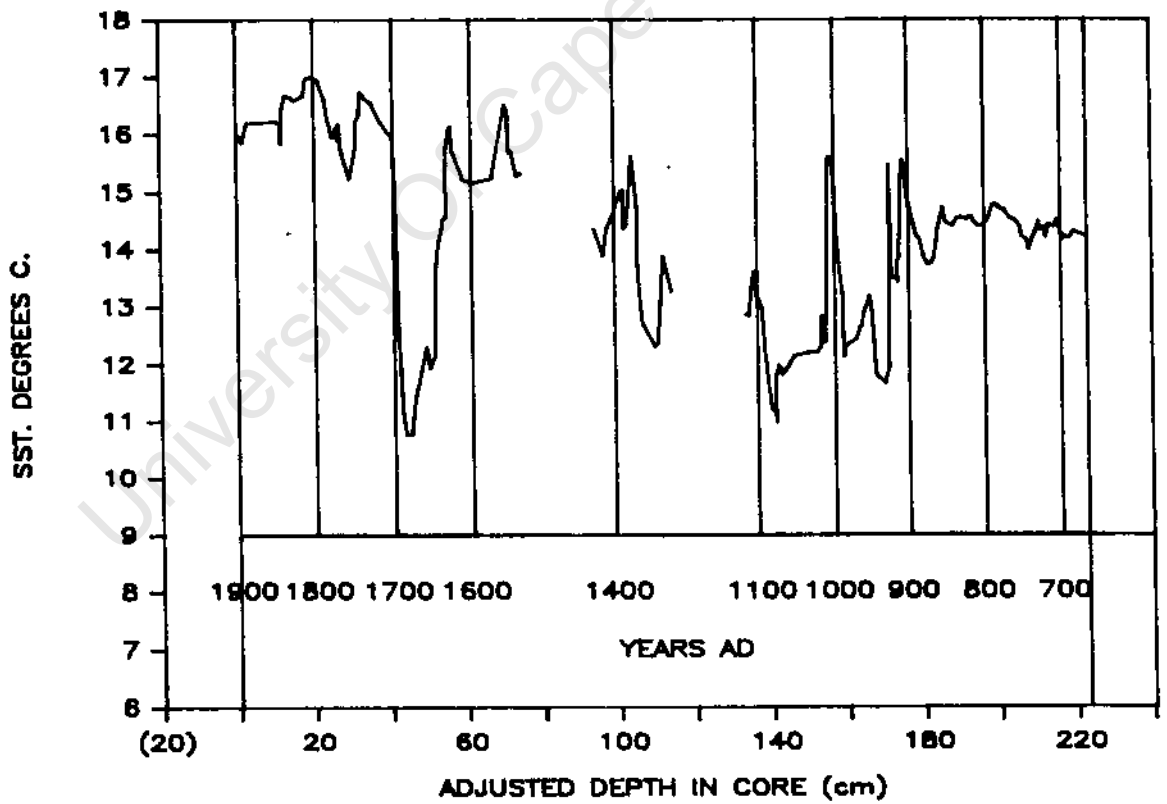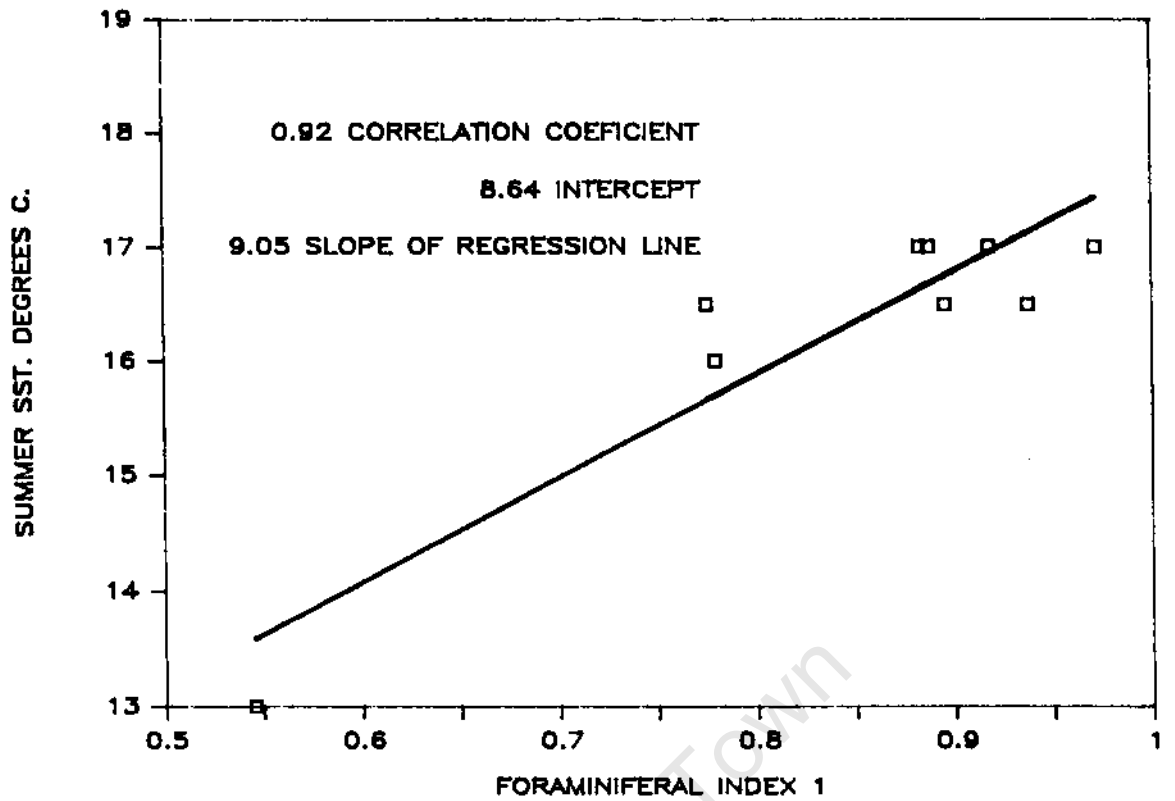
Fig 5.2. The relationship between species distribution and sea surface temperature. The upper graph shows the line of regression. The lower graph converts the regression into sea surface temperature vs depth-in-core.
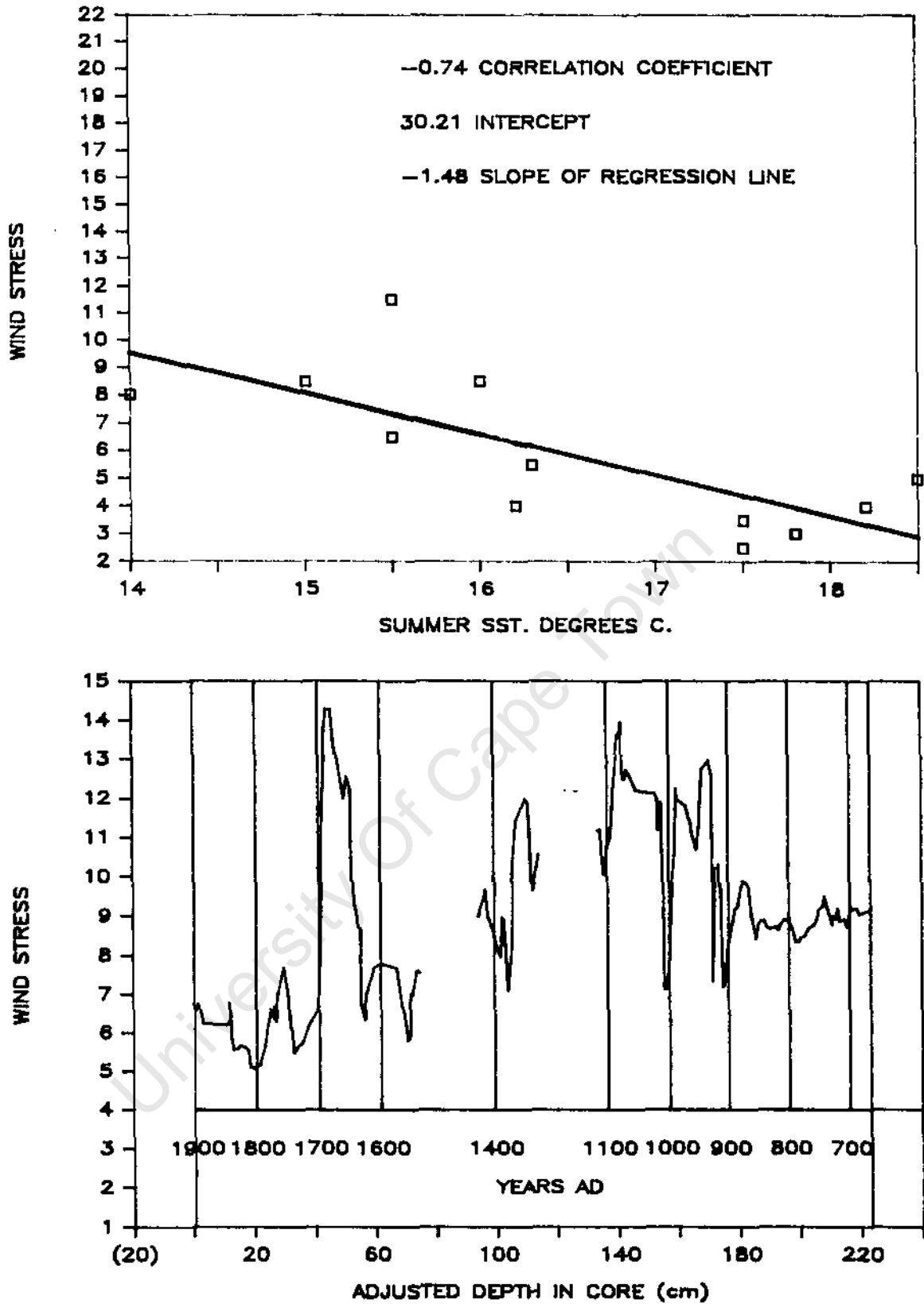
Fig 5.3. The relationship of sea surface temperature to wind stress. Wind stress is measured on a scale of 1-12 (Shannon 1985). The upper graph shows the line of regression. The lower graph converts the regression into wind stress vs depth-in-core.

Fig 5.4. A comparison of the foraminiferal index 1 curve to 5 referenced curves over the same time period. The curves are:

A) Foraminiferal index curve reproduced from fig 5.1.

B) Foraminiferal index curve from Core Y71-1O-117P, Santa Barbara basin (Kipp and Towner 1975).

C) Foraminiferal index curve from Core V12-99, off northern Venezuela (Kipp and Towner 1975).

D) 50-year averages of the mean annual temperature prevailing in central England (Lamb 1965).

E) Deviation of relative atmospheric MC concentration for tree ring analysis (Eddy 1977).

F) 40-year means of dueterium/hydrogen from Bristlecone pines, California (Epstein and Yapp 1976)

any of the curves so that some of the more prominent peaks line up. Consequently, correlation between the referenced curves, and curve A is generally not very good. However, it must be remembered that the foraminiferal index curve of this thesis, (A), has not been dated anywhere down its length. Therefore, no section of the curve can be adjusted due to a possibly changing sedimentation rate (see below). The curve could quite conceivably represent a much longer time span than labelled on its x-axis. This could then explain its lack of correlation with some of the other curves, especially at lower levels.

On the basis of what correlation there is, however, the following can be said for the foraminiferal index curve:

period 1: (100-250 yrs. BP)

This period is characterized by a high concentration of *G. bulloides,* and a low concentration of left-coiling *G. pachyderma.* Correlation with the foraminiferal curve B from Kipp and Towner (1975) is fairly good. This period represents a warming trend in central England and increased ^{14}C values for curve E. The period is referred to as the modem maximum (Eddy 1977), and is generally regarded as the warming phase that succeeded the Little Ice Age.

Period 2: The Little Ice Age (250-450 yrs. BP)

At this point the foraminiferal index drops sharply for a period of at least 50 years. This is due to a sharp and persistent increase in the concentration of left-coiling *G.*

the curve of core Y71-10-117P. In this case however, it is due to the presence of the cold-water species *G. quinquiloba.*

The presence of the Little Ice Age (see section 22.1), a time of cold climate especially in the northern hemisphere, reflects itself in the temperature curve for central England and also in the ^{14}C values of curve E. The trough of the foraminiferal curve of this thesis is very narrow. This could be explained in 4 ways:

a) the cold period does not represent the Little Ice Age,
b) the Little Ice Age off Walvis Bay was brief and deep,

c) during the Little Ice Age, winnowing effects contracted this section of the core, and
d) the sedimentation rate changed.

In the case of (c), if winnowing was more extensive, it would reflect itself in a changing foraminiferal concentration. This is not the case (see fig 4.13). The sedimentation rate (d), however, could have changed in the following way:

The fallout of mud to the sea floor essentially represents the flux of diatoms, as they are the major constituent. The foraminiferal concentration, therefore, is essentially the ratio of foraminifera to diatoms. Diatoms profit from upwelling, which provides nutrients to the euphotic zone. Logically, if the intensity of upwelling increases, so too must the quantity of diatoms and feeding foraminifers. However, there must come a point where, with further increase in upwelling intensity, the water reaching the Core 3 locality is still too unstable for diatom growth. In this way, the flux of diatoms starts to decrease, resulting in an equivalent decrease in the number of foraminifera. So although the concentration of foraminifera does not change, the sedimentation rate does. It slows down with the result that the foraminiferal curve becomes compressed with respect to depth-in-core. At the same time the foraminiferal signal takes on a cold water aspect.

It has already been suggested that variation in sedimentation rate (or diatom flux) in Santa Barbara Basin sediments is linked to climatic fluctuations (Soutar and Crill 1977).

Another point that has not been mentioned is the significant drop in mud density in the uppermost levels (above Core 3), resulting in a changing accumulation rate downcore. If the accumulation at the surface is assumed to be 1.4cm/year for example (DeMaster 1981), and decreases proportionately to 1mm/year by the time core box 2 (in which the cold event occurs) is reached, the position of the cold event hardly changes at all from its present position as seen in fig 5.1.

Period 3: (450-700 yrs. BP)

In Core 3, this period has been disrupted by the first break. Although we cannot see any short-period changes in this interval, it does seem to represent the start of a general decline in the foraminiferal index. Ironically, the more detailed of the two curves from Kipp and Towner, representing Core Y71-10-117P, has a missing section in the same place. It is tempting to compare this lack of data to the more complete curve from Core V12-99, where a cooling trend is quite apparent. On the other hand, it is possible that the peak in the foraminiferal index just before the start of the Little Ice Age period could represent a much earlier period, possibly corresponding to the pronounced peak in the temperatures prevailing in central England (period 4).

Period 4. (700-900 yrs. BP)

Once again this section of curve A is missing. However, I am sceptical that this section corresponds with period 4 at all. It seems more realistic and probable (if a slower sedimentation rate is used, see section 5.4.1), that the peaks occurring in curves D, E and F correspond to the pronounced peak in the foraminiferal index prior to the Little Ice Age Event. If this is correct, it would also result in better correlation with the other curves during period 5. This period is referred to as the Medieval maximum, a warm period similar to the modem maximum (see section 2.2.2).

Period 5: (900-1300 yrs. BP)

In both curves D and E (and to a lesser degree in curve C, although its position is based on a questionable date), this period reflects itself as a general decline in temperature, ^{14}C values and the foraminiferal index. It appears to be spread over a fairly broad interval and would correspond well with what is presently marked as period 3 and 4 for the foraminiferal index curve of this thesis. As curve A is plotted at the moment, there is no correlation.

One of the most interesting sections of curve A is the section presently within period 5. In this section the curve shows no change. Every foraminiferal species curve also showed minimal change (figs 4.3 - 4.10). In the core slab, this section corresponds exactly to the start of the the laminated interval. This gives

support to the theory that laminated sections represent relatively quiet climatic periods and hence stable environments.

5.4.5 Minor species

The distribution of the minor species with depth appears in figs 4.6 - 4.10. The curves of *G. inflate, G. truncatulinoides* and *H. pelagica* are 3-point running averages whereas that of *G. tuber* is not. The reason for this is that the peaks of *G. tuber* are extremely well-defined and would be flattened and widened if subjected to a running average.

Due to the high counting fraction, many of the peaks in these curves seem statistically significant. Moreover, comparison of the curves show corresponding peaks. Most of the peaks are sudden and pronounced, especially in the case of *G. ruber. G. inflate, an* intermediate water species, exhibits a curve that correlates, in places, with the major species curves. Even though the abundance of *G. inflate* remains low for the whole length of Core 3 (less than 4.5%), it still shows a low abundance during the Little Ice Age that suggests intrusion of colder water into the area

In the case of the sudden and short-lived abundances of warm water species *G. tuber, G. truncatulinoides* and *H. pelagica*, one possible explanation for them could be *El Nino*-type events. The best species to show this is *G. tuber*.

5.4.5.1. *G. Rather* concentration downcore: its relation to *El-Nino*

G. ruber is a subtropical species that is apparently normally absent in this region of upwelling (Herbert 1984). However, there are three marked periods downcore where the concentration of highly pigmented *G. tuber (fig* 5.5) suddenly shoots up relative to background values (fig 4.10). The peaks seem to occur at 1730, 1100 and 950 AD, according to my estimates of dates.

El-Nino-type events involve significant warm-water incursions that can have devastating effects to the resident marine ecosystem (see section 2.4.2). It is therefore tempting to speculate that these sudden abundances of the warm-water *G. tuber* species over short (2cm) intervals could be reflecting major *El-Nino*

26

Fig 5.5. Photomicrograph of the range of pigmentation of *G. tuber.* The height of the 5 is 1mm.
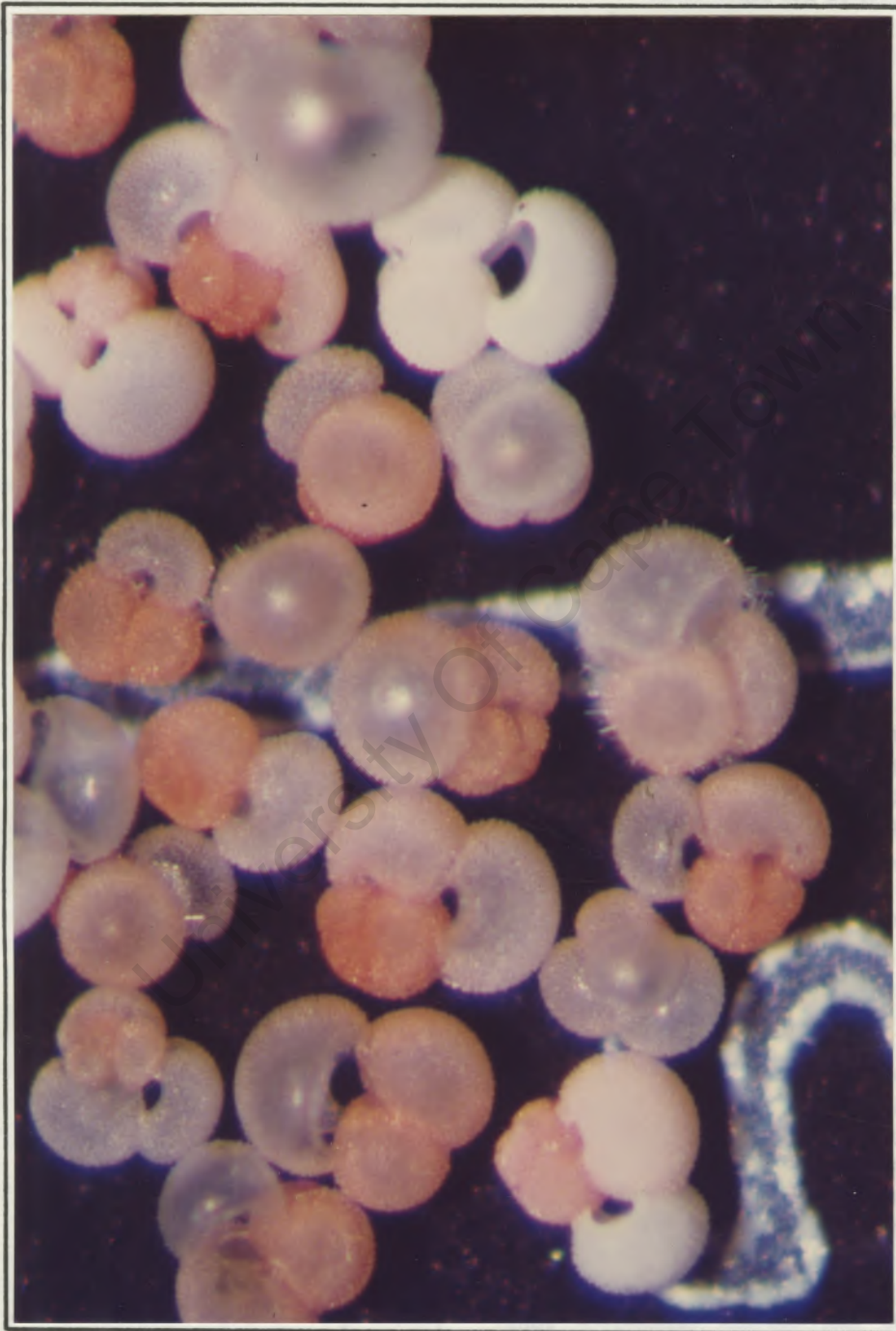
events. Ideally, if this record could be compared to a known onshore temperature and rainfall records for the similar period, correlations could be made. So far, no work has been done in this field that far back, largely to the scarcity of such detailed records. The earliest documented records only seem to go back into the last century (Nicholson 1981, Tyson 1980). I did however, consult with an historian, Dr. N. Worden, who knows of detailed diaries that include daily temperature and rainfall readings at the Cape Town castle for many decades after the 1652 settlement. Although going through them is too big an undertaking for the purposes of this thesis, this might prove a worthwhile avenue for future research.

5.5 Caveats

1) There are no absolute dates.

2) AU the curves *are* based on only a 2cm-thick vertical slab of one core. Although this slice can be regarded as being representative of Core 3, forminiferal species in other areas of the mud belt are not the same (Herbert 19-84).

3) Compaction of the mud has not been taken into account, although it probably plays a fairly small role due to shallow penetration of Core 3. Compaction in this depth interval is a function of the volume of pore water and sediment, where the degree of compaction

$$C = (V_w + V_s)\mathbf{fi}_{\text{na}}l/(V_w + Vs)\text{initial}$$

where:
  V_w = volume of water
  V_s = volume of sediment

As actual crushing of mud only occurs at depths greater than 300m, compaction at this depth is only a function of how much water is lost. As the consistency of the mud did not seem to change much in the samples that I analysed (ie: excluding the uppermost section of the core that was not collected), this may indicate that little compaction has taken place.

4) By stretching and contracting sections of the core, data was either squashed up, and hence "lost", or data was stretched creatingh

lines where no new data exists. The graph, therefore, becomes distorted in places.

5) For two lost boxes a certain amount of erosion or redeposition had to be assumed. A figure that was used represented an average from the other 10 boxes. This obviously creates a degree of unwanted uncertainty lower down in the core.

SUMMARY AND CONCLUSIONS

The research contained in this thesis came from two cores and 12 grab samples that were collected from diatomaceous mud on the inner continental shelf off the coast of South West Africa. A chemical solution ensured that all foraminifera were removed from the mud to prevent any biassing of the results.

A count of about 1000 was used to improve the statistical confidence limits of the minor foraminifers! species. The species found in the size range of 212-710 microns were: left and right-coiling *G. pachyderma, G. bulloides, 0. universe, G. inflate, G. tuber, H. pelagica* and *G. truncatulinoides.* The presence of the fragile species *H. pelagica indicated that* the chemical solution was not very corrosive. The species that proved most interesting were left-and right-coiling a *pachyderm's, G. but-'aides* and *G. ruber.*

Before the results could be compared to other climatic records, both the x and y-axes of the curves had to be defined. A foraminiferal index was assigned to the y-axis. This index compares just two species. Ratioing the abundances of two species was done as a substitute to foraminiferal flux, as the sedimentation rate per interval was not known. Depth-in-core was slightly adjusted (due to effects of winnowing and redeposition) and assigned to the x-axis. The time scale used was based on an average sedimentation rate of 2mm per year.

The resultant curve was divided into 5 stages, from 1900 to 700 AD. The Little Ice Age, the Medieval warm epoch and the recent warm period seem to have been recorded. The comparitively narrow signal in response to the Little Ice Age could be explained in 4 ways:

a) the cold period does not represent the Little Ice Age,
b) the Little *Ice* Age off Walvis Bay was brief and deep,
c) during the Little Ice Age, winnowing effects contracted this section of the core, and
d) the sedimentation rate changed.

Definitely the biggest problem is the lack of any dates. If the sedimentation rate is changed to 1mm/year, the positioning of the "Little Ice Age" event would no longer match up to the other records. However, if it is assumed that the sedimentation rate in the uppermost levels above Core 3 (not sampled) is effectively much higher (due to the soupy, uncompacted nature of the mud), and decreases proportionately until the start of the core, then even if a sedimentation rate is 1mm/year is reached, the position of the Little Ice age event will remain in its present position. This, added to the fact that the period can quite conceivably represent a much broader time span, substantiates the possibility that it does represent a broader Little Ice Age, as documented for northern hemisphere regions.

Within the laminated interval at the bottom of the core, there was no change in the foraminiferal signal. This implies a quiet, undisturbed period of sedimentation.

Most notable within the curves of the 4 minor species are sudden peaks at apparently random intervals dovmcore. The best species to show this is *G. rubes,* whose curve shows 3 distinct and very sudden increases. It is thought that they could represent major *El-Nino* type events which altered the resident ecosystem.

Using this data and its apparent relationship to sea surface temperature, a simple regression between present-day species distribution and temperature enabled the curve of Core 3 to be converted into a plot of summer sea surface temperature.

A palaeo-wind stress curve was also constructed, where the relationship between sea surface temperature and wind stress was made possible by regressing both sets of values from Shannon (1986).

In both instances the sea surface temperature and wind speed estimated by these curves seem extreme. However, both curves are based on regressions with few sample points. More complete scatter plots are needed before more

accurate wind and sea surface temperature curves can be generated.

In any case the curves that have been generated provide, for the first time, comparison to similar research carried out in sediment basins along the eastern Pacific margin. However, these curves should be viewed critically until:
a) the foraminiferal signal of more cores in different regions of the mud belt are produced, and
b) reliable absolute dates are made.

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34

APPENDIX

This appendix contains the following data from Core 3:

- Sample number
- Measured depth-in-core (see section 33.2)
  Adjusted depth-in-core (see section 5.4.1)
- Wet weight of mud samples
- Total foraminiferal count per sample
- Calculated total number of foraminifera per sample
- Individual counts of all species

SAMPLE NUMBER	DEPTH-IN CORE(cm)	ADJUSTED DEPTH(cm)	MUD WET WEIGHT(g)	TOTAL COUNT	TOTAL PER INTERVAL	LEFT. G.PACHY.	G.BULL.	RIGHT. G.PACHY.
TBa	0.5	0.6	50.64	1294	2588	164	751	284
TBb	1.9	1.7	65.97	1130	2260	167	591	274
TBc	3.0	2.0	77.57	1056	1056	175	500	271
TBd	4.3	3.1	74.94	1331	2662	156	873	215
TBe	5.8	10.6	111.14	1503	24048	209	1080	134
TBf	7.5	11.8	68.50	969	1938	129	674	102
TBg	8.5	12.0	57.02	492	492	133	217	104
TBh	9.0	12.1	63.58	524	524	75	297	66
TBi	10.0	12.4	57.82	885	885	74	633	91
TBj	11.0	13.1	61.11	1014	1352	89	707	108
TBk	12.1	14.4	80.45	1143	3048	104	780	124
TBl	13.5	15.4	83.68	978	1956	78	604	158
TBm	14.3	17.0	35.15	1434	2868	131	894	177
TBn	15.5	17.9	65.14	1132	2264	72	699	131
TBo	16.8	18.6	77.61	1069	2138	79	766	104
TBp	17.5	19.5	51.43	1123	2995	59	826	113
321a	18.5	20.4	30.71	1108	1477	76	828	93
321b	19.5	21.7	57.13	1211	3229	79	952	104
321c	20.6	23.4	63.53	1027	4108	67	649	115
321d	21.5	24.4	66.08	1194	3184	184	659	133
321e	22.5	25.4	69.58	1019	2717	153	591	110
321f	23.0	26.2	47.16	1048	2795	121	620	111
321g	24.2	26.4	61.97	452	452	56	228	89
321h	25.2	26.9	50.89	751	751	90	322	263
321i	25.7	27.2	24.60	550	550	87	372	45
321j	26.3	27.9	45.12	1103	1471	131	814	53
321k	27.3	29.2	68.91	1087	2174	270	495	155
321l	27.9	29.8	29.62	766	766	148	290	122
321m	28.9	31.4	78.76	953	3812	72	391	78
321n	29.5	31.8	37.21	783	783	72	335	109
321o	30.7	32.5	55.57	1155	1155	120	694	120
321p	31.4	33.0	61.60	1052	1403	84	659	94
321q	32.5	34.1	73.08	949	2531	47	623	67
321r	34.1	35.7	67.24	1033	2066	123	598	90
321s	35.3	37.8	73.67	1032	4128	86	504	107
322a	37.4	41.3	52.63	1208	3221	120	593	230
322b	38.6	41.9	48.44	1034	1034	253	343	274
322c	40.1	42.6	35.83	656	656	218	127	259
322d	40.9	43.2	37.37	1078	1078	393	228	368
322e	41.4	43.6	24.86	728	728	277	105	299
322f	41.8	44.2	29.20	923	1846	428	125	330
322g	42.8	45.7	38.22	970	1940	358	103	454
322h	44.3	46.9	47.47	704	1408	115	53	476
322i	45.7	49.7	50.87	1282	3419	192	141	843
322j	46.1	50.0	37.00	906	906	157	125	537

SAMPLE NUMBER	DEPTH-IN CORE(cm)	ADJUSTED DEPTH(cm)	MUD WET WEIGHT(g)	TOTAL COUNT	TOTAL PER INTERVAL	LEFT. G.PACHY.	G.BULL.	RIGHT. G.PACHY.
322k	46.8	50.6	40.25	1305	1305	339	155	714
3221	49.2	52.0	56.83	954	954	277	157	455
322m	50.3	52.4	33.11	300	300	51	96	109
322n	51.6	53.3	41.08	762	762	165	291	197
322o	52.3	54.3	39.08	1142	1523	253	354	428
322p	52.9	55.1	62.52	1276	2552	117	348	731
322q	53.9	55.4	22.81	289	289	36	74	156
323.	54.6	56.0	51.10	1061	2122	79	468	454
323b	55.5	56.5	45.80	1054	1405	96	444	457
323c	56.6	57.0	39.64	1033	1033	140	573	236
323d	58.4	59.6	65.28	1237	4948	198	618	334
3231	59.2	61.8	42.18	1483	5932	303	702	388
323f	63.7	67.1		1391	2781	241	751	272
323g	68.1	70.7	28.13	1298	1298	179	799	156
323a	68.5	71.1	24.10	1118	1491	82	790	85
323j	69.4	71.5	44.01	1023	1023	132	556	207
323j	70.1	71.8	21.97	532	532	90	307	81
323k	71.0	72.3	35.01	1092	1092	176	556	208
3231	72.0	73.7	36.88	1326	2652	204	785	205
323.	72.7	74.6	37.47	1155	2310	280	503	248
3258	93.0	94.0	61.89	1207	3279	125	200	321
325b	94.6	96.3	63.09	1125	4500	140	195	284
325c	95.3	97.3	36.73	1225	2450	193	240	412
325d	96.2	99.3	40.76	995	3980	110	268	390
3258	97.9	101.1	35.84	1344	1792	137	352	431
325f	99.1	101.6	68.01	1006	1341	135	230	374
325a	100.1	101.9	48.71	612	612	73	227	192
325j	100.7	102.5	29.17	903	1204	215	323	258
325j	101.6	103.0	37.28	751	751	124	243	236
325k	102.6	103.8	42.45	1261	1261	124	486	380
3251	103.0	104.1	29.12	1176	1176	116	349	478
325m	103.4	104.7	24.49	827	1654	62	206	298
325n	103.8	105.4	18.69	1220	1220	126	253	456
325o	104.1	105.5	21.19	606	606	142	167	244
325p	105.2	106.7	55.42	1297	2594	394	322	363
325q	107.2	109.7	46.99	1138	3035	302	200	337
325r	108.2	110.7	37.56	806	1612	259	146	205
3258	109.0	111.2	49.87	1156	1156	285	345	277
325t	110.2	112.1	35.75	1146	1146	265	321	256
325u	111.0	114.2	38.88	1400	1400	262	449	282
3128	131.5	133.6	86.08	1057	4228	239	143	270
312b	131.9	134.4	50.89	1275	2550	156	193	241
312c	132.6	135.3	33.12	967	967	167	167	378
312d	134.0	135.8	59.94	615	615	113	109	228
3128	135.1	136.7	69.46	1090	1453	**86**	**186**	330

SAMPLE NUMBER	DEPTH-IN CORE (cm)	ADJUSTED DEPTH (cm)	MUD WET WEIGHT (g)	TOTAL COUNT	TOTAL PER INTERVAL	LEFT. G.PACHY.	G.BULL.	RIGHT. G.PACHY.
312f	135.7	137.9	67.57	1108	2955	241	188	371
312g	137.5	138.8	62.77	653	653	128	67	304
312a	138.5	140.3	59.03	887	1774	178	73	440
3121	139.5	141.4	42.59	969	969	200	66	507
3121	139.9	141.4	25.45	100	100	28	11	42
312k	140.4	141.5	27.21	94	94	26	10	44
3121	141.4	142.2	68.25	966	1932	294	171	333
312m	142.3	142.5	57.97	1018	1018	227	146	498
312n	143.0	143.0	49.99	929	1858	225	121	467
312o	143.8	144.5	57.57	1080	5760	301	158	395
312p	145.0	146.1	58.26	1144	4576	216	152	461
312q	147.0	149.5	63.68	1200	6400	240	176	414
312r	148.7	152.3	87.80	1087	8696	239	129	353
313.	150.5	153.2	62.87	950	1900	235	183	253
313b	151.0	153.6	38.35	1197	1596	220	218	312
313c	151.5	154.0	40.33	992	1984	196	166	305
313d	152.0	154.5	48.02	1067	2134	334	148	477
313e	153.5	155.0	51.12	866	866	151	218	339
313f	154.0	155.5	44.45	945	1890	70	268	359
313g	154.7	156.3	43.62	1226	2452	107	438	354
313a	155.3	157.0	25.67	1151	1535	172	457	410
3131	156.0	157.7	61.44	1033	4132	140	260	344
313j	157.5	159.1	64.20	904	3616	266	195	355
313k	158.5	159.4	38.71	808	808	266	158	291
3131	159.0	159.8	44.74	1123	2246	359	192	433
313m	160.0	162.6	50.11	955	7640	231	178	390
313n	160.6	163.5	35.20	1021	2723	215	176	434
313o	161.1	164.0	42.25	1063	2126	268	221	287
313p	162.0	164.7	44.49	857	1714	236	182	343
313q	165.0	166.1	66.02	1351	1351	289	411	486
313r	166.5	166.9	78.82	895	1193	164	210	326
313e	167.4	167.9	41.62	1147	1147	390	187	353
314.	168.5	169.9	77.44	838	3352	339	152	249
314b	170.0	171.2	72.44	1334	1334	548	353	198
314c	170.9	171.4	76.51	358	358	23	143	95
314d	171.9	171.5	60.04	143	143	27	41	36
314e	173.3	172.1	67.41	440	440	47	127	134
314f	173.5	173.2	21.09	1114	1485	255	276	326
314g	174.3	173.5	79.44	341	341	65	95	96
314h	174.5	173.7	28.59	249	249	51	68	94
3141	175.9	174.0	77.97	193	193	34	41	75
314j	176.9	174.2	50.22	135	135	17	27	66
314k	178.2	174.5	71.65	144	144	19	45	60
3141	179.2	174.9	52.29	232	232	26	77	83
314m	180.4	175.5	75.55	474	474	43	167	189

SAMPLE NUMBER	DEPTH-IN CORE(cm)	ADJUSTED DEPTN(cm)	MUD WET WEIGHT(g)	TOTAL COUNT	TOTAL PER INTERVAL	LEFT. G. PACHY	G.BULL.	RIGHT. G.PACHY .
314n	181.7	76.5	65.37	767	767	98	264	279
314o	182.9	77.7	67.46	991	1321	166	247	417
314p	183.9	78.6	70.41	1200	1600	200	340	485
314q	184.9	79.4	53.69	1231	1231	206	329	512
314r	186.2	80.5	68.40	946	1892	173	247	383
315.	187.2	81.4	59.67	1078	2156	216	251	449
315b	188.0	82.3	68.35	1232	3285	228	297	497
315c	189.0	83.2	70.34	1083	2888	190	275	401
315d	190.0	84.2		1035	2722	175	290	364
315.	191.2	85.5	67.64	986	3944	159	305	327
315f	192.1	86.3	57.33	1161	3096	171	374	392
315g	193.2	87.2	43.85	1146	2292	232	326	385
315h	194.0	88.1	48.86	1234	3291	197	353	446
315j	195.0	89.2	60.90	1180	4720	169	346	428
315j	196.1	90.2	59.45	942	3768	155	269	343
315k	197.5	91.9	60.26	1291	5164	188	351	513
3151	197.7	92.0	31.68	1088	2176	155	298	406
315m	198.7	93.0	40.64	1062	2832	161	295	400
315n	199.3	93.5	44.56	1098	2928	148	291	408
315o	200.3	94.8	66.65	1209	6448	167	288	450
315p	201.7	96.5	51.38	1170	4680	186	301	431
315q	202.7	97.5	42.25	1158	3088	157	320	430
315r	204.0	98.7	81.18	1032	5504	127	265	409
315s	205.2	99.6	70.55	1026	4104	138	300	337
31St	205.9	00.3	52.70	895	3580	122	253	340
ma	207.2	01.7	31.42	1155	2310	187	272	447
Cab	208.2	02.9	69.92	1001	4004	138	291	376
CBc	209.7	04.7	83.86	1128	4512	181	272	394
CBd	210.7	05.7	53.67	1043	2781	172	249	433
ale	211.3	06.2	59.72	863	3452	126	228	321
CBf1	212.7	07.6	42.60	1186	2372	194	294	460
CBf2	213.1	08.0	61.98	975	3900	164	255	376
CBE	214.2	09.1	52.03	1010	2693	158	256	387
CBh	214.9	09.8	60.50	1030	2747	152	276	396
CBI	216.0	10.7	96.59	1300	5200	166	358	502
Uri	216.1	10.8	38.15	1223	2446	211	300	502
CBk	217.3	12.1	57.97	1215	3240	187	358	441
COI	217.7	12.5	62.28	907	3628	150	225	357
aim	218.3	13.2	29.10	869	1738	133	244	336
con	219.7	14.5	90.41	854	4555	137	240	287
CBo1	220.9	15.5	43.82	1279	2558	188	350	501
CBo2	221.9	16.4	51.07	1388	2776	244	351	564
CBp	222.2	16.8	33.94	957	1914	159	238	389
CBq	222.4	17.0	63.62	990	3960	171	240	414
CBr	223.3	17.9	65.15	903	3612	136	245	375
CBe	224.2	18.7	66.63	1092	4368	169	281	438

39

Cat	225.2	219.6	79.57	1186	6325	172	300	469
CBu	226.2	220.6	77.25	1124	5995	155	315	430
CBv	228.2	223.2	77.94	1071	5712	143	268	397

SAMPLE NUMBER	G.INFL.	O.UNIV.	H.PEL.	FRAG.	G.RUBER	G.TRUNC.	OTHER
TBa	24	52	14	3	1	0	1
TBb	13	66	17	2	0	0	0
TBc	39	62	3	6	0	0	0
TBd	36	49	0	1	0	1	0
TBe	33	45	1	1	0	0	0
TBf	17	33	9	4	0	1	0
TBg	6	24	8	0	0	0	0
TBh	6	72	0	8	0	0	0
TBi	9	70	0	8	0	0	0
TBj	9	94	3	5	0	0	1
TBk	9	118	5	2	0	0	1
TBl	6	122	3	7	0	0	0
TBm	26	187	1	18	0	0	0
TBn	22	195	0	11	1	1	0
TBo	15	101	1	3	0	0	0
TBp	13	106	4	1	0	1	0
321a	16	92	2	1	0	0	0
321b	26	48	2	0	0	0	0
321c	20	169	4	3	0	0	0
321d	19	189	7	3	0	0	0
321e	27	123	2	9	4	0	0
321f	48	125	1	22	0	0	0
321g	10	59	1	8	1	0	0
321h	28	44	4	0	0	0	0
321i	9	35	1	1	0	0	0
321j	11	85	6	3	0	0	0
321k	43	113	2	6	0	0	3
321l	38	156	0	12	0	0	0
321m	19	376	1	16	0	0	0
321n	3	236	0	27	0	1	0
321o	6	200	4	10	0	1	0
321p	10	196	2	9	1	1	0
321q	13	191	0	7	1	0	0
321r	37	137	10	6	32	0	0
321s	56	169	15	1	94	0	0
322a	11	229	18	6	1	0	0
322b	10	130	14	8	0	0	2
322c	4	36	9	2	0	0	1
322d	7	59	21	2	0	0	0
322e	6	26	15	0	0	0	0

41

SAMPLE NUMBER	G.INFL.	O.UNIV.	H.PEL.	FRAG.	G.RUBER	G.TRUNC.	OTHER
322f	12	21	3	4	0	0	0
322g	5	34	16	0	0	0	0
322h	5	52	2	1	0	0	0
322i	3	99	3	1	0	0	0
322j	4	79	4	0	0	0	0
322k	4	88	1	3	1	0	0
322l	1	59	0	4	1	0	0
322m	2	39	1	2	0	0	0
322n	7	88	11	3	0	0	0
322o	1	95	10	1	0	0	0
322p	8	56	12	4	0	0	0
322q	5	15	3	0	0	0	0
323a	9	37	8	6	0	0	1
323b	3	47	1	5	0	1	2
323c	12	61	2	6	0		
323d	9	68	1	6	0	0	3
323e	13	70	1	5	0	1	0
323f	10	94	16	6	0	1	2
323g	6	118	30	7	0	0	3
323h	1	115	42	3	0	0	0
323i	7	89	26	3	0	0	3
323j	2	38	13	1	0	0	0
323k	13	68	64	4	0	0	3
323l	4	106	20	2	0	1	0
323m	1	114	7	1	0		0
325a	8	534	16	2	0	0	1
325b	10	478	14	0	0	0	4
325c	17	331	26	5	0	1	1
325d	22	195	5	2	1	1	1
325e	24	339	51	2	0	4	4
325f	23	192	38	11	0	0	3
325h	12	78	24	3	0	0	3
325i	9	85	9	2	0	1	1
325j	11	83	46	5	0	1	2
325k	30	165	61	2	2	2	9
325l	5	207	12	8	0	0	1
325m	1	251	3	4	0	1	1
325n	8	361	4	12	0	0	0
325o	4	38	6	3	0	1	1
325p	14	189	9	6	0	0	0
325q	11	264	20	4	0	0	0
325r	7	176	9	4	0	0	0
325s	14	206	21	5	0	3	1
325t	11	256	26	5	0	5	0
325u	18	370	16	3	0	0	0

42

SAMPLE NUMBER	G.INFL.	O.UNIV.	H.PEL.	FRAG.	G.RUBER	G.TRUNC.	OTHER
312a	21	372	3	8	0	0	1
312b	31	634	10	8	0	1	1
312c	9	231	8	7	0	0	0
312d	6	148	1	10	0	0	0
312e	10	446	10	14	8	0	0
312f	15	245	5	1	41	1	0
312g	1	136	13	4	0	0	0
312h	8	175	4	9	0	0	0
312i	12	170	1	8	0	1	4
312j	2	16	0	1	0	0	0
312k	0	12	2	0	0	0	0
312l	13	137	8	6	0	3	1
312m	5	104	25	9	1	1	2
312n	11	76	7	10	0	2	10
312o	6	207	2	4	0	3	4
312p	16	275	15	4	1	1	3
312q	12	343	6	7	1	0	1
312r	12	343	4	2	4	0	1
313a	24	226	20	6	0	1	2
313b	45	331	63	7	0	1	0
313c	64	235	21	1	0	0	4
313d	6	92	6	2	0	0	2
313e	18	112	22	1	0	2	3
313f	15	212	16	1	1	0	3
313g	25	236	54	5	1	2	4
313h	31	68	10	2	0	1	0
313i	31	226	21	7	1	3	0
313j	16	68	1	1	0	2	0
313k	8	71	10	2	0	1	1
313l	17	97	18	1	2	3	1
313m	15	125	4	8	1	1	2
313n	28	148	14	2	1	3	0
313o	33	233	9	4	0	7	1
313p	12	76	6	0	1	1	0
313q	8	128	17	0	2	8	2
313r	9	143	21	8	10	1	3
313s	6	176	17	2	9	3	4
314a	1	48	4	3	38	3	1
314b	15	84	24	0	109	0	3
314c	0	55	38	3	1	0	0
314d	0	16	22	0	1	0	0
314e	3	104	22	1	0	0	2
314f	5	235	6	8	1	1	1
314g	3	48	27	3	0	0	4

SAMPLE NUMBER	G.INFL.	O.UNIV.	H.PEL.	FRAG.	G.RUBER	G.TRUNC.	OTHER
314h	1	21	12	2	0	0	0
314i	2	26	10	2	1	1	1
314j	1	12	10	1	0	0	1
314k	0	11	8	1	0	0	0
314l	0	14	29	3	0	0	0
314m	4	32	35	3	0	0	1
314n	4	85	21	8	1	0	7
314o	5	107	30	12	0	3	4
314p	5	121	36	11	1	1	0
314q	11	128	29	12	0	2	2
314r	9	110	17	2	1	0	4
315a	7	138	13	3	0	1	0
315b	4	186	9	5	1	3	2
315c	8	172	28	7	0	1	1
315d	7	171	21	5	0	1	2
315e	5	170	14	2	0	1	3
315f	5	195	14	7	2	1	0
315g	7	171	15	6	1	0	3
315h	11	207	11	5	0	0	4
315i	7	213	12	3	0	0	2
315j	9	155	6	3	2	0	0
315k	12	205	14	3	0	2	3
315l	10	197	13	8	0	0	1
315m	9	181	8	4	2	0	2
315n	5	228	10	7	0	1	0
315o	11	273	12	6	^a 0	1	1
315p	5	230	11	2	1	1	2
315q	13	206	21	6	0	4	1
315r	10	202	11	4	2	1	1
315s	12	214	18	4	0	2	1
315t	4	159	9	6	1	1	0
CBa	3	224	7	10	0	2	3
CBb	16	157	13	4	0	4	2
CBc	5	260	9	3	2	1	1
CBd	4	165	12	8	0	0	0
CBe	6	171	8	2	0	1	0
CBf1	9	215	8	6	0	0	0
CBf2	10	159	6	3	1	1	0
CBg	9	183	10	3	1	1	2
CBh	6	170	20	6	0	2	2
CBi	13	239	13	7	1	1	0
CBj	9	182	14	3	1	0	1
CBk	6	200	17	4	1	1	0
CBl	5	153	9	6	0	1	1

SAMPLE NUMBER	GAM.	O.UNIV.	H.PEL.	FRAG.	G.RUBER	G.TRUNC.	OTHER
CBm	8	123	11	B		3	
Can	5	171	10	1		3	
CBo1	9	214	11	2		1	
Cj1o2	14	189	14	3		6	
CO	13	145	8	3		0	
CBq	5	144	11	3		2	
CBr	12	128	6	0		0	
CB.	B	7B9	4	1		0	
CBE	12	216	8	7		1	
CBu	11	200	8	3		0	
CBv	9	227	20	5		1	