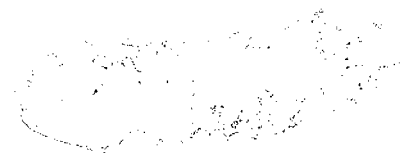




INFLUENCES ON THE HYDROLOGY  
OF THE CAPE COLUMBINE/ST. HELENA  
REGION

BY

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A THESIS SUBMITTED IN FULFILMENT OF THE REQUIREMENTS  
OF THE DEGREE OF MASTER OF SCIENCE.

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DECLARATION

No portion of this thesis has been previously submitted in support of an application for any other degree or qualification in this or any other University.

H.N. Waldron

1985.

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## CHAPTER 1

### INTRODUCTION

#### (i) Statement of Intent

The area encompassing Cape Columbine and St. Helena Bay off the South-West coast of Africa lies within one of the world's major upwelling centres - the Southern Benguela System. Cape Columbine is a major site for active upwelling within this system, others are located at the Cape Peninsula and in the north, at Hondeklip Bay. Nelson and Hutchings (1983) state that of these three sites, only the Cape Peninsula has been the subject of intensive study. Cape Columbine lies between Saldanha Bay and Lamberts Bay and is within a large pelagic and rock lobster (*Jasus lalandii*) fishery. Bailey and Chapman (1984) report that 29% of the total west coast pelagic fish catch, (109,684 tons) came from the area off Saldanha-St. Helena Bay in 1981 increasing to 33%, (125265 tons) in 1982. Rock lobster landings account for approximately 41% by weight of the West Coast catch (1523 tons). In view of its importance both commercially and oceanographically, a research project into the marine processes occurring in the Cape Columbine Area is important in our understanding of the Benguela System as a whole.

Because of the complex nature of marine systems and their interdependence on physical, chemical and biological processes and phenomena it was decided to adopt an interdisciplinary approach.

The overall objective of the thesis is to investigate and interpret hydrological events occurring at the Cape Columbine upwelling site and the adjacent coastal waters, with special reference to St. Helena Bay. The first step in the study involves monitoring the meteorological occurrences which resulted in the prevailing hydrology and thus give a general background to the observed structure. It became necessary to establish two sub-systems in the area which can be distinguished on the basis of the time scales within which they operate. Generally speaking, outside St. Helena Bay the waters have a 3-5 day synoptic variability governed by meteorological conditions, but within the semi-closed system of the Bay itself a longer time span of around 25 days governs the processes in this separate but inextricably linked water body.

Within the 3-5 day cycle there were found active and passive phases during which upwelling and physico-biological stabilization occurred respectively. The 25 day residence time permitted the full maturation of the ageing upwelled water and lended itself to studies of its origins and mode of formation.



A natural development in the work lead to the categorization of different water types occurring in the area which further involved exploring the pathways that exist between them. This is crucial to an understanding of the system as a whole and necessitates using both direct and indirect evidence in order to unravel its complexities.

Having established the parameters and possible inter-relationships existing within the overall system it became possible to study the semi-closed system of St. Helena Bay and identify mechanisms and processes occurring within the water and investigate their implications for the area in general. This incorporated monitoring patterns of horizontal water movement in the Bay, and demonstrating the methods by which nutrients can reach the photic zone in the absence of active upwelling. Concentrations of nutrients and chlorophyll<sub>a</sub> were used to support the evidence presented for vertical mixing.

The nutrient levels occurring in the Bay and within the area generally were also used to gain an understanding of an oxygen-depleted water mass which is shown to be closely associated with St. Helena Bay water. Matters relating to its remote or local origins are dealt with within the context of a credible time scale. The same data were used to identify nutrient limitation in the area.

(ii) Literature Review

Several works have been completed in recent years which deal with the Benguela System as a whole and provide essential reading. Nelson and Hutchings (1983), in their account of the Benguela upwelling area consider the general features, including bottom topography, circulation patterns and the influence of Agulhas water on the west coast system. The presence of low oxygen water is also noted together with the relationship between sea level adjustment and warm water events. Their chapter on the macroscale meteorology of the system gives an excellent description of the cyclic weather pattern typical of the summer conditions which governs the upwelling pulse. Also included is a review of work done on mesoscale coastal upwelling processes.

Shannon (1985) has written comprehensively on the Evolution of the Benguela and its physical features and processes and Chapman and Shannon (1985) considered the chemistry and related processes. These two works form part of a review of the present state of knowledge of the main processes governing the Benguela System.

The works mentioned above consider the Benguela System as a whole and give a comprehensive background to the Cape Columbine upwelling site and St. Helena Bay region in this general context. However, research specific to the study area has been carried out intermittently since the 1950's.

Clowes (1954) performed a study which included phosphate levels in the area and suggested that increased phosphate concentrations near St. Helena Bay resulted from the southward-flowing inshore current. This acted as a transport mechanism from Namibian waters.

Buys (1957) studied the temperature variations in the upper 50m of the water column in the St. Helena Bay area between September 1950 and August 1954. This investigational report gives an account of the method used to establish any periodic, and therefore predictable, cycles of temperature within the upper 50m. An unsuccessful attempt was made to correlate this temperature data with commercial fish catch figures. The same author made a 1959 study of the hydrographical environment and commercial catches between 1950 - 1957. His conclusions relevant to the present study were that "..... in the coastal area the waters have for the most part the same origin throughout the year, namely the upwelled waters which to a greater or lesser extent have been heated by the sun". He also noted that the Agulhas Current exerts a variable influence during summer and autumn

in the study area.

Duncan (1964) investigated the seasonal occurrence of thermoclines off the south-west Cape between 1955 - 1961 in the same study area as Buys. He noted their seasonal variations, frequency of occurrence at certain positions, their depth distribution and the temperatures at which they occur. It was demonstrated that, especially in the coastal region, solar radiation was responsible for the formation of thermoclines in cold upwelled water.

Currents and patterns of water movement were the subject of a drift card and drift bottle study made by Duncan and Nell (1969). They sought to establish a seasonal variation in the movement of surface water off the west and south-west coasts of South Africa. An inshore southward current and offshore northward current was found on the west coast during summer together with a westward drift from Cape Agulhas after rounding Cape Point. Winter showed either a general southward movement on the west coast or the typical summer pattern.

Several cases of mass mortality of marine organisms during the summer months of 1967-68 on the west coast of South Africa, lead to the DeDecker (1970) study of an oxygen-depleted subsurface current in the region. He describes such a current circulating within 20 miles of the coast and

includes its seasonal and long-term fluctuations over a period of 10 years. The current is traced back to the sub-surface oxygen minimum in the South-East tropical Atlantic and he identifies it as an offshoot of the Deep Compensation Current postulated by Hart and Currie (1960). An oxygen-depleted water body is described in the present study and an attempt is made to discover its origins and mode of formation.

A two part study was made of the southern Benguela region by Jones (1971) and Bang (1971) resulting from their cruise on H.M.S. Hecla in 1966. Bang (1971) essentially complements the detail of Jones (1971), who studied temperature, salinity, dissolved oxygen and nutrients between Cape Town and Orange River. This included an E-W transect extending from St. Helena Bay to 15°E. He noted that the upwelling cycle in the area was at a quiescent stage but, importantly, introduced the concept of ageing of upwelled water. It was maintained that the lower salinity water at the surface indicated past upwelling, and that since stability resulted from atmospheric heating one could expect low salinity surface waters for a considerable period. This would only occur in the absence of wind generated turbulence. The nutrients information was also of relevance because it gave information relating to the degree of biological activity. Depletion at the surface coupled with regeneration near the bottom indicated a quiescent stage in the upwelling cycle.

Chapman (1983), in his study of iodine speciation noted the close association between the low oxygen water around St. Helena Bay and a mixed water body with constant value of  $\sigma_t = 26.8$ . This research is of extreme relevance to the present study since Chapman concludes that the oxygen poor water is produced locally rather than brought from a distance, which disagrees with DeDecker (1970). He also makes a first order estimate of the time necessary to reduce the normal oxygen content of the water to zero. This dovetails the study made into residence times for water in St. Helena Bay, which forms part of this thesis.

Currents and patterns of water movement have been the subject of study by Holden (1983, 1984). The former study shows the existence of a perennial net southward flow at depths below 80m over the 180m isobath west of Cape Columbine. This is for periods greater than 10 days and displays a maximum value in winter. Holden (1984) found currents in the coastal area north of St. Helena Bay to be sluggish and the existence of a cyclonic cell was also suggested.

The work of Bailey and Chapman (1984), which concerns the nutrient status of the St. Helena Bay Region, investigates the chemistry of the oxygen-deficient water mass mentioned earlier. Comparisons are made between concentrations of nutrient overlying the sediment and those within the

upwelling source water. Mechanisms for the formation of oxygen-deficient water are discussed in the context of a local cyclonic gyre and deviations from the Redfield ratio. They found nitrate to be the limiting nutrient.

In view of the importance of the Cape Columbine upwelling site and the St. Helena Bay region to the Benguela System as a whole it must be considered to be relatively understudied. This thesis gives a physico-biological perspective to events occurring in the area and investigates methods of nutrient renewal to surface waters in the absence of active upwelling. This involves, for the first time, a quantitative approach into aspects of vertical mixing.

### (iii) Research Plan

The first two chapters of this thesis provide a general background to the work conducted in the area and comprise of firstly, an introductory chapter and secondly a chapter giving the research rationale and essential features in the data. The research rationale gives details of the study area and the location of hydrographic stations. Also included are details relating to the deployment of equipment, sampling methods and analysis. The next section provides an overview of the data and selects typical and essential features which merit further scrutiny. Aspects of wind, temperature,

salinity, currents, oxygen and nutrients and Chlorophyll<sub>a</sub> were selected.

These data were then subjected to interpretation in Chapter three. The thermohaline structure of the water column is described together with its mode of development and formation. Patterns of water movement in the study area are described and related to the presence of certain other physical parameters.

The relationship between Chlorophyll<sub>a</sub> and nutrients is investigated and certain anomalous data points are discussed in relation to nutrient influx to the euphotic zone. The occurrence of a primary nitrite maximum also gives an indication of processes occurring in the water column.

A study into the occurrence and origins of an oxygen depleted layer is carried out. This feature has been described previously in the literature and a statistical study of the nutrient ratios occurring in the area generally and within the layer itself was performed.

Turbulent and diffusive mechanisms of vertical mixing were investigated quantitatively and also included was a study of the possible evolution of salt fingering layers.



In order to give a credible time scale for the occurrence of certain oceanographic processes, the wind data were used to calculate the residence time for a particle of water in St. Helena Bay.

The final chapter discusses various points resulting from the study and deals with the inter-relationships that were found to have occurred between the different sets of data.

## CHAPTER 2

### THE RESEARCH RATIONALE AND ESSENTIAL FEATURES OF THE DATA

#### (i) The Study Area

Fig 1 shows the area studied during a cruise of the R.S. Africana on the 24 and 25 March 1984. St. Helena Bay, which lies at the southern end of Africa on the west coast (Latitude  $32^{\circ}40'S$ ), provides a passive environment within the Benguela upwelling system and is adjacent to the Cape Columbine active upwelling site (Latitude  $32^{\circ}50'S$ ). As mentioned earlier this is one of three major upwelling locations on the west coast of Southern Africa, their respective locations are shown in Fig 2.

On the first day 12 stations were occupied in St. Helena Bay along a line approximating to the 60m depth contour. Sampling began at station 1A at 1400 hrs and ended at station 3D at 0100 hours on day 2. The line running west from Cape Columbine consisted of five stations approximately 5 nautical miles apart, and forms the Cape Columbine transect. Stations were occupied between 1430 hrs and 1730 hrs on day 2.

(ii) Equipment and Methodology

Temperature and salinity data were collected using the CTD (Conductivity, Temperature, Depth) apparatus. It was thus possible to obtain continuous profiles of these parameters. The CTD incorporated a rosette of 12,5 litre Niskin bottles and water samples were taken at stations 1A, 1D, 2A, 3A and 3D in St. Helena Bay and at all stations on the Cape Columbine transect. Sampling depths were at ten metre intervals from the surface to 50m. In addition to this at the deeper stations on the Cape Columbine Transect, samples were taken at various depths below 50m to a maximum of 297m over the Cape Canyon (Station CC2).

Current data were collected using an array of 4 Neil Brown Acoustic current meters. At each current metering station the CTD apparatus was used to reveal the 2 layer structure in the water column and the array of current meters was then deployed so as to straddle the density interface between these layers (i.e. the pycnocline). Current metering was only done in St. Helena Bay.

Wind data in the ten days preceding the sampling programme were obtained from the Sea Fisheries Research Institute weather station at Stompneus (see Fig 1) and prevailing meteorological data were available from the ship's in-house information system.

In St. Helena Bay the ship was permitted to drift freely while the current meters were deployed. During this period CTD casts were done every hour (e.g. Stations 1A, 1B, 1C, 1D) and water samples were taken at the beginning and end of the current meter deployment (i.e. 1A and 1D). The ship then steamed to the location of station 2A where the process was repeated. The method of data collection is summarised below.

<u>Station No.</u>	<u>Current Metering</u>	<u>CTD casts</u>	<u>Water samples</u>	<u>Met. Data</u>
1A	Continuous	Y	Y	Y
1B	Continuous	Y		Y
1C	Continuous	Y		Y
1D	Continuous	Y	Y	Y
2A	Continuous	Y	Y	Y
2B	Continuous	Y		Y
2C	Continuous	Y		Y
2D	Continuous	Y	Y	Y
3A	Continuous	Y	Y	Y
3B	Continuous	Y		Y
3C	Continuous	Y		Y
3D	Continuous	Y	Y	Y

On the Cape Columbine transect CTD casts and water samples were taken at every station, current meters were not deployed.

(iii) Analysis of Samples

At water sampling stations oxygen was analysed on board by Winkler titration, using the azide method of Montgomery et al (1964) to prevent nitrite interference. Shore analysis was performed on all other samples. Phosphate levels were obtained according to the method of Murphy and Riley (1962) and silicate, nitrate and nitrite according to Strickland and Parsons (1972). Analysis of samples was modified for use with the Technicon Auto Analyzer II as described by Mostert (1983). Chlorophyll a samples were measured according to UNESCO (1966).

(iv) Wind Regime

The wind conditions for the ten days preceding this study are presented in Fig 3. The data was available from the weather station at Stompneus and represents the general wind pattern over the St. Helena Bay/Cape Columbine area.

The outstanding feature is the strong south-easterly wind event lasting from the afternoon of 1 March 1984 until the evening of 22 March 1984. The average wind speed during this period was  $8.5 \text{ ms}^{-1}$  (17 knots) with maximum speeds observed during the late afternoon and evening ( $10 - 15 \text{ ms}^{-1}$ , 20 - 30 knots). For the next 2 days prior to the collection of

hydrological data, light and variable winds were recorded averaging 3 to 4  $\text{ms}^{-1}$  (6 to 8 knots).

Therefore during the period before this study there were 3.5 days with wind conditions favourable to Ekman transport of surface waters and strong upwelling followed by 1.5 days of light winds, permitting the water column to "relax" and equilibrate.

Wind data were taken at each station during the course of hydrological sampling. The average wind speed on day 1 in St. Helena Bay was  $4.25\text{ms}^{-1}$  (8.5 knots) with a range of  $3\text{ms}^{-1}$  to  $6\text{ms}^{-1}$  (6 knots to 12 knots). On day 2, during the sampling of the offshore transect at Cape Columbine, there was an average wind speed of  $8.7\text{ms}^{-1}$  (17 knots) with a range of  $7\text{ms}^{-1}$  (14 knots to 20 knots). In St. Helena Bay the wind was coming from the east (i.e. offshore) while on the following day a SSE wind prevailed during the whole sampling period.

(v) Temperature and Salinity

(a) St. Helena Bay

The essential features of the temperature and salinity structure in St. Helena Bay are shown in Fig 4a. Profiles

have been drawn for stations 1B, 2D and 3C. The most striking characteristic in each of the 3 profiles is the presence of an homogeneous water body underlying the thermocline with temperature and salinity constant at just below 10°C and 34.75‰ respectively. This forms a Bottom Mixed Layer (BML) and is discussed in Chapter 3(i). A warmer surface layer is found overlying the thermocline which shows a gradual increase in temperature with sea surface temperature (SST) values of 14.4°C at Station 1B and 13.3°C at Station 3C. Initially this drop in SST was attributed to normal heat loss during the night since Station 1B was sampled at 1500 hrs on day 1 and Station 3C at 0100 hrs on day 2. However, a heat balance calculation performed for one particular station (Station 1B), showed that an overnight heat loss of between 400 Wm<sup>-2</sup> and 1000 Wm<sup>-2</sup> would be necessary to account for such a temperature decrease in the upper waters. This figure is much too high when compared to normal levels of heat loss (say 100 Wm<sup>-2</sup>) and therefore the lower surface temperature observed at Station 3C is attributed to the advection into the area of water having upwelled more recently than its Station 1B counterpart. It would thus not have had the chance to warm up to the same extent.

The salinity structure within the thermocline shows some small variability but is otherwise about the value of 34.75‰. This variability in the thermocline region is

important in the analysis of diffusive mixing processes and the problem is addressed in detail in Chapter 3 (vi) (b).

(b) Cape Columbine transect.

The Cape Columbine transect gives a contrasting picture with respect to temperature and salinity, and profiles from Stations CC1, CC3 and CC5 are included in Fig 4B. Station CC1 has the same characteristics as the St. Helena Bay stations with a BML below 35m underlying the sunwarmed surface layer (SWSL) and separated by a strong thermocline. The sea surface temperature (SST) was approximately 14°C. Again, salinity shows little variation within the thermocline and reaches a maximum of 34.82‰ in the surface layer. An essentially constant value of 34.75‰ found within the BML.

The contrast between the thermohaline structure of St. Helena Bay and the Cape Columbine transect and the similarity between the water structure of St. Helena Bay and Station CC1 are shown in Fig. 4C.

From Fig. 4B it can be seen that between Stations CC3 and CC5 the SST rises from 15.0°C to 16.6°C but there is no BML evident at either location. Station CC3 has a layer of low salinity water at the surface extending to 30 m depth with



values approximately 34.80‰. Below this layer is found water of higher salinity 34.97‰ which gradually decreases to a bottom minimum of 34.58‰. Station CC5 exhibits a wind-mixed surface layer (16.6°C, 34.98‰) and a strong thermocline below which, temperature and salinity both decrease with depth to bottom values of 9°C, 34.68‰ respectively.

(vi) Currents

Current measurements were made for a period of one day only, during sampling in St. Helena Bay. Current meters were deployed while the ship was free drifting at Stations 1, 2 and 3 respectively. Fig. 5A shows the current vectors at the various depths for each of these three stations. Each station shown in Fig 5A represents the average of approximately 3 hrs of current measurements. Adjustment has been made to the data to account for ship's drift and included in Fig. 5A are the wind vectors for each of the three stations.

The near surface currents are seen to move in the opposite direction to that of the wind, it is therefore evident that the waters of St. Helena Bay were not reacting in direct response to the wind. The upper 16m of the water column has current speeds ranging from 18cms<sup>-1</sup> at Station 1 to 55cms<sup>-1</sup>

at Station 3. The BML shows a southward and shoreward movement at Stations 1 and 2 respectively with current speeds ranging from  $26\text{cms}^{-1}$  at Station 1 to  $50\text{cms}^{-1}$  at Station 2. The BML at Station 3 is seen to move offshore at approximately  $10\text{cms}^{-1}$ .

Fig. 5B shows the progressive vectors for Stations 1, 2 and 3, in the surface and bottom layers. Both layers seem to exhibit a general anticyclonic rotation in the St. Helena Bay area.

(vii) Dissolved Oxygen

(a) St. Helena Bay

The levels of dissolved oxygen found in St. Helena Bay are shown in a vertical section of St. Helena Bay stations in Fig. 6A. Typical surface values of  $8\text{ ml l}^{-1}$  were found. A sharp oxycline is present below which the levels drop to  $2\text{ ml l}^{-1}$ . Minimum values were generally found at the base of the water column ( $0.43\text{ ml l}^{-1}$  at Station 2D) with the exception of Station 3D where the oxygen minimum ( $0.59\text{ ml l}^{-1}$ ) was found at a depth of 40m. Oxygen depleted (O.D.) water is a widely reported feature within the Benguela System (Copenhagen, 1953; DeDecker, 1970; Bailey, 1979;

Boyd, 1981; Chapman 1983) and is defined as having oxygen content  $\leq 2 \text{ ml l}^{-1}$  (Chapman, 1983). The O.D. water is seen to be clearly associated with the BML lying below the  $10^{\circ}\text{C}$  isotherm which is marked as a dotted line in Fig. 6A.

(b) Cape Columbine transect.

Dissolved oxygen profiles from the Cape Columbine transect are shown in Fig. 6B. Again Station CC1 has the same form as the St. Helena Bay stations, the O.D. water lies below the  $10^{\circ}\text{C}$  isotherm and comprises the BML. A surface maximum value of  $7.2 \text{ ml l}^{-1}$  is observed. The remaining stations, which lie further offshore, show no evidence of an O.D. layer. A more uniform distribution can be seen with levels of around  $6 \text{ ml l}^{-1}$  at the surface decreasing to  $4 \text{ ml l}^{-1}$  at the base of the water column.

Oxygen saturation values in the water column were plotted at each station (Fig. 7). A pattern emerges which clearly distinguishes St. Helena Bay plus Station CC1 from the offshore stations of the Cape Columbine transect. At the nearshore stations (St. Helena Bay and Station CC1) saturation values of up to 145% are seen in the surface waters decreasing rapidly to values less than 10% saturation. The offshore stations have saturated surface values of around 110% but there is not the same sharp

reduction in the sub-surface water.

(viii) Nutrients and Chlorophyll<sub>a</sub>

(a) St. Helena Bay

Profiles showing the typical distribution of nitrate, silicate, phosphate and Chlorophyll<sub>a</sub> against depth have been prepared for one of the St. Helena Bay nutrient sampling stations (Fig. 8). The profiles show the surface waters to be nutrient depleted but with high levels of chlorophyll<sub>a</sub>. A contrasting enrichment of nutrients occurs in the bottom waters. As expected, the amount of Chlorophyll<sub>a</sub> in the bottom waters was low. The relationship between Chlorophyll<sub>a</sub> and nitrate, silicate and phosphate are dealt with quantitatively in Chapter 3 (iii). Vertical sections have been drawn showing the horizontal distribution of nitrate, silicate and PO<sub>4</sub>. (Fig. 9). They show an intrusive body of nutrient-rich water within the BML (NO<sub>3</sub> > 20 µg at l<sup>-1</sup>, SiO<sub>3</sub> > 30 µg at l<sup>-1</sup>, PO<sub>4</sub> > 2.2 µg at l<sup>-1</sup>). In all cases the water body is in close contact and possibly transcends the interface between the BML and the warmer surface water. This feature is of great importance with respect to the replenishment of nutrients to the euphotic zone. In the event of vertical mixing occurring at the interfacial boundary then high levels of nutrients are in a position to

be transported upward. The data is analysed for vertical mixing processes in Chapter 3 (vi).

(b) Cape Columbine transect

Nutrient and Chlorophyll<sub>a</sub> profiles have been drawn for 3 of the stations on the Cape Columbine transect (Fig. 10). Once again the lowest values of nutrients were recorded in the surface waters with nutrient enrichment occurring at the base of the water column. Chlorophyll<sub>a</sub> was only measured to a depth of 50m but at Station CC1 gave a similar picture to that obtained in St. Helena Bay with highest values at the surface and a decrease with depth. Chlorophyll<sub>a</sub> values were lowest at the outermost Station, CC5. Nitrate and Silicate sections from the Cape Columbine transect are shown in Fig. 11. These show a pool of nutrient-enriched water lying on the shelf inshore of the Cape Canyon. At Station CC1, this water is again in close proximity to the boundary between the BML and the surface water which lies at approximately 30m depth.

The nitrite profiles for both St. Helena Bay and Cape Columbine (Figs. 12a and 12b respectively) clearly display a sub-surface primary nitrite maximum.

In St. Helena Bay maximum values of approximately 0.3  $\mu\text{g l}^{-1}$  were observed at a depth of between 10m and 20m. The

Cape Columbine transect showed maximum values of approximately  $0.5 \mu\text{g at l}^{-1}$  at depths of between 20m and 40m. The exception to this was station CC1 which had a characteristic St. Helena Bay maximum value.

## CHAPTER 3

### INTERPRETATION OF DATA

#### (i) Thermohaline structure of the water column

Shannon (1985) refers to the Cape Columbine upwelling area as being controlled to a large extent by the bathymetry and by the influence of the orography on the wind field. The 300m isobath is approximately 30 km west of Cape Columbine resulting in deep water being available in close proximity to the coast. The main shelf break is modified by a major submarine valley, the Cape Canyon which has a North-South orientation.

Clowes (1950), Stander (1964) and Shannon (1966) state that South Atlantic Central Water upwells to the surface and to subsurface depths along the coast between Cape Frio ( 18°S) and Cape Point ( 34°S) and would therefore constitute the upwelled water found in the Cape Columbine area ( 32°40'). Sverdrup, Johnson and Fleming (1942) and Orren (1963) contend that this Central Water is formed in the sub-tropical convergence region by the sinking and northward spreading of mixed sub-tropical and sub-Antarctic water masses. Nelson (1984) further states that the upwelled water originates from a maximum depth of 200m. According to Clowes, 1950; Buys, 1957, 1959; and Duncan, 1964, a major

front exists in the Cape Columbine upwelling area in the upper 100m at an approximate longitude  $17^{\circ}30'$ . It is in the vicinity of the upper shelf break which lies 20 km - 30 km west of Cape Columbine.

The temperature section from the Cape Columbine transect is shown in Fig. 13A. The front is manifested as a weak surface feature only. Temperatures of  $>15^{\circ}\text{C}$  are observed west of Station CC3 and the lowest outcropping temperature value is the  $14^{\circ}\text{C}$  isotherm. The isotherms are uplifted towards the coastal boundary. The overall picture is typical of a senescent upwelling event, the isotherms having been permitted to 'relax' in the period of lighter winds following the strong south-easter mentioned earlier.

The temperature section has its limitations as a means of interpretation however, owing to the non-conservative properties of temperature, especially in surface waters. The more conservative property of salinity is considered in Fig. 13B where the section is shown from the Cape Columbine transect. It is already apparent from Fig. 4B that there is a less saline body of water lying in the upper 30m at Station CC3. Fig. 13B shows the overall extent of this low salinity water and more importantly, because of the conservative nature of salinity, it is possible to identify the offshore origins of the upwelled water. Fig. 13B shows a band of water, originating at Station CC5 between about



125m and 200m. This upwelling water has moved shoreward and upward forming a pool of water in the inshore region. This picture agrees with Nelson (1984) who states that upwelled water comes from a depth of less than 200m. Also evident from Fig 13B is a body of water lying below the band of upwelling water which seems to play little or no active part in the dynamic processes occurring. In the present study it was observed below the 34.70‰ isohaline.

The front between the upwelled water and offshore water is not a clearly distinct feature according to the temperature section in Fig. 13A. The picture is more clear in Fig. 13B, however, the limits of the front are still not clearly defined since the regions labelled as salinity inversions (which also appear as temperature inversions in Fig 13A) indicate the possibility of mixing through interleaving. In this case the front is likely to extend beyond Station CC5. The salinity and temperature microstructure of these regions is discussed later.

The origin of the homogeneous water mass ( $T = 9.8$ ,  $S = 34.75\text{‰}$ ,  $\sigma_t = 26.8$ ) observed in St. Helena Bay and at Station CC1 can also be seen from Fig. 13B. It is seen lying on the inner shelf inshore of the Cape Canyon and its source depth at CC5 of 180 - 190m is evidenced by tracing the band of water between the 34.76‰ and 34.74‰ isohalines in Fig. 13B and the 9.8°C isotherm in Fig. 13A.

The temperature section for St. Helena Bay is included in Figure 13C. This again shows the same homogeneous water type forming a bottom layer, below the sun-warmed surface layer. The 10°C isotherm is also uplifted from a depth of nearly 30m at Station 1A to approximately 14m at Station 3. This line of stations runs from SW to NE on a bearing towards Elands Bay.

Duncan (1964) and Chapman (1983), in their studies of the area show a similar thermohaline structure to that reported here. Buys (1959) states that in the coastal area the waters have for the most part the same origin throughout the year, namely upwelled water which to a greater or lesser extent has been heated by the sun. In addition, Chapman (1983) reports the uplifting of the 10°C isotherm as indicative of relict upwelled water and Boyd (1981) states that offshore movement of water near a coast can cause the lower layer to rise by continuity. The current data presented in Fig. 5 supports the "piling-up" of 10°C water against the coastal boundary.

The south-easterly, upwelling-favourable wind followed by a calm period lends support to this pattern of events. Duncan (1964), however, attributes the sloping 10°C isotherm to the Autumn onset of northerly winds, pushing warm surface waters over the cold water which has been moved up by the variable southerlies. The absence of any northerly winds in the data

would refute this idea.

The picture that emerges is that of a well-mixed wedge of relict upwelled water within St. Helena Bay, deepening shorewards and overlain by a stratified, sun-warmed surface layer. The presence of the same homogenous water mass in the inshore region of the Cape Columbine transect provides an interesting clue to the possible pathways existing in the system and is discussed in Chapter 4.

(ii) Water Movements

The current data collected in St. Helena Bay do not give a long time series of water movements in the area since the current meters were only deployed for a period of three hours at each of the three current metering stations. The results from this work do however give a 'snapshot' of events occurring in the area on a particular day and are a valuable aid to the interpretation of the local hydrography. Clowes (1954) and Holden (1984) state that the currents in the St. Helena Bay area are sluggish and Bang (1976) reports speeds of around  $10 \text{ cms}^{-1}$ . Fig. 5 shows the currents during the present study with a maximum current speed of  $55 \text{ cms}^{-1}$  in the sun-warmed surface layer at Station 3. The maximum current in the BML occurred at Station 2 with a value of  $50 \text{ cms}^{-1}$ . Current speeds of around  $10 \text{ cms}^{-1}$  were found in the

BML at Station 3. The currents reported here are therefore greater than those found in the earlier study and demonstrate the variability occurring within the area.

The direction of the surface current was opposite to that of the wind at Stations 1 and 2 indicating that the water movements have a strong inertial component. Duncan and Nell (1969) and Holden (1984) report the existence of a cyclonic cell in the Bay but, the results reported here indicate an anticyclonic rotation which suggests that the cyclonic cell is not a permanent feature.

In order to investigate the potential for vertical mixing as a result of current shear it was decided to treat the water column as a two-layer system with the  $10^{\circ}$  isotherm as interface between the SWSL and the BML. Stations 2 and 3 were found to have the greatest potential for mixing due to current shear. Station 2 showed a  $90^{\circ}$  difference in current orientation but no appreciable difference in speed ( $3 \text{ cms}^{-1}$ ) and at Station 3, a  $45 \text{ cms}^{-1}$  speed difference occurred between the adjacent layers but with no directional difference. At station 1, both layers were moving in the same direction and with an  $8 \text{ cms}^{-1}$  speed difference. This aspect of the study is discussed quantitatively in Chapter 4 (vi) where the data is treated for both turbulent and diffusive mixing mechanisms.

Evidence of water movement in the St. Helena Bay area is inferred indirectly from the nutrient data collected during the study. Fig. 9 shows the sections for nitrate, silicate and phosphate respectively. They indicate a 'core' of high nutrient water extending from the northern part of the study area at Station 3 as far south as station 2A. These sections, on the face of it, indicate that the water body is moving south. The currents presented in Fig. 5 agree with the southward movement of the BML at Station 3. According to station 2 however it would be expected for the head of the high nutrient core to swing around to the east and therefore shorewards resulting in its possible recirculation. This would explain the absence of the high nutrient water at Station 1 and agrees with the existence of an anticyclonic cell within the bay. An alternative explanation is possible which assumes a wholly local nutrient regeneration process. In this case the high nutrients lying to the northern end of the core are part of an older section of water which has moved from the south, where lower nutrient values are found. This problem is discussed later in Chapter 4.

(iii) Relationship between Chlorophyll and Nutrients

A regression and correlation analysis was performed to show the relationship between:

- (a) Chlorophyll vs Nitrate
- (b) Chlorophyll vs Silicate
- (c) Chlorophyll vs Phosphate

The stations in St. Helena Bay and Station CC1 on the Cape Columbine transect all yielded coherent results. However, Stations CC2, CC3, CC4 and CC5 were all in deeper water (down to 300m), and since chlorophyll<sub>a</sub> was only measured at discrete depths to 50m it was not possible to obtain the complete picture at these stations.

Fig. 14 shows the regression lines for chlorophyll<sub>a</sub> vs each of the three nutrients at all the St. Helena Bay nutrient sampling stations and a summary of the product moment correlation coefficients for the same stations plus station CC1 is given in Table 1.

TABLE 1

Station No	ALL STATIONS	1A	1D	2A	2D	3A	3D	CC1
Chlorophyll <sub>a</sub> vs NO <sub>3</sub>	-0.87	-0.96	-0.99	-0.97	-0.83	-0.82	-0.99	-0.99
Chlorophyll <sub>a</sub> vs SiO <sub>3</sub>	-0.84	-0.89	-0.60	-0.95	-0.87	-0.87	-0.96	-0.93
Chlorophyll <sub>a</sub> vs PO <sub>4</sub>	-0.64	-0.71	-0.71	-0.87	-0.60	-0.69	-0.95	-0.94

The strong negative correlation found to exist between chlorophyll<sub>a</sub> and each of the nutrients show that high levels of chlorophyll<sub>a</sub> are associated with low nutrient values in the surface waters and vice versa in the bottom waters. An interesting feature to note from Fig. 14 however, is the existence of data points away from the main regression line. These shall be referred to as "outliers". These outliers are notated with the station number from which they originate.

It can be seen that in respect of Chlorophyll<sub>a</sub> vs both NO<sub>3</sub> and PO<sub>4</sub>, outlying data points are found at stations 2A, 2D and 3A. Chlorophyll<sub>a</sub> vs SiO<sub>3</sub> shows outliers at Stations 2A and 3A only. The situation at Station 2A is caused by an increased level of phytoplankton productivity resulting in enhanced chlorophyll<sub>a</sub> values. It would also appear that NO<sub>3</sub> has been taken up preferentially to PO<sub>4</sub> at Station 2A since on the Chlorophyll<sub>a</sub> vs PO<sub>4</sub> graph there persist high values of PO<sub>4</sub> despite the enhanced phytoplankton production.

At Stations 2D and 3A the outliers are caused by an unusually high nutrient reading for the given level of Chlorophyll<sub>a</sub> and are thought to result from an influx of nutrients to the SWSL from the BML. Table 2 shows the physical and chemical data from the 9m depth sampling level at stations 2D and 3A respectively. This relates to the specific data points of the outliers shown in Fig. 14.

TABLE 2

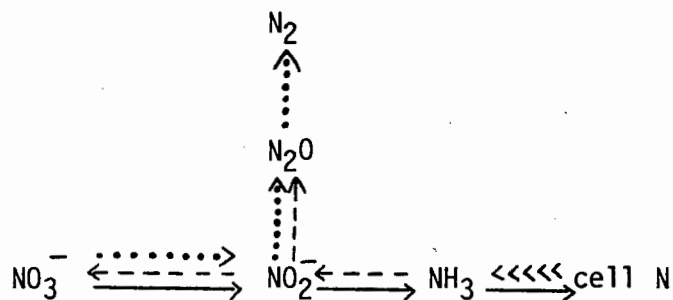
Station No	Depth (m)	Sal ‰	Temp (°C)	NO <sub>3</sub> (µg at l <sup>-1</sup> )	SiO <sub>3</sub> (µg at l <sup>-1</sup> )	PO <sub>4</sub> (µg at l <sup>-1</sup> )
2D	9	34.73	11.67	16.6	10.7	2.1
3A	9	34.73	10.79	23.4	20.2	2.42

It can be seen that in both instances the nutrient values were obtained from the base of the SWSL, just above the 10°C isotherm (Temp 11.67°C and 10.79°C respectively). The nutrient sections in Fig. 9 show the core of high nutrient water lying in the region of this boundary layer, and in the cases quoted here, transcending the layer.



(iv) The Primary Nitrite Maximum

A diagrammatic representation is given below showing the position held by nitrite in the processes of denitrification, assimilation, ammonification and nitrification:



(From Olson, 1981)

Olson (1981) made a study of the production of nitrite from nitrate and ammonia and the uptake of nitrate and ammonia using <sup>15</sup>N tracers. Nitrite holds an intermediate position in the processes of nitrogen assimilation and regeneration and in denitrification. The study of its distribution is therefore of importance in understanding the marine nitrogen cycle (Rakestraw, 1936).

Olson (1981) found that the sub-surface nitrite maximum (as shown in Figs. 12A and 12B) occurs near the 1% light level and coincides with the upper part of the nitrate gradient.

Secchi disc readings were used to estimate light penetration depths ( $3 \times \text{Secchi depth} = 1\% I_0$ ) at the St. Helena Bay stations and the 1% light level was found to be approximately 9m - 12m depth. Maximum values of  $\text{NO}_2$  were observed at 10m - 12m. This is thought to be an acceptable agreement with Olson (1981) considering the imprecision inherent in the use of Secchi discs. No light penetration readings were taken on the Cape Columbine transect. Both the nitrate and nitrite profiles from Stations 3A and CC4 are shown in Fig. 15 and it can be seen that the nitrite maximum occurs at the upper limit of the nitrate gradient which also shows agreement with Olson (1981).

Previous work conducted on the occurrence of nitrites by Brandhorst (1959) found that nitrite near the bottom of the euphotic zone in well-oxygenated water was the result of ammonia oxidation by nitrifying bacteria while Vaccaro and Ryther (1960) state that the nitrite source is due to its excretion by phytoplankton during nitrate reduction. Wada and Hattori (1971) in their work in the Central North Pacific attribute ammonia as being the main source of nitrite at the depth of the nitrite maximum, and Miyazaki et al (1973, 1975) found both nitrate and ammonia to contribute to nitrite in the euphotic zone in Sagami Bay and in the Western North Pacific.

Olson (1981) concludes that ammonia is the predominant source of nitrite in the Primary Nitrite Maximum in subtropical waters and in the Ross Sea in Summer, but that both nitrate and ammonia were important in the Scotia Sea in early Spring. He further states that during a period of upwelling off the Southern California coast (which is more relevant to the conditions found off the west coast of South Africa) nitrate reduction by phytoplankton may be important as a source of nitrite in situations where  $\text{NO}_3$  is present in near surface waters. During the present study, a large standing stock of phytoplankton is implied by the high chlorophyll<sub>a</sub> values measured in St. Helena Bay and high nitrate values have been found in the upper parts of the water column thus indicating concurrence with the Californian upwelling case.

(v) (a) The Oxygen Depleted Layer

The oxygen depleted water ( $< 2 \text{ ml l}^{-1}$ ) observed below the thermocline in St. Helena Bay and at Station CCl on the Cape Columbine transect is clearly associated with the BML ( $\sigma_t = 26.8$ ) shown in Fig 6A, and as such agrees with the work carried out by DeDecker (1970), Chapman (1983) and Bailey and Chapman (1984). It is further stated by Chapman (1983) that in St. Helena Bay, water with a  $\sigma_t$  value of 26.8 is present on the shelf at all times of the year except mid-

winter and is closely associated with the oxygen depleted (O.D.) water.

Oxygen supersaturation in surface waters, provided there is an absence of physical dissipation and in-situ temperature changes, represents the excess of photosynthesis over respiration. Oxygen depletion, on the other hand occurs when organic compounds are broken down accompanied by a consumption of oxygen. Andrews and Hutchings (1980) therefore regard the presence of O.D. water as an indicator of nutrient regeneration. The question arises as to whether the O.D. water reported in this study is of a local or remote origin. DeDecker (1970) contends that the O.D. water occurring as far South as Cape Town is associated with the deep compensation current postulated by Hart and Currie (1960) and that the oxygen-depleted water has a discrete source to the north. Bailey and Chapman (1984) feel that the oxygen depletion in St. Helena Bay results from local processes in an essentially semi-closed system, and Chapman and Shannon (1985) state that the temperature and salinity values at the three sites of oxygen-depleted shelf water occurring in the Benguela System, i.e.

- (a) between 2<sup>0</sup> and 24<sup>0</sup>S lying north of the principal upwelling centre
- (b) Orange Bight - South of Luderitz and North of Hondeklip
- (c) St. Helena Bay, near the Cape Columbine upwelling centre

(Visser, 1969), indicate that the O.D. water is formed locally. The physical properties of the 3 water types are typical of their respective latitudes rather than indicative of a common source.

In the present study the relationship between oxygen and nutrients is explored in the context of nutrient regeneration and a study is made of the origins of the oxygen depleted layer. It was decided to approach the topic by posing the following questions:

- (a) What is the extent of nutrient regeneration occurring on the shelf compared to offshore waters?
- (b) What stage has the regenerative process reached in terms of the sequential breakdown of phosphate, nitrate and silicate?
- (c) Do the ratios of certain nutrients indicate the water to be of remote or local origin?

Calvert and Price (1971) in their study of upwelling and nutrient regeneration in the Benguela Current made a comparison of the nutrient concentrations of the shelf water with those in offshore waters of the same salinity, assuming that salinity is a conservative property.

A similar comparison is made in the present study. Values of

nitrate, phosphate and silicate concentrations have been superimposed on the salinity section of the Cape Columbine transect. (Fig. 16A). The water lying on the inner shelf can be seen to be nutrient enriched compared to waters further offshore of the same salinity.

The homogeneous body of oxygen depleted water in St. Helena, whose salinity is constant at 34.75‰ is also found to be enriched in nutrients compared to water of the same salinity offshore. (Mean  $\text{NO}_3 = 22.5\mu\text{g at l}^{-1}$ ,  $\text{PO}_4 = 2.14\mu\text{g at l}^{-1}$ ,  $\text{SiO}_2 = 27.9\mu\text{g at l}^{-1}$ ).

The evidence given above clearly shows that nitrate, phosphate and silicate are found in greater quantities in the nearshore region of the Cape Columbine transect and in St. Helena Bay when compared with offshore waters for a given value of salinity. Therefore, in answer to the first question, nutrient regeneration on the inner shelf occurs to a greater extent than in offshore waters. One would therefore expect a higher degree of oxygen depletion to occur.

In open oceanic water Redfield et al (1963) have shown that the nutrients nitrate, silicate and phosphate are released in constant atomic proportions N : Si : P of 16 : 16 : 1 respectively. Grill and Richards (1964) make the distinction that during nutrient regeneration, the ratios of change of

the nutrients vary with time. Initially phosphate is released more rapidly than both the rate of ammonification and silica solution from diatom tests. Later a relatively constant ratio of N : P of 16 : 1 is found whereas silicate gradually increases relative to phosphate. The increase in the level of silicate is due to the continued solution of the diatom tests after most of the phosphate has been released from the cells. Clearly an examination of the nutrient ratios in the study area will indicate which stage the regenerative process has reached. Three different ratios have been measured:

(a)  $\text{NO}_3$  :  $\text{SiO}_3$

(b)  $\text{NO}_3$  :  $\text{PO}_4$

(c)  $\text{SiO}_3$  :  $\text{PO}_4$

In the work of Redfield et al (1963), nitrate and phosphate are used to represent values of nitrogen and phosphorous respectively and the same has been done in the present study. Since ammonium and nitrite have been neglected then the value used for total nitrogen is understated. However, Probyn and McQuaid (1985) have found that under upwelling conditions nitrate contributes 96% to the total concentration of nitrogen. Nitrite concentrations were extremely low in comparison with nitrate (1%) and Bailey (pers. comm.) states that measured values of ammonium were higher than reality owing to experimental error. For these

reasons nitrate concentration is used in the ratios since this is by far the major component.

Previous studies of inter nutrient relationships in the Benguela System carried out by Calvert and Price (1971), Andrews and Hutchings (1980), Bailey and Chapman (1984), made use of regression equations to obtain the nutrient ratio, although an integration technique was applied to certain of the Andrews and Hutchings data. The regression method was used by Redfield et al (1963) to ascertain the predicted oceanic ratio between nutrients. Each data point on their graphs represents the concentrations of the pair of elements determined from discrete samples of sea water collected at varying depths throughout the water column. The lower values were from the biologically productive surface waters where the nutrients have been consumed, and high values represented samples from greater depth. They go on to state that the slope of the line drawn through the points gives the ratio of the difference in concentration of the elements in question, however they emphasize that these ratios do not represent the proportions in which the elements are available in sea water, but rather the ratios of change in their concentration resulting from biological activity.

In order to discover the origins of the O.D. water, the present study considers the bottom layer of homogeneous



water found in St. Helena Bay and at Station CC1 on the Cape Columbine transect. Since the water at both locations is at the bottom part of the water column, the regression relationship will indicate ratios of change resulting from regenerative processes. Regressions for each of the nutrient ratios are shown in Fig. 16B. The availability of the various nutrients (i.e. occurrence) is shown in Table 3.

TABLE 3

Ratios of nutrient occurrence in the oxygen depleted layer in St.  
Helena Bay and Station CC1 on the Cape Columbine transect

Station No	Oxygen (ml l <sup>-1</sup> )	NO <sub>3</sub> :SiO <sub>3</sub>	NO <sub>3</sub> :PO <sub>4</sub>	SiO <sub>3</sub> :PO <sub>4</sub>
CC1	1.34	1.05	10.9	10.4
	1.31	1.00	10.5	10.5
	1.96	1.04	10.4	10.0
2A	0.89	1.10	11.5	10.5
	0.77	0.85	11.2	13.3
	0.76	0.80	12.1	15.1
	0.53	0.64	7.6	11.8
2D	0.71	0.72	10.2	14.2
	0.43	0.64	10.1	15.9
3A	1.58	1.16	9.7	8.3
	1.74	1.16	13.0	11.2
	1.13	0.89	11.8	13.3
	0.71	0.66	8.9	13.6
	0.49	0.61	8.5	14.1
3D	0.95	0.91	12.8	14.1
	?	0.78	11.0	14.1
	0.59	0.72	11.4	15.8
	0.88	0.68	10.5	15.3
Mean values		0.86	10.7	12.9

The predicted Redfield oceanic ratio of  $\text{NO}_3 : \text{PO}_4$  is 16 : 1. The ratio of occurrence of these two nutrients in the bottom 0.D. water of St. Helena Bay was consistently less than this ratio, having a mean value of 10.7 (see Table 3). This indicates a higher proportion relative to nitrate in the water. The regression slope for the same two nutrients (Fig. 16B) showing the ratios of change in concentration due to regeneration is 7.0. Again, this is lower than Redfield's predicted ratio, showing that  $\text{PO}_4$  is being regenerated to a greater extent than  $\text{NO}_3$ . Since  $\text{PO}_4$  is released more rapidly than nitrate in the initial stages of regeneration (Grill and Richards, 1964), then its relative abundance and greater rate of regeneration indicate the water to be of recent and therefore local origin, in terms of breakdown of organic matter and oxygen depletion.

The results gained from the  $\text{SiO}_3 : \text{PO}_4$  ratios of occurrence and regeneration are not as conclusive. The ratio of occurrence is again consistently less than Redfield's ratio of 16 : 1. It has a mean value of 12.9 showing that  $\text{PO}_4$  is slightly more abundant than  $\text{SiO}_3$ . The regression slope for  $\text{SiO}_3 : \text{PO}_4 = 15.7$  showing that the nutrients are being released in constant atomic proportions. According to Grill and Richards (1964) this would indicate a later stage of the regenerative process when silicate gradually increases relative to phosphate. This picture does not, however, agree with the early stage regeneration suggested by the  $\text{NO}_3$

:  $\text{PO}_4$  ratio above. A possible explanation for this is the enhanced liberation of  $\text{SiO}_3$ . Mortimer, (1971) has shown that this occurs in bottom sediments where oxygen concentrations are less than  $1.4 \text{ ml l}^{-1}$ , as is the case in the present study.

The evidence found so far would therefore seem to suggest that  $\text{PO}_4$  is being released more rapidly than  $\text{NO}_3$ , indicating a recent and local nutrient regeneration. This rapid regeneration of  $\text{PO}_4$  is not clearly shown by the  $\text{SiO}_3 : \text{PO}_4$  ratio, owing to the fact that enhanced silica liberation occurs in oxygen depleted waters. This being the case, then further supportive evidence should be provided from the  $\text{NO}_3 : \text{SiO}_3$  ratio. Enhanced  $\text{SiO}_3$  liberation would again offset the results.

The mean ratio of occurrence of the two nutrients is 0.86 compared to a predicted Redfield ratio of 1. The waters are therefore slightly enriched with  $\text{SiO}_3$  compared to  $\text{NO}_3$ . The regression slope = 0.3 which means that  $\text{SiO}_3$  is being released to a greater extent than  $\text{NO}_3$ . This is the expected result, given that  $\text{SiO}_3$  liberation is enhanced in these waters.

In order to test whether enhanced  $\text{SiO}_3$  liberation is general in the area or confined to oxygen depleted water, a comparison was made with the well oxygenated bottom water

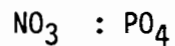
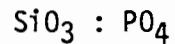
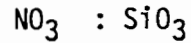
(>4 ml l<sup>-1</sup> below 50m) of the Cape Columbine transect (Fig. 16C). The ratio of occurrence between NO<sub>3</sub> and SiO<sub>3</sub> was found to be 1.6 indicating a relative abundance of NO<sub>3</sub>. The regression relationship was also 1.6 indicating that NO<sub>3</sub> was being liberated faster than SiO<sub>3</sub>. These two results fit a pattern of local nutrient regeneration. This gives further support to the contention that anomalous ratios obtained in the adjacent bottom water of St. Helena Bay were due to enhanced SiO<sub>3</sub> regeneration in oxygen-depleted water, and that processes occurring there are also localised.

Shannon (1985) notes that observed low NO<sub>3</sub> : SiO<sub>3</sub> ratios in St. Helena Bay could also be due to the occurrence of nitrate reduction to ammonia or elemental nitrogen.

(v) (b) Utilization and limitation of nutrients

Whereas bottom waters were studied in order to demonstrate patterns of nutrient regeneration and oxygen depletion, utilization and limitation of nutrients is confined to the upper layers. In St. Helena Bay and at Station CC1 this was defined as water lying above the 10°C isotherm and therefore within the biologically productive SWSL. The surface water at the remainder of the offshore stations was defined as that lying between 0m - 50m depth, ensuring that samples came from within the photic zone.

Again, the nutrient ratios which have been considered are:



These relationships for St. Helena Bay and Cape Columbine transect are represented graphically in Figs. 16D and 16E respectively. The regression for each ratio has also been fitted in each case.

It has already been stated that the slope of the line drawn through the points does not represent the proportions in which elements are available in sea water, but rather the ratio of change in their concentration resulting from biological activity. In surface waters, this ratio of change will indicate the uptake of the various nutrients during photosynthesis. The position of the intercept of the regression line with the x or y axis is also important since it shows which nutrient is limiting. This is apparent because it shows that, according to the relative uptake, and availability of the two nutrients considered, one will be totally depleted before the other. Note that actual data values in the uppermost surface samples will also help in this interpretation.

In St. Helena Bay surface water (Fig. 16D), the  $\text{NO}_3 : \text{SiO}_3$  regression has a slope = 1.1. This is almost identical to the predicted Redfield slope of 1 for the two nutrients, showing that they are being utilized in equal proportions. The intercept lies very close to the origin, but gives some evidence that when  $\text{NO}_3$  is completely exhausted, there remains a small amount of  $\text{SiO}_3$  ( $1 \mu\text{g at l}^{-1}$ ). Surface data values support the evidence for  $\text{NO}_3$  limitation. (E.g.  $\text{SiO}_3 = 1.7 \mu\text{g at l}^{-1}$ ,  $\text{NO}_3 = 0.7 \mu\text{g at l}^{-1}$ ).

The  $\text{SiO}_3 : \text{PO}_4$  ratio in St. Helena Bay surface waters gives a slope of 8.7. This is substantially lower than the predicted Redfield ratio of 16. Since utilization rather than regeneration is now being considered, this indicates a higher uptake rate of  $\text{SiO}_3$  relative to  $\text{PO}_4$ . The position of the intercept shows that  $\text{SiO}_3$  is depleted first and is therefore limiting over  $\text{PO}_4$ . Actual surface values show higher relative quantities of  $\text{PO}_4$  than  $\text{SiO}_3$  ( $\text{PO}_4 = 0.58 \mu\text{g at l}^{-1}$ ,  $\text{SiO}_3 = 1.7 \mu\text{g at l}^{-1}$ ) and therefore support this contention.

The regression for  $\text{NO}_3 : \text{PO}_4$  has a slope of 9.9 indicating that  $\text{NO}_3$  is being taken up to a greater extent than  $\text{PO}_4$ . The intercept shows  $\text{NO}_3$  to be limiting over  $\text{PO}_4$ , again supported by actual surface values ( $\text{PO}_4 = 0.58 \mu\text{g at l}^{-1}$ ,  $\text{NO}_3 = 0.7 \mu\text{g at l}^{-1}$ ).

In summary, the biologically active surface waters of St. Helena Bay utilize  $\text{NO}_3$  and  $\text{SiO}_3$  in approximately the same proportions as those predicted by Redfield (i.e. 1 : 1) while  $\text{PO}_4$  is utilized the least. (Note that the  $\text{PO}_4$  data points relative to the predicted Redfield slope show it to be the most abundant nutrient). There was evidence to show that  $\text{NO}_3$  was more limiting than  $\text{SiO}_3$  and the  $\text{PO}_4$  was the least limiting nutrient.

The surface waters of the Cape Columbine transect were subjected to a similar analysis (Fig. 16E). The relationship between  $\text{NO}_3$  :  $\text{SiO}_3$  gave a regression line with a slope = 1.7. This is greater than Redfields predicted slope of 1.0 and therefore indicates that  $\text{SiO}_3$  is being utilized faster than  $\text{NO}_3$ . The regression line virtually passes straight through the origin and therefore nutrient limitation is not readily apparent.

The  $\text{SiO}_3$  :  $\text{PO}_4$  slope (4.98) showed the relative uptake of  $\text{SiO}_3$  to be much higher than that of  $\text{PO}_4$ . Surface data values show  $\text{SiO}_3$  to be limiting (e.g.  $\text{SiO}_3 = 1.6 \mu\text{g at l}^{-1}$ ,  $\text{PO}_4 = 0.5 \mu\text{g at l}^{-1}$ ), however the regression line does not give any definite indication since its intercept is nearly through the origin. Given the balance of evidence, with high rates of  $\text{SiO}_3$  uptake and lower relative surface concentrations, it seems likely that  $\text{SiO}_3$  is limiting over  $\text{PO}_4$ .



$\text{NO}_3$  can be clearly seen as the limiting nutrient in the relationship between  $\text{NO}_3$  and  $\text{PO}_4$ . There are just over 0.2  $\mu\text{g}$  at  $1^{-1}$  of  $\text{PO}_4$  remaining after  $\text{NO}_3$  has been totally depleted. The slope of the  $\text{NO}_3 : \text{PO}_4$  regression is 12 and therefore compared to Redfield, indicates a more rapid uptake of  $\text{NO}_3$ .

The picture regarding nutrient limitation in the waters off Cape Columbine does not show any major difference between  $\text{NO}_3$  and  $\text{SiO}_3$ , both nutrients however, are limiting over  $\text{PO}_4$ . The fact that  $\text{NO}_3$  is clearly the limiting nutrient with respect to  $\text{PO}_4$  and that  $\text{SiO}_3$  is only marginally limiting over  $\text{PO}_4$  gives indirect evidence that  $\text{NO}_3$  is more limiting than  $\text{SiO}_3$  in the system. This overall result now gives broad agreement with the St. Helena Bay waters as far as nutrient limitation is concerned.

Patterns of utilization between the various nutrients were found to differ at the two sites. In Cape Columbine waters,  $\text{SiO}_3$  was taken up faster than  $\text{NO}_3$ , with  $\text{PO}_4$  being the least utilized. The comparative results are summarized below:

	St. Helena Bay	Cape Columbine Transect
Utilization	$\text{NO}_3 + \text{SiO}_3 > \text{PO}_4$	$\text{SiO}_3 > \text{NO}_3 > \text{PO}_4$
Limitation	$\text{NO}_3 > \text{SiO}_3 > \text{PO}_4$	$\text{NO}_3 > \text{SiO}_3 > \text{PO}_4$

(vi) Mixing Processes

(a) Turbulent

In a column of water the greater the stability of stratification then the greater the work required to displace water bodies in a vertical direction. i.e. In stratified water turbulence is inhibited. The Richardson number gives the ratio between buoyancy and velocity shear and thus gives an indication of whether stratification or shear is dominant. The same formula as that applied by Krauss (1981) has been used to calculate the Richardson number

$$\text{viz. } Ri = \frac{(\sigma_{n+1} - \sigma_n) \Delta Z \times 10^{-3} g}{(u_{n+1} - u_n)^2 + (v_{n+1} - v_n)^2}$$

where  $n + 1$  and  $n$  represent two different levels in the water column

$\sigma$  = sigma - t value

$\Delta Z$  = distance (m) between  $n$  and  $n + 1$

$u$  = northerly current component

$v$  = easterly current component

This calculation gives a value for the Bulk Richardson number (Ri(B)). Ri(B) provides an approximation to the Gradient Richardson Number, Ri(G)

where  $Ri(G) = \frac{g/\rho (\delta\rho/\delta z)}{(\delta u/\delta z)}$

$g$  = acceleration due to gravity

$\rho$  = density

$z$  = depth

$u$  = velocity

In order for  $Ri(B)$  to be a good approximation to  $Ri(G)$  it is necessary to measure both velocity and density gradients on length scales down to the Ozmidov length ( $\epsilon^{1/2}/N^{3/2}$ ; where  $\epsilon$  = rate of dissipation of energy,  $N$  = Brunt-Vaisala frequency), which is an appropriate length for the prediction of Kelvin-Helmholtz instability (Simpson, 1975). This length is thought to be around 30cm although Woods and Fosberry (1967) carried out dye studies which indicated that the shear is concentrated into regions of approximately 10cm thickness.

Where  $Ri(G)$  is less than some critical value ( $Ri(CRIT)$ ) then turbulence will occur. If  $Ri(G) > Ri(CRIT)$  then conditions will be stable. Simpson (1975) has deduced from the Miles and Howard theorem that for characteristic oceanic profiles of shear and density, active turbulence will occur whenever  $Ri(G) \leq 0.25$  for a time long enough to allow the growth of instabilities in the shear flow.

In this present study the Bulk Richardson Number is calculated and it was not possible to resolve velocity according to the Ozmidov scale owing to equipment limitation. Presented here is therefore a somewhat diluted approximation to the Gradient Richardson Number and the interpretation of its value will be less definitive as a result.

In other words;

$Ri(B) < Ri(CRIT)$ :- There must be more turbulence than stability over the depth range measured

$Ri(B) > Ri(CRIT)$ :- There must be a sub-region of greater stability, and over the depth range there is more stability than turbulence

Current meters had been deployed in the SWSL and within the BML below the  $10^{\circ}C$  isotherm at each of the three current metering stations. The boundary region between these two layers was of greatest interest with regard to vertical mixing and the Bulk Richardson number would indicate the presence or absence of turbulence within this zone.

Measurements from current meters deployed on either side of the interface were used in the calculation. Fig. 17 gives a schematic representation of the current meter deployment and relevant data points. Table 4 gives a summary of the measurements used in the calculation of the Bulk Richardson Number.

TABLE 4

	Station 1	Station 2	Station 3
Depth (m) n	23	15	10
Depth (m) n + 1	33	18	13
$\Delta Z$ (m)	10	3	3
$U_n$ ( $\text{ms}^{-1}$ )	-0.16	0.47	-0.42
$V_n$ ( $\text{ms}^{-1}$ )	0.074	0.01	-0.35
$\sigma_n$ ( $\text{Kg m}^{-3}$ )	26.64	26.73	26.71
$U_{n+1}$ ( $\text{ms}^{-1}$ )	-0.24	0.006	0.01
$V_{n+1}$ ( $\text{ms}^{-1}$ )	0.1	0.5	-0.1
$\sigma_{n+1}$ ( $\text{Kg m}^{-3}$ )	26.83	26.83	26.83

Station 1

$$Ri(B) = \frac{\text{Buoyancy}}{\text{Velocity shear}} = \frac{0.01862}{0.007076} = 2.63$$

### Station 2

$$\text{Ri(B)} = \frac{\text{Buoyancy}}{\text{Velocity shear}} = \frac{0.00294}{0.4554} = 0.0065$$

### Station 3

$$\text{Ri(B)} = \frac{\text{Buoyancy}}{\text{Velocity shear}} = \frac{0.003528}{0.2474} = 0.0143$$

The criterion has already been established that turbulence occurs when Richardson number values  $\leq 0.25$ . Krauss (1981) further states that such values would also indicate the presence of breaking internal waves. According to the calculations made above and within our self-imposed limits of interpretation it is possible to state that within the boundary layer at Stations 2 and 3 there was more turbulence than stability with the possible presence of breaking waves. In the presence of such mechanisms, the likelihood of vertical transport across the interface through turbulent mixing is predicted. The Ri(B) value for Station 1 indicates that stability dominates over turbulence and vertical transport through this means would not be expected.

The reason for the much lower Ri(B) numbers at Stations 2 and 3 can be attributed to the increase in velocity shear

rather than decrease in buoyancy. Compared to Station 1, the buoyancy force at Stations 2 and 3 is reduced by approximately 80% whereas velocity shear has increased by 6400% and 3400% respectively.

(b) Diffusive Mixing (Salt Fingering/Double Diffusion)

Vertical mixing by salt-fingers has been well described in the literature, (Stern, 1960; Turner and Stommel, 1964; Turner, 1967; Gregg, 1973; Tait and Howe, 1968). It arises because of the differential diffusion rates between heat and salt. In a two layer system in which warmer, saltier water overlies cooler, less salty water then the upper layer loses heat and the lower layer gains it faster than the salt is transferred (100 x faster). The upper water, having lost heat becomes denser and tends to sink while the lower water becomes less dense and tends to rise. Salt fingers are the result. A schematic diagram of this type of process is shown in Fig. 18.

The continuous temperature and salinity data obtained from the CTD permitted detailed profiles of each to be drawn across the interface between the two water layers in St. Helena Bay (Fig.19A). The scaling of the temperature and salinity axes is important with regard to studying the diffusive mixing processes, however this is dealt with later

in the section.

A fairly complex microstructure is observed, however, a regular feature in the salinity profiles is the 'bump' which occurs at the top and bottom of the thermocline. These 'bumps' are found at every station and are too regular to be interpreted as artefacts. The complex microstructure with the occurrence of similar steps and layers to those observed by Tait and Howe (1968) offers qualitative evidence that the boundary layer between the SWSL and the BML is a potential zone for diffusive mixing processes. It was decided to apply the work of Ruddick in obtaining a practical indicator of the stability of the water column to double-diffusive activity and thus adopt a quantitative approach to the problem.

Turner (1973) has shown that the single most important indicator of the relative strength of double-diffusion is the gradient ratio  $R_\rho$ , where:

$$R_\rho \equiv \frac{\alpha \frac{\partial T}{\partial Z}}{\beta \frac{\partial S}{\partial Z}}$$

and: T = temperature

S = salinity

Z = depth (nB.+ve downwards)

Ruddick (1983) introduces a sketch of the  $\frac{\partial T}{\partial Z}$  vs  $\frac{\partial S}{\partial Z}$  plane which shows the regions of instability to double-diffusive convection (reproduced in Fig. 19B). The axes



have been scaled in terms of their contribution to the density gradient. Ruddick further states that the convention is that Z is positive downward and :

$$\frac{1}{\rho} \left( \frac{d\rho}{dz} \right) = -\alpha \frac{dT}{dz} + \beta \frac{ds}{dz}$$

Therefore, having represented any given point in the water column on Fig. 19B, the slope of the chord from that point to the origin =  $R\rho$

In the present study it has been possible to dispense with the need for such a sketch in order to obtain values of . The following technique has been used:

$$\text{since } \frac{1}{\rho} \left( \frac{d\rho}{dz} \right) = -\alpha \frac{dT}{dz} + \beta \frac{ds}{dz} \quad \text{----- } \textcircled{1}$$

$$\text{then } \alpha = -\frac{1}{\rho} \left( \frac{d\rho}{dT} \right)_s$$

$$\beta = \frac{1}{\rho} \left( \frac{d\rho}{ds} \right)_T$$

The waters of the St. Helena Bay area were found to have values of  $\alpha$  and  $\beta$  of around  $200 \times 10^{-3}$  and  $800 \times 10^{-3}$  respectively. This equates to a ratio of 1 : 4. In other words, a  $4^{\circ}\text{C}$  change in temperature is the equivalent of a 1% change in salinity, in terms of its effect on density.

The temperature and salinity axes in Fig. 19A. have been scaled on this basis. The result of this is to compare ( $\alpha T$ )

with  $(\beta S)$  and effectively eliminate  $\alpha$  and  $\beta$  from Turner's equation.  $R_p$  now simply becomes  $\frac{\partial T / \partial z}{\partial S / \partial z}$  which can be calculated directly from the temperature/salinity profiles. (Note: the scaling of the axes and consequent elimination of  $\alpha$  and  $\beta$  from Turner's equation mean that unit rather than actual values should be applied to  $\frac{\partial T}{\partial z}$  and  $\frac{\partial S}{\partial z}$  when making the  $R_p$  calculation)

Having established the method for obtaining a value for  $R_p$ , the next step is to interpret this value in terms of stability, instability or marginal stability. The category into which the calculated  $R_p$  value fits can be read off the sketch in Fig. 19B, however it is first necessary to establish the criteria for these categories.

Stated simply, the stability criterion is that  $\frac{\partial \rho}{\partial z} > 0$ . Alternatively, (from equation (1)),  $\frac{\partial(\beta S)}{\partial z} - \frac{\partial(\alpha T)}{\partial z} > 0$

$$\text{or } \frac{\partial(\alpha T)}{\partial z} < \frac{\partial(\beta S)}{\partial z}$$

This stability criterion applies for all possible signs of  $\frac{\partial(\alpha T)}{\partial z}$  and  $\frac{\partial(\beta S)}{\partial z}$  and leads to a categorization based on  $R_p$ . This is presented below; note that  $\alpha$  and  $\beta$  are not included.

STRONG STABILITY	MARGINAL STABILITY	
$\frac{\delta T}{\delta Z} < 0$ <p style="text-align: center;">and</p> $\frac{\delta S}{\delta Z} > 0$	FINGERING	DIFFUSIVE
	$\frac{\delta T}{\delta Z} < 0$ <p style="text-align: center;">and</p> $\frac{\delta S}{\delta Z} < 0$	$\frac{\delta T}{\delta Z} > 0$ <p style="text-align: center;">and</p> $\frac{\delta S}{\delta Z} > 0$
Then	and	and
$R_p = \frac{\delta T / \delta Z}{\delta S / \delta Z} < 0$	$\frac{\delta T}{\delta Z} < \frac{\delta S}{\delta Z} < 0$	$0 < \frac{\delta T}{\delta Z} < \frac{\delta S}{\delta Z}$
	Then	Then
	$R_p > 0$ and is such that $R_p > 1$	$R_p > 0$ and is such that $R_p < 1$

Ruddick's sketch (Fig. 19B) also shows a sub-division of diffusive and fingering categories into weak and strong sectors depending on their  $R_p$  value.

In summary:

<u>R<sub>p</sub> value</u>	<u>Stability Category</u>
1 - 2	Strong fingering
2 - 00	Weak fingering
0.5 - 1.0	Strong diffusive
0 - 0.5	Weakly diffusive

In Fig. 19A, the R<sub>p</sub> value and hence the strength of double diffusive activity has been noted on the portion of the profile over which it applies. Both weak and strong fingering processes can be seen to occur.

(c) Evolution of fingering layers

If the double-diffusive processes discussed above are treated as progressive with time, then the effect of different rates for the diffusion of heat and salt, must be considered on the marginally stable layers. Fourier's Law may be applied to quantify the extent of heat transfer (Q):

$$Q = -k \frac{\partial T}{\partial Z} \quad \text{where } k = \text{thermal diffusivity.}$$

Fick's Law, by comparison gives the amount of salt transfer (N<sub>s</sub>) by molecular diffusion:

$$N_s = -D \frac{\partial S}{\partial Z} \quad \text{where } D = \text{molecular diffusivity.}$$

Gregg (1973) states that heat diffuses about 100 x faster than salt. The result of this is that fingering stability and diffusive stability develop differently when time is brought into consideration. The arrows drawn in Fig. 19B show the development of weak fingers to strong fingers leading to instability, whereas when diffusion is considered, the trend is for strongly diffusive layers to weaken, leading to a stable condition.

This pattern of development becomes more clear when one considers the effect of the differing rates of diffusion on the parameter  $R_p = \frac{\alpha \delta T / \delta z}{\beta \delta S / \delta z}$ , in the context of the criteria established for marginal stability.

The zones of salt fingering, together with their relative intensities have already been established. It was therefore decided to show the evolution of fingering layers in the manner envisaged above.

A fairly quiescent environment with little or no turbulent mixing was felt to be the most appropriate, and therefore Stations 1A, 1B, 1C and 1D were chosen for this task in the light of Richardson number results. The key features in the salt fingering analysis were the 'salinity bumps' occurring in the profiles, hence salinity profiles from the above four stations have been plotted adjacently, and specific zones in

the water column have been linked with adjacent stations by the superimposition of a  $\sigma_t$ -section (Fig. 20). Salt fingering can be seen to develop from weak fingering layers at Station 1A ( $R\rho = 2.6$  and  $2.3$ ) to strong fingering at Station 1C ( $R\rho = 1.0$  and  $1.9$ ). The relationship of fingering layers between adjacent stations was not so readily apparent at Stations 2 and 3 but this would be expected from the turbulence existing there according to the Richardson Number calculations.

(vii) Residence Time

Wind data collected during the ten day period prior to the cruise (Fig. 3) were used to compute the Ekman transport of surface water and hence the residence time for a particle of water in St. Helena Bay. Northerly components ( $u$ ) and Easterly components ( $v$ ) of wind velocity were used to calculate a value for the transport of water using the formulae:

$$\bar{T}^x = \frac{\bar{\tau}^y}{f\rho_0} \text{ m}^2 \text{ s}^{-1}$$

$$\bar{T}^y = -\frac{\bar{\tau}^x}{f\rho_0} \text{ m}^2 \text{ s}^{-1}$$

Where  $f$  is negative

$\bar{T}$  = Mean Ekman transport

$\tau$  = Mean Wind Stress

$f$  = Coriolis Parameter

=  $2\Omega \sin \lambda$

where:  $\Omega$  = angular vel. of  
earth's rotn.

$$= 7.29 \times 10^{-5} \text{ sec}^{-1}$$

$\lambda$  = geographical

latitude

$\rho_0$  = Density ( $1 \times 10^3 \text{ Kg m}^{-3}$ )

In this particular case,  $\bar{T}^x$  is the component for offshore transport and  $\bar{T}^y$  is the longshore transport.

Note on mean wind stress ( $\tau^x, \tau^y$ )

$$\tau^x = C_D \rho_{\text{air}} \sqrt{u^2 + v^2} \cdot u \text{ Nm}^{-2}$$

$$\tau^y = C_D \rho_{\text{air}} \sqrt{u^2 + v^2} \cdot v \text{ Nm}^{-2}$$

where  $C_D$  = drag coefficient. Garratt

(1977) applies the following formula in the calculation of  $C_D$ :

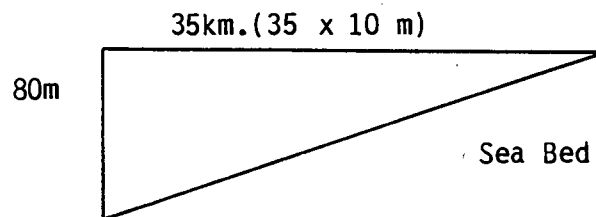
$C_D = (0.73 + 0.069 \sqrt{u^2+v^2}) \times 10^{-3}$ , it is applicable for high wind speeds.

Values for Ekman Transport were obtained as follows:

(offshore transport)  $\bar{T}^x = 0.64 \text{ m}^2\text{s}^{-1}$

(longshore transport)  $\bar{T}^y = 0.092 \text{ m}^2\text{s}^{-1}$

In order to compute a residence time for a particle of water in St. Helena Bay the cross sectional area of the bay was calculated using the 80m depth contour as its seaward limit



Cross-sectional area,  $A = (35 \times 10^3) (80/2) = 1.4 \times 10^6 \text{ m}^2$ .

The residence time (seconds) for a particle of water in the predefined limits of St. Helena Bay is given by:

$$\frac{A}{\bar{T}} \times \text{Residence Time (days)} = \frac{A}{\bar{T}(8.6 \times 10^4)}$$

The following values were obtained:

$$\text{Residence Time}(x) \text{ (Offshore component)} = \frac{A}{\bar{T}^x(8.6 \times 10^4)} = 25 \text{ days}$$



$$\text{Residence Time}(y) \text{ (Longshore component)} = \frac{A}{\bar{v}(8.6 \times 10^6)} = 176 \text{ days}$$

The offshore component for residence time has the dominant effect and therefore the turnaround time for water in St. Helena Bay is thought to be in the region of 3-4 weeks. This value may be an underestimate since Shannon (1966) suggests the presence of a cyclonic gyre in the bay which would cause water to be recirculated.

## CHAPTER 4

### Discussion

The waters of St. Helena Bay and off Cape Columbine provided an ideal oceanographic setting for the study of two contrasting yet closely linked systems. The surface waters, and more especially those off Cape Columbine were found to respond directly to wind stress resulting in a time scale of 3 - 5 days for variability. This period of synoptic variability has an "active" phase during which upwelling favourable winds are present, followed by a "passive" phase when upwelling ceases and the system is permitted to equilibrate physically and develop biologically.

The active phase is characterized by a sharp thermohaline front between offshore surface waters and newly upwelled surface waters. Outside the front, surface temperature and salinity have values typical of oceanic water found in the area (usually 35‰, 18°C). The surface waters inside the front are characterized by much lower temperatures with the possibility of outcropping 10°C isotherms. Salinity is also lower with values between approx 34.7‰ and 34.9‰. This newly upwelled water has lower oxygen values (approx. 4ml l<sup>-1</sup>) and enhanced nutrient levels when compared with its surface counterpart lying outside the front. Since no

biological activity has yet taken place within the euphotic zone, Chlorophyll<sub>a</sub> values are also low.

The present study, however, was undertaken during the passive phase of the synoptic variability and vertical sections of temperature and salinity for the Cape Columbine transect (Figs. 13A and 13B resp.), show conditions after a period of post-upwelling relaxation. The isotherms can be seen to have re-aligned themselves and the temperature front is a broad surface feature only. The more conservative property of salinity, however, clearly shows the separation of upwelled water from surface waters lying offshore during this post-upwelling phase. It is important to note that the passive phase results in sun-warming of surface waters inside the front together with phytoplankton growth. Oxygen levels increase together with increases in Chlorophyll<sub>a</sub> and depletion of nutrients at the surface. Nutrient regeneration occurs as a continuous process in the bottom waters over the inner shelf.

The present study also shows the existence of a water mass within St. Helena Bay which has an associated time scale of approximately 25 days. This is especially the case with the BML occurring below the 10°C isotherm ( $\sigma_t = 26.8$ ). Longer term processes of nutrient regeneration and oxygen depletion were found to have occurred. In addition, the waters of the most inshore station (Station CC1) on the

Cape Columbine transect have been shown to have similar characteristics, forming part of the same hydrographic regime.

The important point to emerge from this comparison is that the 3-5 day synoptic variability may not be the appropriate time scale, apart from in the surface waters off Cape Columbine. The longer time scale associated with St. Helena Bay means that its water is not necessarily formed by the previous upwelling event but is more likely the result of several previous synoptic cycles.

Andrews and Hutchings (1980) described four water types associated with the Southern Benguela upwelling area. These were primarily defined on the basis of temperature, though characterisation of associated salinities and nutrients were also provided. The water types are:

- (a) Oceanic water which is found to lie outside the oceanic front and above the thermocline. In their study it was found to have temperature and salinity values of  $>18^{\circ}\text{C}$  and  $>35\text{‰}$  respectively. The water was fairly well oxygenated (approx.  $6 \text{ ml l}^{-1}$ ) but was low in nutrients and Chlorophyll<sub>a</sub>.
- (b) Upwelling water originating from South Atlantic Central Water. This was found to have temperatures between  $8^{\circ}\text{C}$  and

10°C and its salinity was lower than that of oceanic water (approx. 34.7‰). It was also characterised by low levels of Chlorophyll<sub>a</sub> and large concentrations of nutrient (PO<sub>4</sub> ≈ 1.4 μg at l<sup>-1</sup>; SiO<sub>3</sub> ≈ 16.0 μg at l<sup>-1</sup>; NO<sub>3</sub> ≈ 20 μg at l<sup>-1</sup>). Oxygen values were approximately 4.2 ml l<sup>-1</sup>.

(c) Shelf water which lay under the upwelling water. Temperature was 8.0°C and typical salinities below 34.6‰ were found. The shelf water is similar to upwelling water in origin but remains below the photic zone and plays little part in the upwelling system. It was found to have low values of oxygen and Chlorophyll<sub>a</sub> (4 ml l<sup>-1</sup> and 0.5 μg l<sup>-1</sup> respectively) and enhanced nutrient concentrations.

(d) Mixed water. This was formed through the mixing of Oceanic and Upwelling waters and comprised the greatest proportion of all water in the study area. The authors further state that it has variable conservative and very variable non-conservative characteristics due, in part, to its origin and, in part, to the intense biological activity that occurs within it.

The Andrews and Hutchings classification deals with waters occurring at the Cape Peninsula upwelling site whereas the present study is concerned with waters occurring off Cape Columbine. Shannon (1985) points out that it is implicit in the classification of Andrews and Hutchings that only water

of 8°C - 10°C upwells, and that water between 10°C and 18°C is mixed.

The Andrews and Hutchings categorisation of water types has been imposed on the Cape Columbine transect temperature section (Fig. 21). This shows a pool of shelf water lying below the 8°C isotherm and confined to the basal region of the Cape Canyon. Overlying the Shelf Water, Upwelling water forms a broad band between the 8°C and 10°C isotherms moving up onto the inner shelf. The remainder of the vertical section comprises of mixed water lying above the upwelling water, with no evidence of Oceanic Water.

The present study gives a more detailed thermohaline structure on the Cape Columbine transect. Vertical sections of temperature and salinity are shown in Figs. 13A and 13B respectively. They show broad agreement on the existence of shelf water and upwelling water, however, the shelf water forms a much larger water body compared to when the Andrews and Hutchings criteria were applied. In this instance the 34.70‰ isohaline forms the boundary, and the water does not funnel up onto the inner shelf. The upwelling water moves inshore and upwards into the photic zone in the same manner envisaged by Andrews and Hutchings. There is evidence from the salinity section, however, that certain features are present in both the bottom waters of the inner shelf and surface water inside the salinity front, which do not show

up in the Andrews and Hutchings classification.

The first of these features is a layer of well-mixed bottom water with constant temperature and salinity values ( $9.8^{\circ}\text{C}$ ,  $34.75\%$ ,  $\sigma_t = 26.8$ ). This can be seen below a depth of 35m at Station CC1, but does not extend offshore as far as Station CC2.

The other feature shown in the salinity section forms a body of water at the surface between Stations CC3 and CC1. The same feature can be seen in the temperature section, overlying the  $14^{\circ}\text{C}$  isotherm. It is referred to in the present study as, Maturing Upwelled Water. The former classification by Andrews and Hutchings would have included this feature in the broad classification of Mixed Water. Mixing, however, is not responsible for the formation of this water since it has retained the characteristic salinity values of upwelling water ( $\approx 34.80\%$ ). It differs from upwelling water on the basis of temperature with values of approximately  $14^{\circ}\text{C}$ . This is the result of sun warming. Further differences compared to Upwelling Water include increases in surface oxygen and Chlorophyll<sub>a</sub> concentrations with concomitant decreases in nutrient levels. These changes result from the maturing processes, and thus biological activity, that this water has undergone following upwelling, and they occur during the passive phase of the synoptic cycle.

The overall effect of this re-classification, is to expand the Andrews and Hutchings category of Upwelling water to allow for processes of maturation and at the same time contract their category of Mixed Water, which is no longer felt to comprise the greatest proportion of all water in the study area.

Mixing does occur at the upwelling front and evidence for this was found at Stations CC3, CC4 and CC5. Temperature and salinity data in Figs. 13A and 13B showed evidence of inversion layers and these are labelled on the diagrams.

Fig. 22 gives a detailed picture of the temperature and salinity in the top 100m at these three stations. Temperature and salinity anomalies can be seen at both Stations CC3 and CC5. CC4 shows a salinity inversion only.

Mixing is predicted as a result of these inversions. The evidence suggests the presence of interleaving layers of water over a broad front. Cross-frontal mixing will occur as a result of this, but not to such an extent as to form the large body of mixed water envisaged in Fig. 21.

Water with the Andrews and Hutchings characteristic oceanic values ( $>18^{\circ}\text{C}$  and  $>35.00\%$ ) was not present in either of the vertical sections apart from pockets of high salinity



water (up to 35.06%) in the frontal mixing zone. It thus seems likely that in the present study, the transect did not extend beyond the front.

The differentiation between water types in this study is based primarily on salinity. Salinity is a conservative property and although other non-conservative parameters are introduced in the broad definitions, they merely show the developmental changes that have occurred in the "salinity-tagged" water type.

Within the upwelling system five categories of water are introduced. Two water types from the Andrews and Hutchings classification are retained, namely Oceanic water and Shelf water. Mixed water is omitted and three sub-categories of upwelled water are introduced replacing both the former upwelling and mixed water types. Active and passive phases of the upwelling cycle are introduced into the classification and although temperature and salinity values are given, they are not intended to be definitive. It is recognized that on a different occasion, following, for example, advection or entrainment from another area, other temperature and salinity values may be present, however this would not change the overall structure which is presented here.

A summary of the five water types is given below:-

- (1) Oceanic Water - Water with a salinity  $> 35.00\%$ . It lies outside the upwelling front and is found above the broad band of upwelling water. Surface temperatures will usually be  $> 18.00^{\circ}\text{C}$ .
- (2) Shelf Water - this was found below the upwelling water but played no active part in upwelling or biological processes. Its salinity was  $< 34.70\%$  and temperature,  $< 9.4^{\circ}\text{C}$ .
- (3) Upwelling Water - this water forms a band between the Oceanic water and Shelf water. It is brought to the surface layer during active upwelling but has not yet been subjected to a post-upwelling maturation. Its salinity range was  $34.70\%$  to  $34.90\%$  with temperatures between  $9.4^{\circ}\text{C}$  and  $11^{\circ}\text{C}$ . Chlorophyll<sub>a</sub>, oxygen, and nutrients are the same as those in Andrews and Hutchings upwelling water.

It is important to note that the general category of South Atlantic Central Water contains both Shelf water and Upwelling Water, the latter appearing uppermost in the water column.

- (4) Maturing Upwelled Water - The salinity range for this water type lies in the upper half of that quoted for upwelling water, in this case  $34.78\%$  -  $34.90\%$ . It is upwelling water

which has been permitted to develop in the photic zone during the passive phase of the upwelling cycle. This results in large variations in its non-conservative properties depending on the extent of sun-warming and levels of biological production. Generally, temperature values will lie between those of Upwelling and Oceanic waters, oxygen and Chlorophyll<sub>a</sub> values will be enhanced and nutrients will be depleted in comparison to upwelling water.

- (5) Inshore Bottom Mixed Water - This homogeneous body of water was found with constant salinity of 34.75‰ and temperature = 9.8°C at the innermost Station (CC1) on the Cape Columbine transect, and at all stations in St. Helena Bay. It is formed during the general upwelling process, however, its enhanced residence time (within St. Helena Bay) permits a full maturation. It is oxygen depleted (< 2 ml l<sup>-1</sup>) and nutrient enriched.

A summary of these water types is shown in Fig. 23. This should be compared with the previous classification shown in Fig. 21.

Having established the different water types occurring in the Cape Columbiné system it now becomes essential to give a dynamic perspective, by exploring the pathways that exist between them. This is done in the context of both the

active and passive phases and within the 3-5 day and 25 day time scales which have already been established.

During the active phase, within the 3-5 day period of synoptic variability, the main water types in evidence are oceanic water and newly upwelled water. (The shelf water is taken to be a constant feature in this analysis.) Oceanic water at the surface is transported offshore during upwelling and the offshore water lying at depth is the source for newly upwelled water in the nearshore region. In addition, the active phase of the 3-5 day variability has a pulsing effect on St. Helena Bay within the context of its 25 day residence time.

The passive phase is characterized by oceanic water separated from the nearshore region by a broader boundary layer. The offshore deep water and nearshore deep water are unchanged. However, the newly upwelled water in the surface nearshore region forms the body of maturing upwelled water which has a higher temperature, dissolved oxygen and Chlorophyll<sub>a</sub> and lower nutrients than its predecessor.

The presence of Inshore Bottom Mixed Water at the innermost Cape Columbine station and within St. Helena Bay shows an association between the two regions and the potential existence of a pathway from one to the other.

There is no doubt that the water occurring at these two locations is of the same type since the signature properties agree with the classification outlined above. i.e. Well mixed water of specific temperature and salinity, exhibiting oxygen depletion and nutrient enhancement.

In order to explain the presence of the same water at Cape Columbine (Station CC1) and within St. Helena Bay it is necessary to consider three possible pathways:

- (a) Newly upwelling water on the Cape Columbine transect forming a well-mixed body of bottom water on the inner shelf which advects northwards and eastwards into St. Helena Bay.
- (b) Water comprising the Inshore Bottom Mixed Water in St. Helena Bay occurring as a relict water body from previous upwelling events which advects southwards around Cape Columbine.
- (c) Upwelling water which forms a mixed bottom layer on the inner shelf in the region of Station CC1 and simultaneously, forms a similar water body in St. Helena Bay as part of the same upwelling process, but on a line further to the north. Timescales are important when considering these possible pathways. Holden (pers. comm.) has distinguished from his current metering study, a N-S

oscillatory water movement caused by the passage south of a coastal low from the Luderitz region. This is a regular meteorological event (Nelson and Hutchings, 1983). The pulsing effect operating within the 3-5 day synoptic variability would be superimposed on any overall trend in pathways acting in the 25 day time scale.

The evidence from which it is possible to identify the operating pathway is restricted to the nutrient and oxygen structure between the two locations. The short term current metering done in St. Helena Bay and the offshore origins of Inshore Bottom Mixed Water shown in Fig. 13B do not indicate pathway directions as a long term trend.

The relationship of the waters between Station CC1 and St. Helena Bay is demonstrated by its inclusion in the nutrient sections of St. Helena Bay (see Fig. 24). With the inclusion of CC1, the picture suggests an independent development of the respective Inshore Bottom Mixed Water Bodies as outlined in (c) above.

If CC1 is omitted (as in Fig. 9), then the intrusion of high nutrient water in St. Helena Bay can be interpreted in two ways. If nutrient regeneration (and therefore oxygen depletion) is essentially a local phenomenon then since nutrient levels in the bottom waters are greater at Stations 2 and 3 than at Station 1, then it suggests a

movement northwards (as outlined in (a) above). However, if the intrusion has conservative properties then this suggests a southward advection as stated in (b) above.

The present study permits any one of the three possible pathways depending on how the data is interpreted. Therefore it is not within the scope of this thesis to give any definite answers in this respect. The author suggests, however, that the identification of this pathway should be of prime importance in future studies relating to the area.

Another pathway has been shown to exist within the matured water of St. Helena Bay between the BML and the SWSL. This acts to transport nutrients to the euphotic zone, thus supporting further productivity in the absence of active upwelling. The vertical mixing mechanisms responsible for the establishment of this pathway have been outlined in Chapter 3 (vi) and are discussed later in the present chapter.

The bulk of this study was taken up by investigating the hydrology of the Inshore Bottom Mixed Water and its overlying Sun-warmed Surface Layer. Its long residence time of around 25 days in the relatively sheltered environment of the Bay provided an excellent regime for the study of events and processes in a mature body of upwelled water. The water column in St. Helena Bay consisted of a two layer

system. The surface layer of sun-warmed water overlying a well-mixed bottom layer. Surface temperatures of the sun-warmed surface water ( $13.5^{\circ}\text{C} - 14^{\circ}\text{C}$ ) were  $3^{\circ}\text{C} - 4^{\circ}\text{C}$  higher than those found in newly upwelled water yet salinities were the same. Compared to oceanic water, temperatures were between  $2^{\circ}\text{C}$  and  $3^{\circ}\text{C}$  lower and salinities were quite different.

In Shannon (1985), G. Hughes is quoted as saying that heat budget calculations can not account for the extent of warming that has occurred in the surface layer, yet the virtually isohaline nature of the water column in St. Helena Bay gives strong evidence for a common source, with no evidence for an advection of warmer surface water. Perhaps the heat budget calculations did not take into account the longer residence time which has been found for waters in the Bay. Within the constraints of the physical evidence available, it is inevitable that the warm surface layer in St. Helena Bay is the result of insolation. Further evidence for the maturation process is given by the high levels of dissolved oxygen (up to 145% supersaturation) in the photosynthetically active surface layer. In contrast oxygen depletion has occurred in the BML due to local nutrient regeneration. Fig. 7 shows the distinction between these two layers very clearly. The sloping of the  $10^{\circ}\text{C}$  isotherm (Fig. 13C) gives further evidence for a body of relict upwelled water in the Bay



(Chapman, 1983).

The BML maintains constant temperature and salinity characteristics, (just below 10°C, 34.75‰) and its offshore origins can be seen on the salinity section of the Cape Columbine transect (Fig. 13B). The diagram shows the 34.75‰ isohaline and the inshore body of mixed water sitting on the shelf. At each station on the transect, the 34.75‰ isohaline coincides with the BML's characteristic temperature value and thus its offshore origins can be identified. A band of water can be seen to follow a predestined upwelling path onto the inner shelf.

The homogeneous nature of St. Helena Bay water is thought to result from internal waves impinging on the coast along the band of upwelling water and "shaking out" as mixing cells after crossing the Cape Canyon. Homogeneity is then further maintained by bottom friction induced by tidal currents and inertial oscillations.

The patterns and intensity of water movement in St. Helena Bay were found to be at variance with some of the previous work conducted in the area. Currents have been reported as sluggish by Bailey and Chapman (1984). The pattern of water movement in the Bay can be seen in Fig. 5B. This shows an anticyclonic rotation and is contrary to the cyclonic cell reported by Duncan and Nell (1969) and Holden (1984). The

anti-clockwise movement of the water ( $180^{\circ}$  in the BML) over a period of about 12 hours does however lend support to the contention that a strong inertial component dominates water movements in this area. In addition to the anti-clockwise rotation the surface current direction is opposite to that of the wind at Stations 1 and 2. Holden (Pers. Comm.) states that in the St. Helena Bay area, inertial currents (with a time scale of 24 hours), together with tidal effects (semi-diurnal time scale), and a 5-6 day synoptic variability are the main factors influencing water movement. The possibility of underlying trends within the 25 day residence time of water in St. Helena Bay, and the movement of water between St. Helena Bay and Cape Columbine have been discussed earlier.

Vertical mixing is necessary as a post upwelling event to supply the photic zone with a fresh influx of nutrients and thus sustain productivity. The high degree of negative correlation between Chlorophyll<sub>a</sub> and each of the three nutrients indicates that nutrients are depleted where Chlorophyll<sub>a</sub> is the most abundant. This is the expected picture. If one takes a more penetrating look at the data, however, a more complete idea emerges. The highest values for Chlorophyll<sub>a</sub> were found at Stations 2 and 3 reaching a peak of  $37.8 \mu\text{g l}^{-1}$  at Station 2A. Each of the nutrient sampling stations at Station 1 showed lower levels, indicating lower primary productivity. The high mid-water

levels of nitrate, silicate and phosphate (Fig. 9) mean that there is a fresh supply of nutrient-rich water available to the surface layer. Klein and Coste (1984) state that strong nutrient entrainment periods are associated with strong current shear and strong temperature and nitrate gradients at the mixed layer base within the thermocline. The difference in the present study is that the mixed layer underlies the thermocline, but the analogous conditions regarding nutrients and current shear are readily apparent.

The study undertaken in Chapter 4 (vi) shows that both turbulent and diffusive vertical mixing processes occur in St. Helena Bay. The Richardson Number analysis indicated a dominance of turbulence at Stations 2 and 3. The evidence for Station 1 showed non-turbulent conditions to persist. This evidence for turbulent mixing across the interface between the Inshore Bottom Mixed Water and the SWSL corroborates the higher levels of Chlorophyll<sub>a</sub> found at Stations 2 and 3 compared to Station 1. An influx of nutrients due to vertical mixing would provide the impetus for fresh primary production. Table 2 actually shows unexpectedly high levels of nutrients lying in water above the BML and at the base of the SWSL. Mixing due to internal waves is predicted at Richardson Number  $\leq 0.25$  (Krauss, 1981) which is the case at Stations 2 and 3. Indirect evidence for the presence of internal waves can be seen in

Fig. 6A where the 10°C isotherm is out of phase with the 2ml<sup>-1</sup> oxygen isoline in spite of the fact that they are associated. Pingree et al (1979) attribute such an occurrence to the passage of internal waves causing a vertical displacement. The temperature and oxygen data are asynoptic to the extent of a few minutes and in this event a vertical displacement of water would be possible due to the passage of an internal wave.

The method used to quantify diffusive mixing was found to be easy to apply and yielded coherent results. Evidence was found for both weak and strong salt-fingering (Fig. 19A) which generally occurred at the base and top of the thermocline, where 'bumps' of lower salinity water can be observed. The Richardson number calculated for Station 1 indicated a suppression of turbulence by buoyancy forces, it was therefore gratifying to observe diffusive processes occurring as an alternative method of vertical mixing in the absence of turbulence. The surface Chlorophyll<sub>a</sub> values were less at Station 1 than at Stations 2 and 3 indicating the lower nutrient fluxes associated with diffusive mixing. The turbulent conditions at Station 2 and 3 lead to a more complex thermohaline microstructure and the appearance of unstable layers. Since conditions at Station 1 were relatively tranquil, it was possible to isolate, between stations, levels in the water column having the same  $\sigma_t$

values, and subsequently to establish a developmental association between salt-fingering layers at adjacent stations (Fig. 20). This type of approach permitted the monitoring of changes in fingering layers with time and upheld the contention that weak fingering develops into strong fingering layers which then leads to instability. The conditions at Stations 2 and 3 were not suitable for this type of study owing to the high turbulence.

With regard to the origins and mode of formation of oxygen-depleted water in St. Helena Bay, it has been shown to be nutrient-enriched compared to water of the same salinity offshore. This indicates that nutrient regeneration and hence oxygen depletion are enhanced on the inner shelf.

The analysis performed on the bottom water in St. Helena Bay, showed, from the ratio of occurrence, the relative abundance of the various nutrients in the oxygen-depleted water and the information regarding regeneration rates, gained from the slope of the regression lines, helped to complete the picture. The ratio of occurrence obtained for both  $\text{NO}_3 : \text{PO}_4$  and  $\text{SiO}_3 : \text{PO}_4$  showed  $\text{PO}_4$  to be the most abundant nutrient in the oxygen depleted water. Furthermore,  $\text{PO}_4$  was found to be regenerated faster than  $\text{NO}_3$  but at approximately the same rate as  $\text{SiO}_3$ . The abundance of  $\text{PO}_4$  in the water together with its enhanced regeneration over  $\text{NO}_3$  point towards a recent and therefore

local mechanism for oxygen depletion. (It has already been stated that according to Grill and Richards (1964),  $PO_4$  is released initially). In the case of  $SiO_3 : PO_4$ , which showed equivalent rates of regeneration, this can be explained by the enhanced liberation of  $SiO_3$  in oxygen depleted water (Mortimer, 1971) offsetting the rate of  $PO_4$  liberation.

The  $NO_3 : SiO_3$  ratio of occurrence showed  $SiO_3$  to be in higher relative concentrations, and the slope of regression indicated  $SiO_3$  to be liberated faster than  $NO_3$ . This apparent anomaly which suggests a remote origin for the water body is again thought to result from enhanced  $SiO_3$  regeneration in oxygen-depleted water. Note that the regression analysis from the Cape Columbine transect (Fig. 16C) showed  $SiO_3$  to be regenerated more slowly than in the bottom water of St. Helena Bay. Further work by Grasshoff (1975) found that silica resorption is enhanced in anoxic areas owing to the liberation of Fe ions. These Fe ions along with Al stabilize the coating of organic matter which protects the biogenic silica when conditions are oxic (Lewin, 1961).

The balance of evidence presented here supports local nutrient regeneration and hence locally induced oxygen depletion. Chapman (1983) calculated that it would take between 17 and 23 days for decomposition following local

primary production to deplete the water below the thermocline of oxygen. The residence time of 25 days calculated for a particle of water in St. Helena Bay together with the established pathway for its origin provides the appropriate setting for these processes to occur. Chapman and Shannon (1985) present a comprehensive picture of the formation and advection of low oxygen water in the Benguela system as a whole in their review of its chemistry and related processes. The results presented here agree closely with their conclusions of a locally and biochemically produced body of oxygen-deficient water over the inner continental shelf.

The study into relationships between nutrients in the surface waters of St. Helena Bay and off Cape Columbine yielded interesting results and provided an insight into the utilization and limitation of nutrients in the Southern Benguela. Nitrate was found to be the limiting nutrient, although the evidence for this conclusion was not so clear cut in Cape Columbine surface waters.  $PO_4$  was always found to be the least limiting nutrient. Nitrate limitation agrees with previous studies by Andrews and Hutchings (1980), Barlow (1980), and Bailey and Chapman (1984).  $SiO_3$  has only been found to be limiting in the Northern Benguela System by Bailey (1979) and Boyd (1983).

The utilization of nutrients in the surface water by

phytoplankton was seen to differ between Cape Columbine waters and those in St. Helena Bay. Off Cape Columbine,  $\text{SiO}_3$  was utilized to a greater extent than  $\text{NO}_3$ , with  $\text{PO}_4$  uptake being the lowest. In St. Helena Bay, the utilization of  $\text{SiO}_3$  and  $\text{NO}_3$  was in constant atomic proportions of approximately 1 : 1.  $\text{PO}_4$  remained the least utilized nutrient.

Since diatoms require  $\text{SiO}_3$  and dinoflagellates have no such requirement, Chapman and Shannon (1985), discussed the effect of changes in the relative numbers of diatoms and dinoflagellates on nutrient limitation. They contend that the configuration of the phytoplankton population could affect the relative  $\text{NO}_3$  :  $\text{SiO}_3$  balance and determine which should be limiting. The present study adds the extra dimension of nutrient utilization in addition to nutrient limitation, and therefore provides a supplementary method for forecasting which group of phytoplankton will dominate. Although  $\text{NO}_3$  was found to be limiting in both St. Helena Bay and off Cape Columbine,  $\text{SiO}_3$  uptake was found to exceed that of  $\text{NO}_3$  in the latter area. This points to a dominance of diatoms in the water. Nutrient uptake in St. Helena Bay showed  $\text{SiO}_3$  and  $\text{NO}_3$  being utilized in equivalent proportions and thus allows for the existence of a mixed phytoplankton population.

In the present study, nutrient regeneration, utilization



and limitation have been interpreted on the basis of comparing nutrient ratios with predicted open oceanic ratios found by Redfield et al (1963), i.e.  $\text{NO}_3(\text{N}) : \text{SiO}_3(\text{Si}) : \text{PO}_4(\text{P}) = 16 : 16 : 1$  respectively. Complications, however, may arise when making open oceanic assumptions within a major upwelling system such as the Southern Benguela.

It has been shown that the source water for the inshore region at the Cape Columbine upwelling site is South Atlantic Central Water. This water is modified by nutrient utilization and sun-warming in the photic zone, to form Maturing Upwelled Water, and by nutrient regeneration and mixing on the inner shelf to form Inshore Bottom Mixed Water. It is therefore suggested that in order to obtain the complete picture regarding utilization, a comparison should be made between Maturing Upwelled Water and South Atlantic Central Water; and regeneration, by comparing Inshore Bottom Mixed Water with South Atlantic Central Water. A necessary prerequisite for this type of approach is the characterization of the nutrient status of South Atlantic Central Water. It is then hoped that studies of a more definitive nature may take place.

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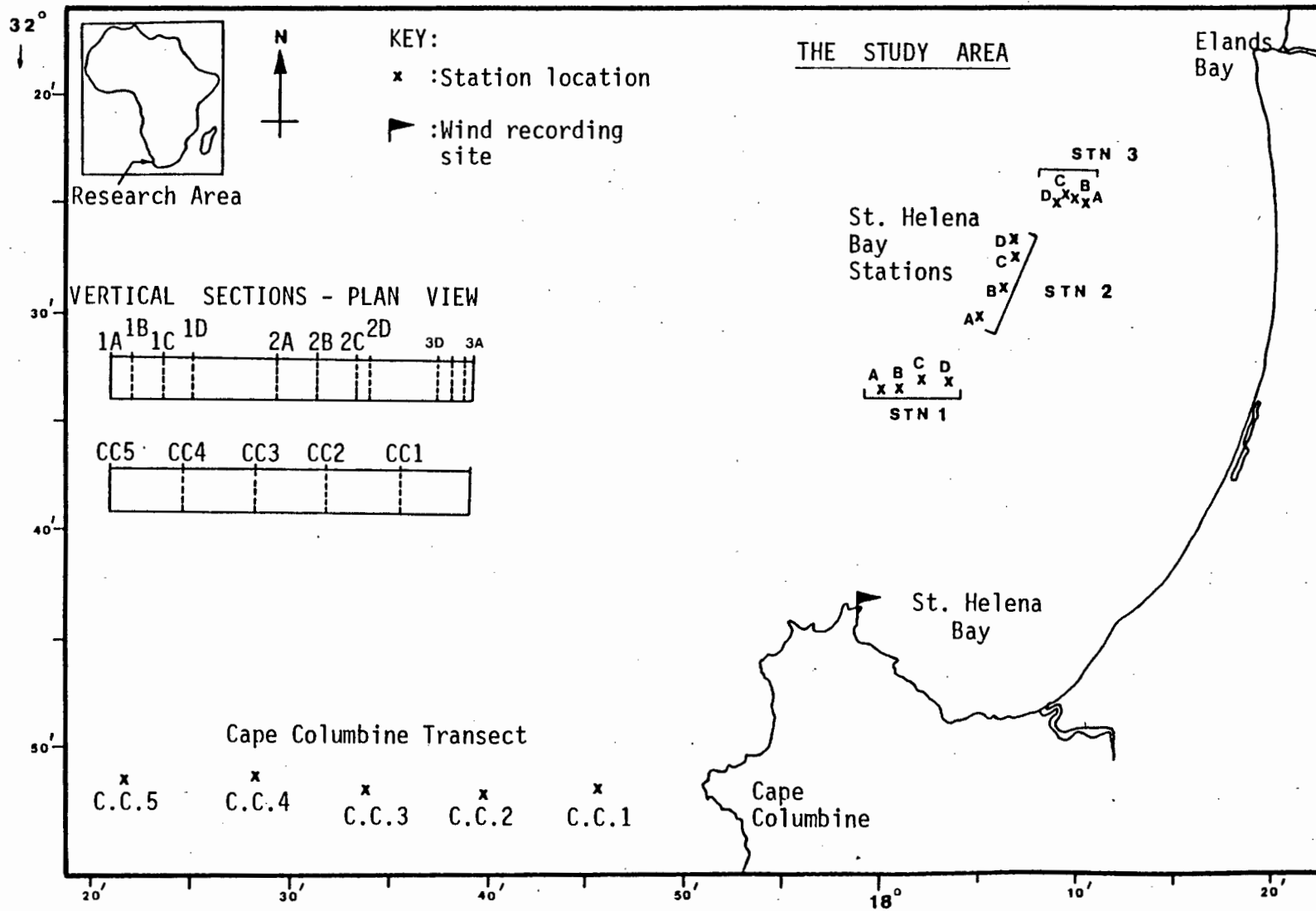
VACCARO, R.F. and J.H. RYHER, (1960) Marine phytoplankton and the distribution of nitrite in the sea. J. Cons. int. Explor. Mer, 25, 260-271.

VISSER, G.A. (1969) Investl. Rep. Divn. Sea Fish. S. Afr., 75, 1-26.

WADA, E. and A. HATTORI, (1971) Nitrite metabolism in the euphotic layer of the central North Pacific Ocean. Limnol. Oceanogr., 16, 766-772.

WOODS, J.D. and G.G. FOSBERRY, (1967) The structure of the summer thermocline. In: Underwater Association Report 1966-67 (London), pp5-18. Published by the Underwater Association, 181, Gloucester Avenue, London, N.W.10.

FIG. 1



A montage of three upwelling sites south of the Orange River (a, b and c) defined by aerial radiation thermometry

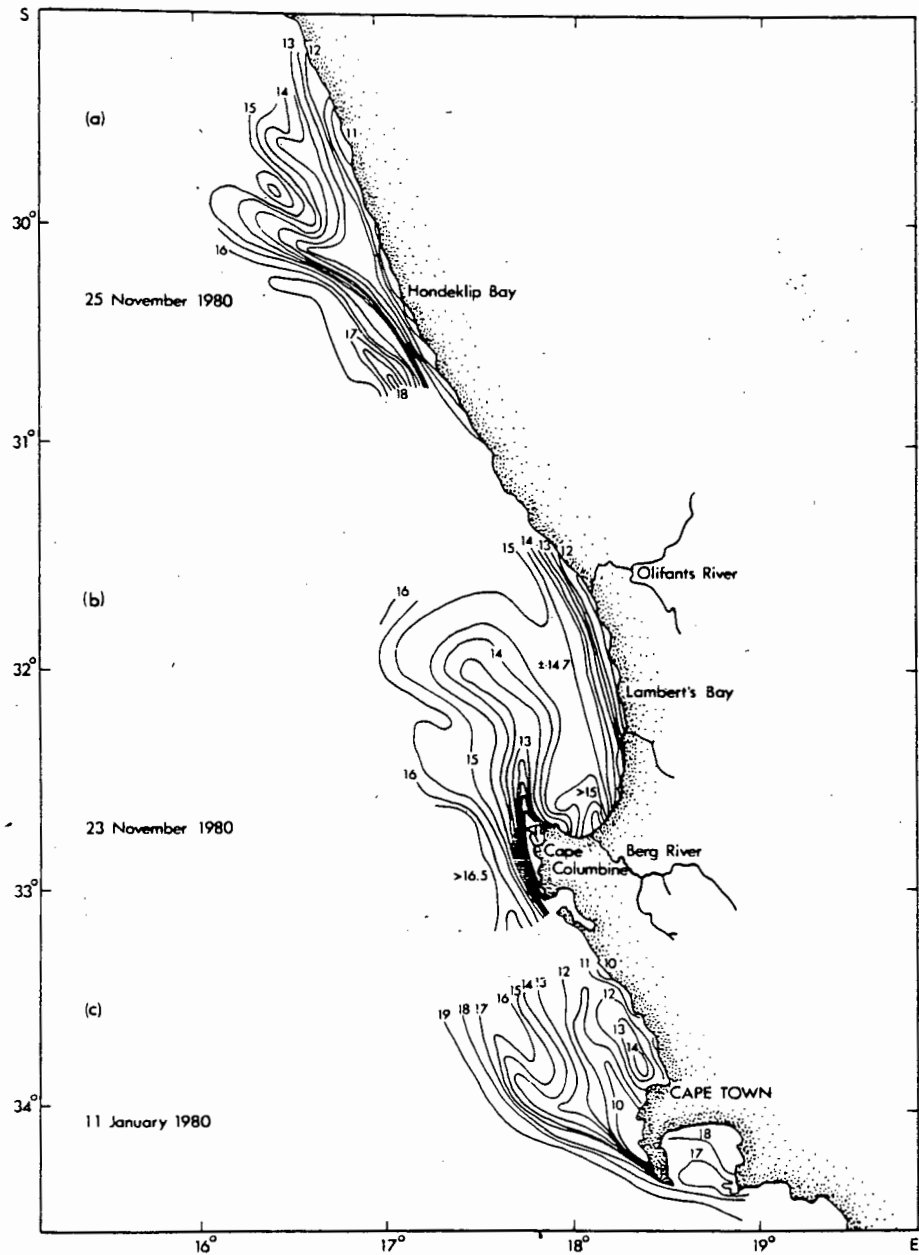


FIG. 2 From Nelson and Hutchings (1983).

The Wind Regime: Ten Days Preceding the study.  
Data from Stompneus Weather Station

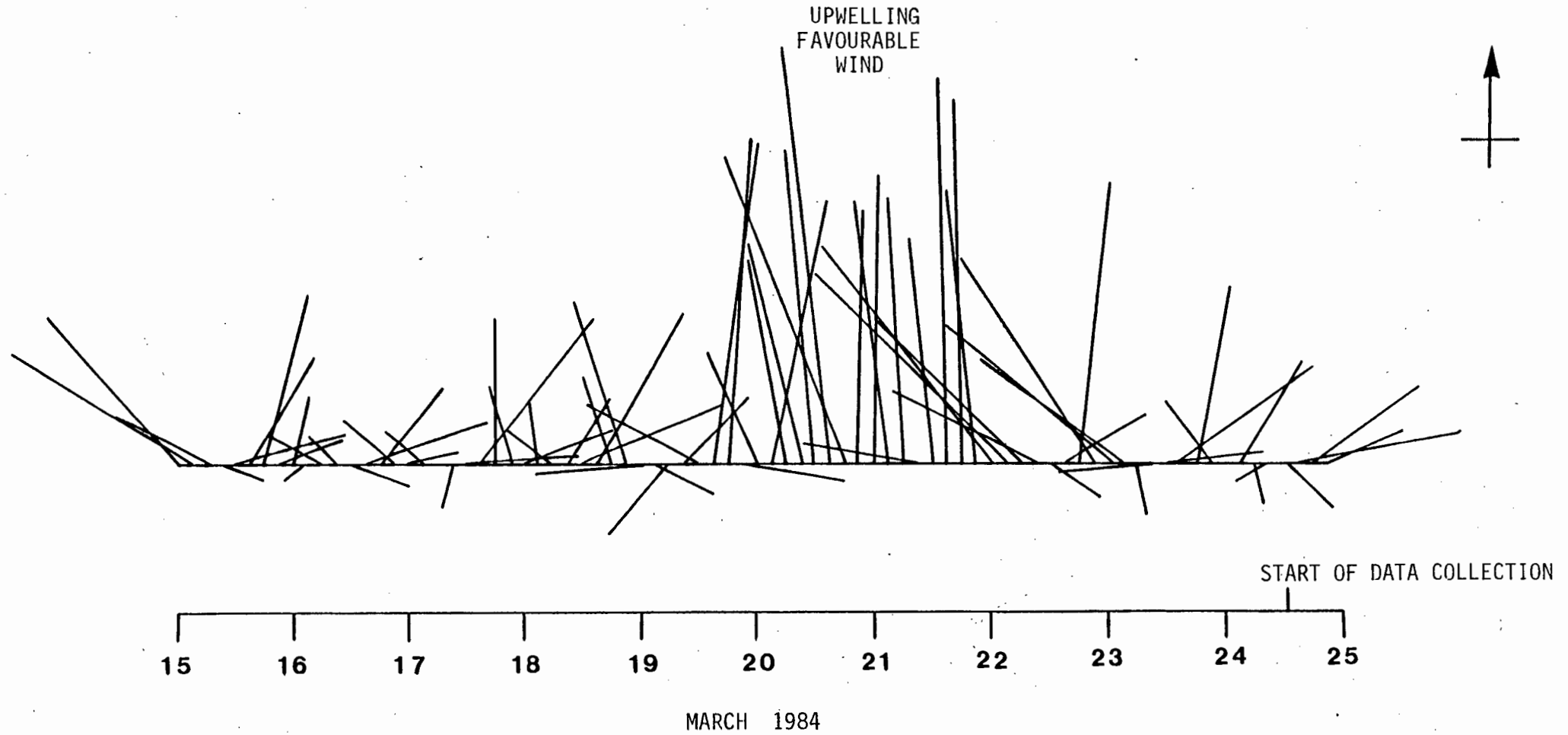


FIG. 3 Wind Vector Diagram

Scale:  $\frac{10 \text{ knots}}{5 \text{ ms}^{-1}}$

A Bottom Mixed Layer (BML) is shown below the Sun Warmed Surface Layer (SWSL)

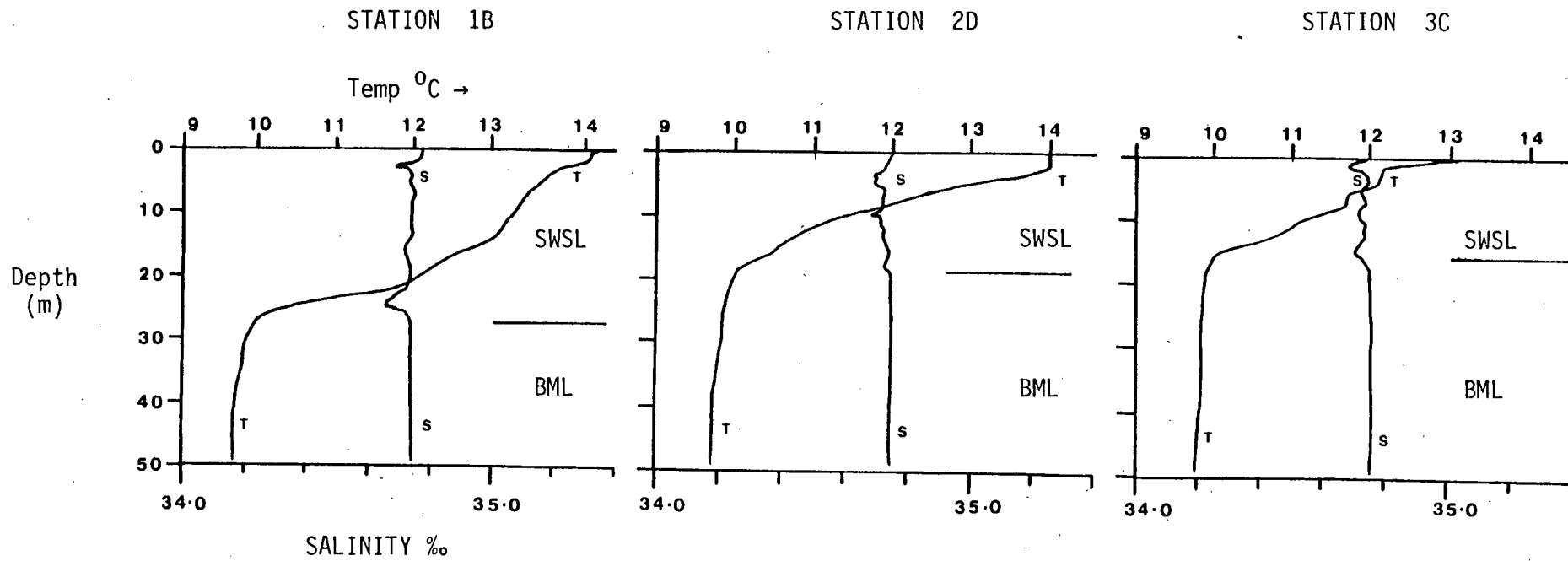
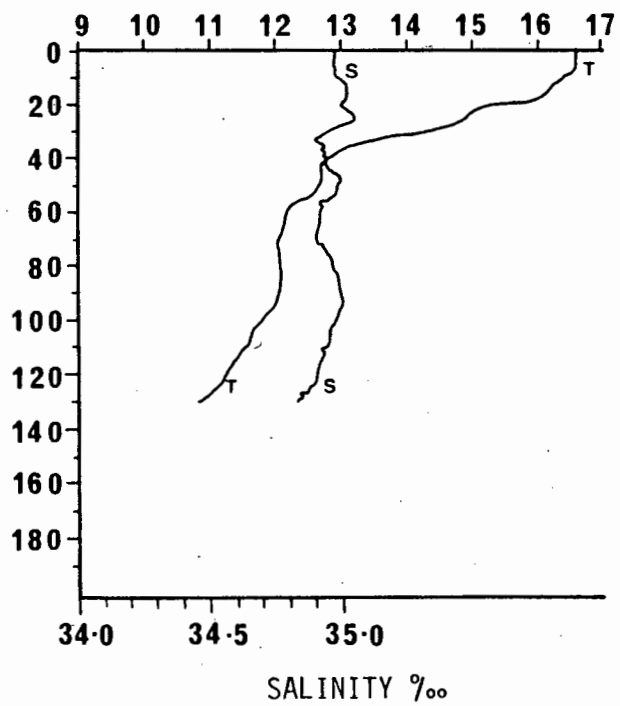


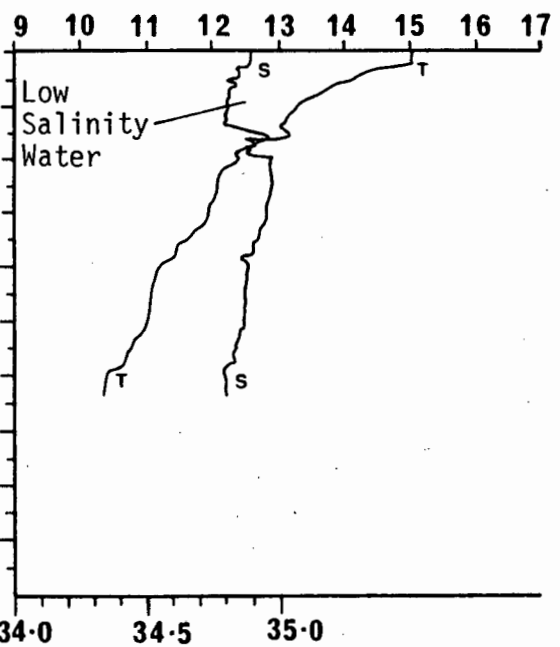
FIG. 4A Temperature and Salinity profiles - St. Helena Bay

STATION CC5

Temp °C



STATION CC3



STATION CC1

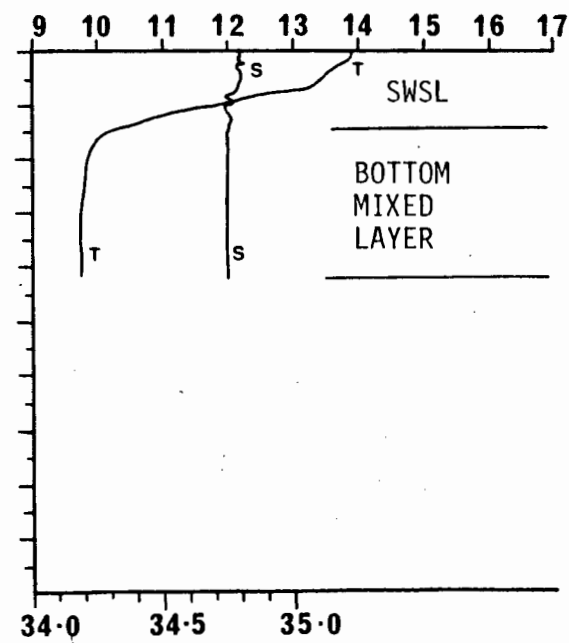


FIG. 4B Temperature and Salinity profiles: Cape Columbine Transect.



Temperature and Salinity Profiles: Cape Columbine Transect and St. Helena Bay  
 (Similar Thermohaline Str. Evident at Stns. CC1 and 1B)

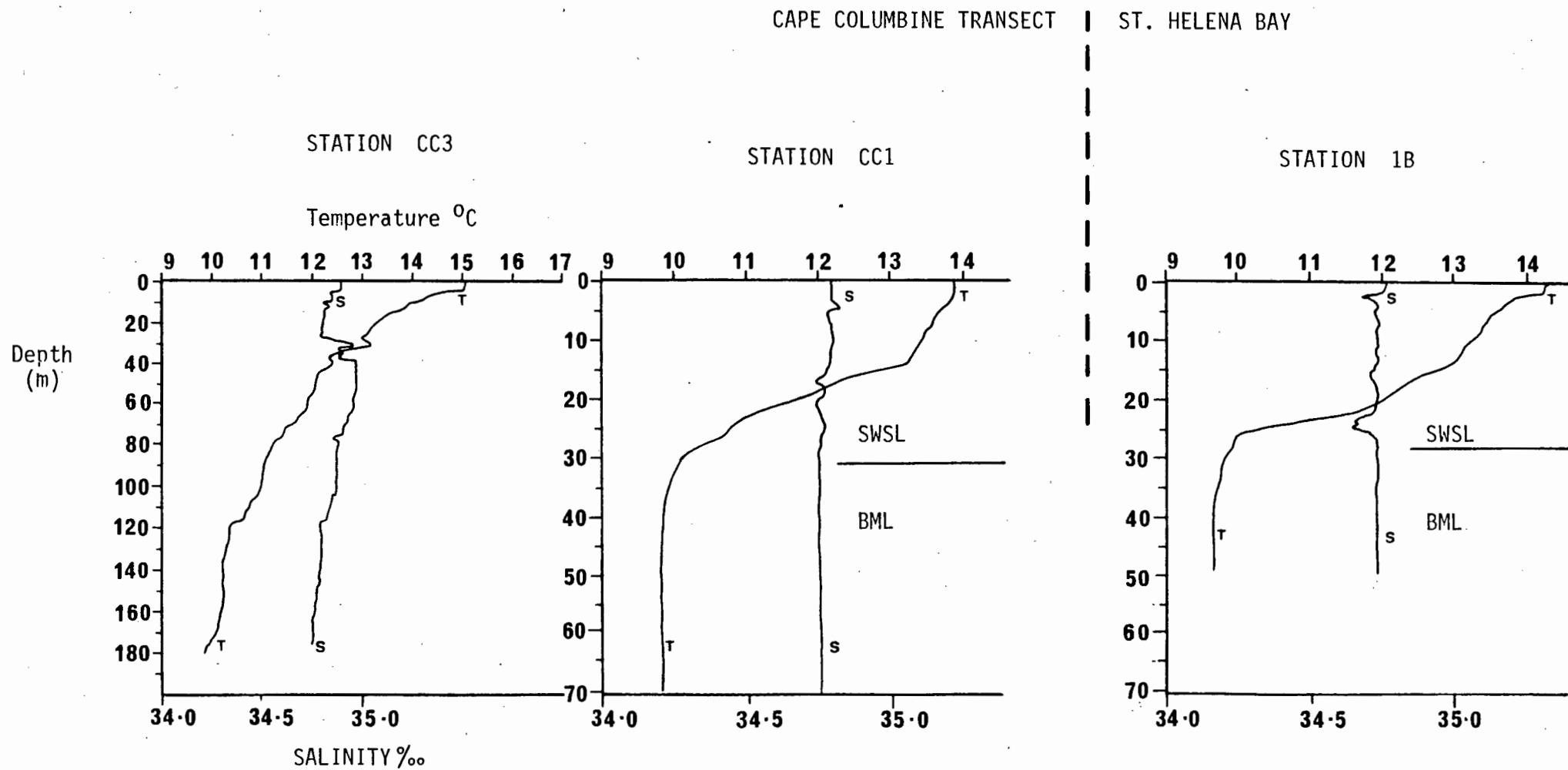
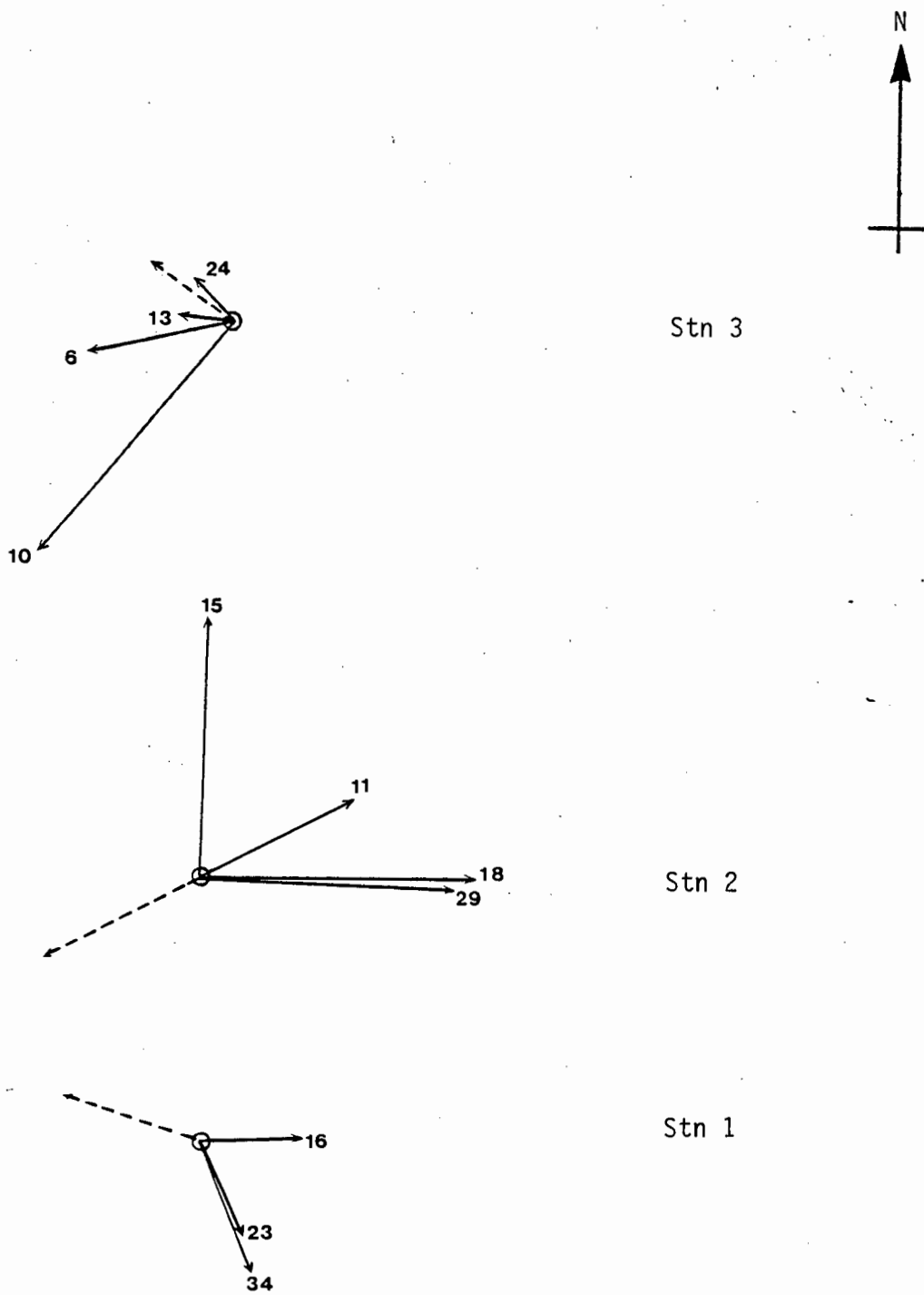


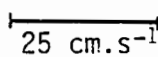
FIG. 4C

CURRENT AND WIND VELOCITIES

- St. Helena Bay



KEY:

Current vector -  25 cm.s<sup>-1</sup> (Currents at depths (m) indicated)

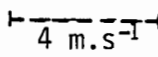
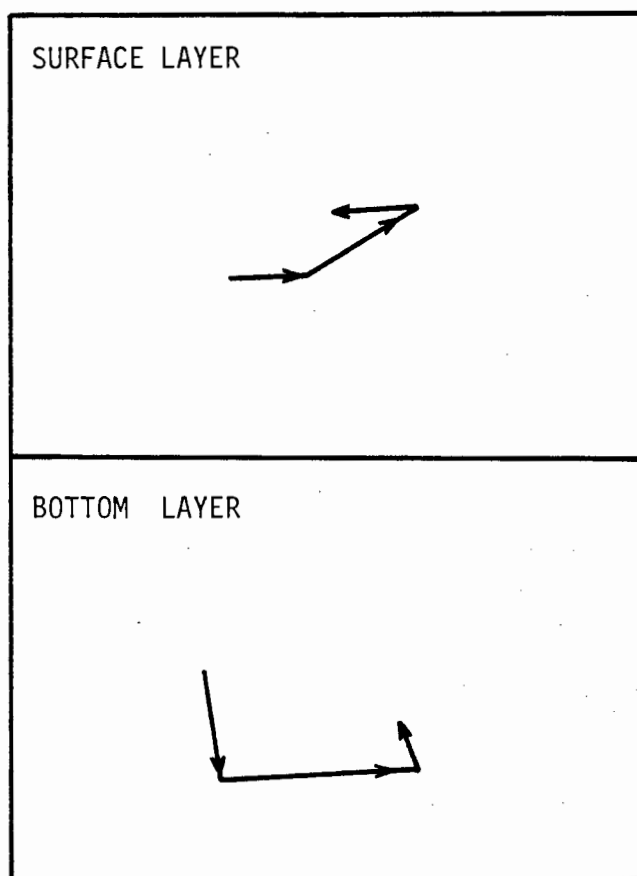
Wind vector -  4 m.s<sup>-1</sup>

FIG. 5A

PROGRESSIVE CURRENT VECTORS  
SHOWING ANTICYCLONIC ROTATION




SCALE :  25 cm.s<sup>-1</sup>

FIG. 5B

Showing the body of oxygen depleted water below the 2 ml l<sup>-1</sup> isoline and its close association with the 10°C isotherm

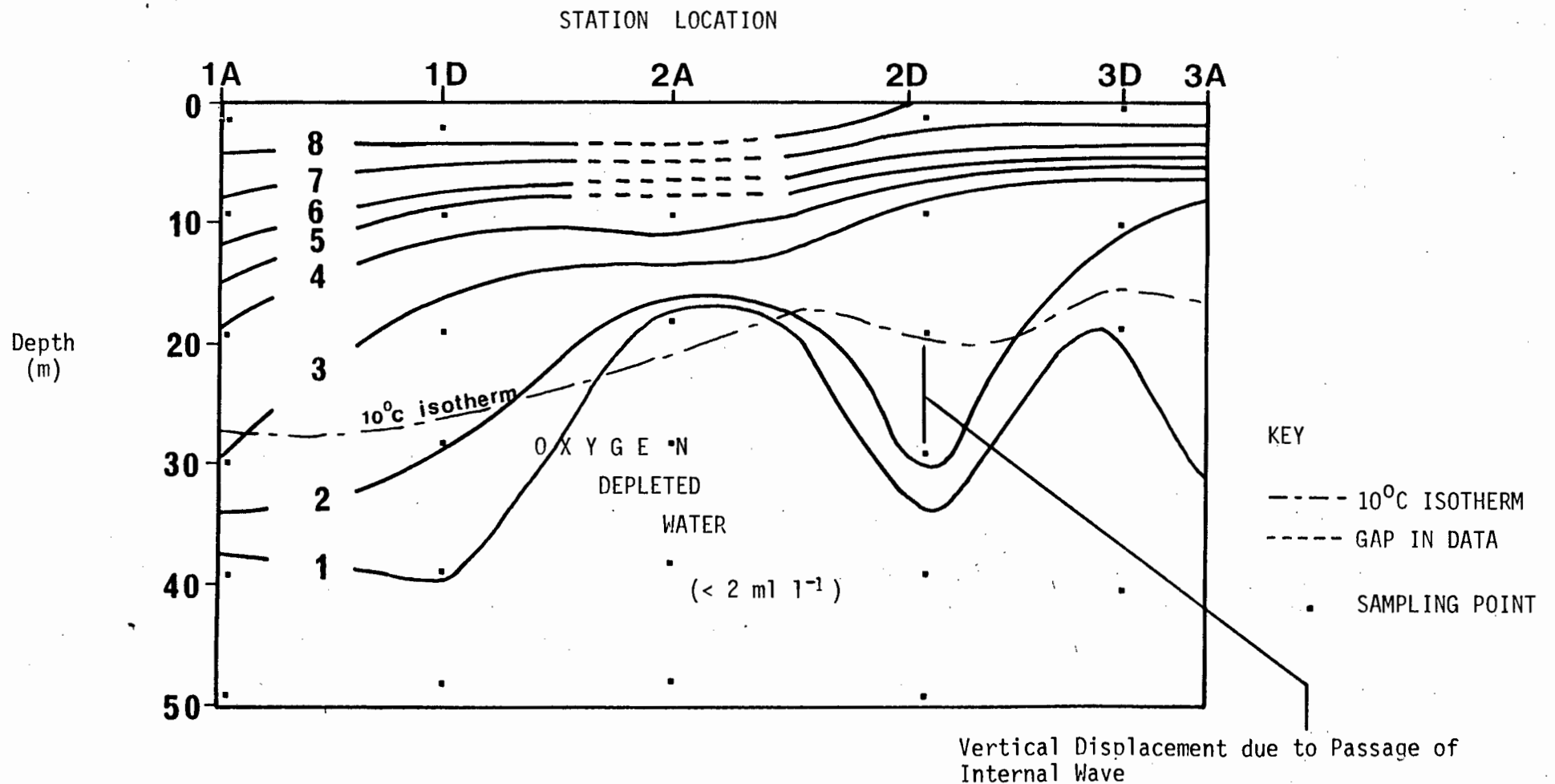


FIG. 6A Vertical Section of Oxygen in St. Helena Bay

Dissolved oxygen profiles: Cape Columbine Transect  
(Note the presence of oxygen depleted water at Station CC1).

NB CC5, CC4 and CC3 are drawn to same depth scale

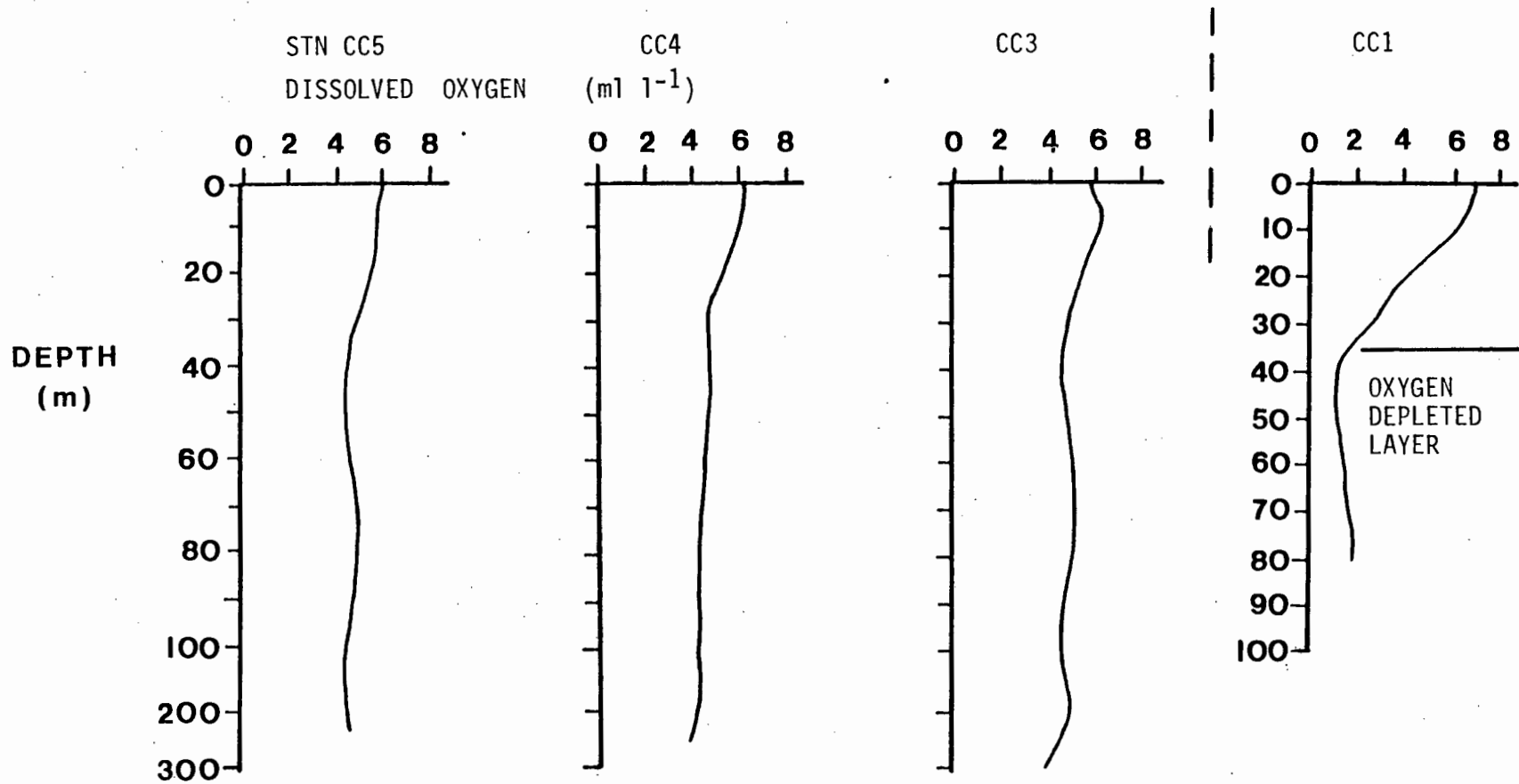


FIG. 6B

Oxygen saturation values, 0-50m, St. Helena Bay and Cape Columbine Transect

( NEARSHORE STATIONS ) ( OFFSHORE STATIONS )

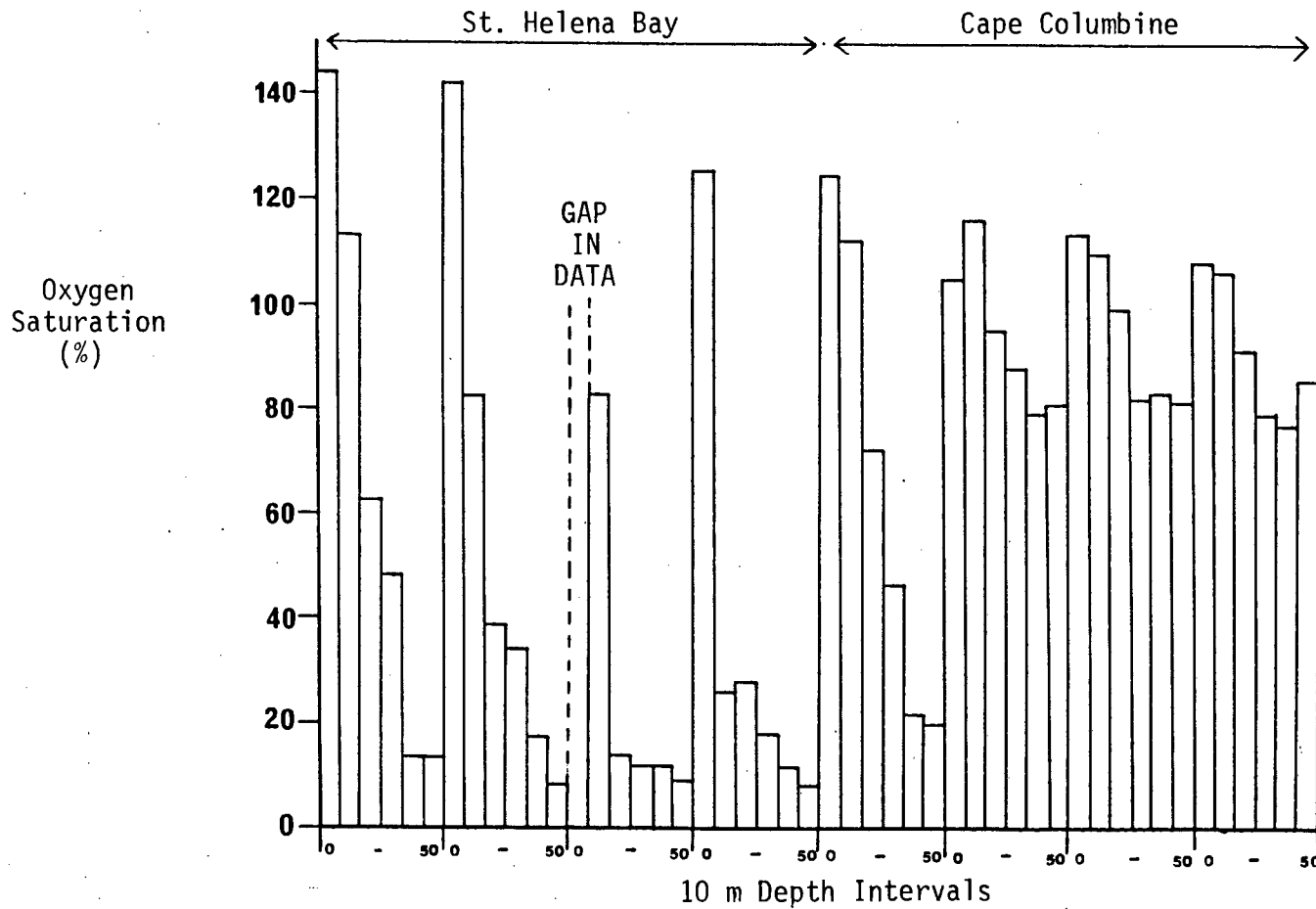


FIG. 7

Nutrient and Chlorophyll<sub>a</sub> profiles: St. Helena Bay  
( $\mu\text{g l}^{-1}$ ) ( $\mu\text{g l}^{-1}$ )

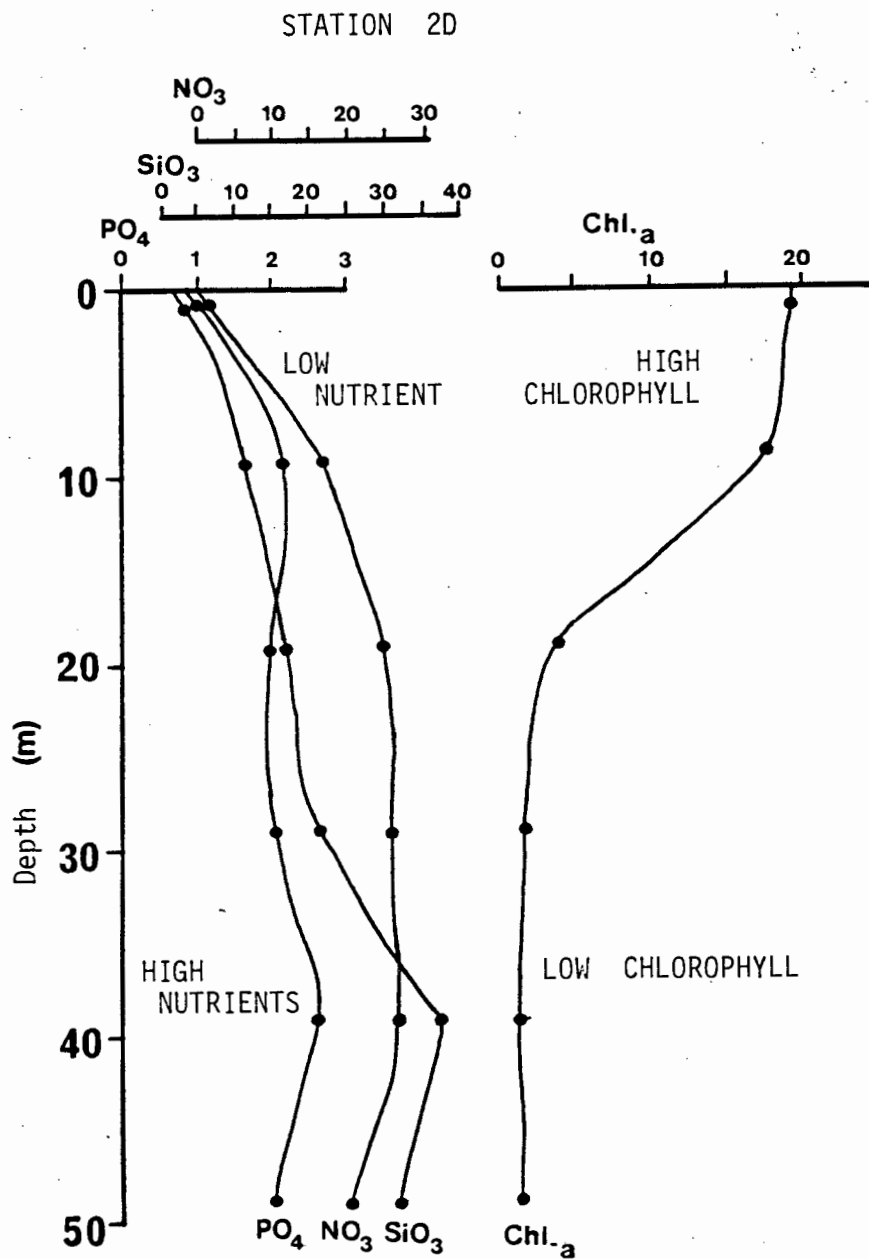
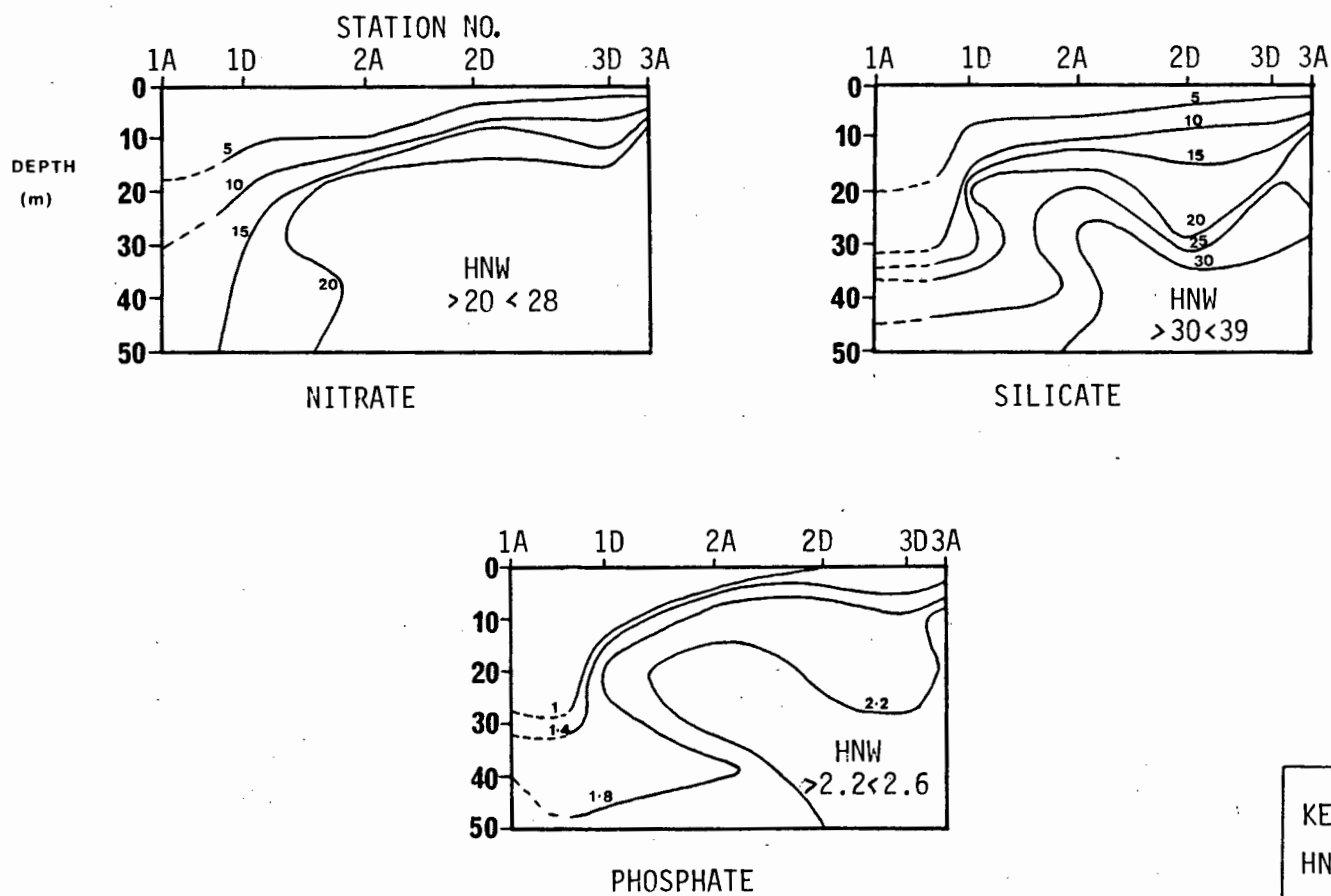


FIG. 8

Vertical Sections of Nutrients in St. Helena Bay  
 High Nutrient water is in close proximity to Surface Water



KEY:  
 HNW:- High Nutrient Water  
 Units:-  $\mu\text{g at l}^{-1}$

FIG. 9



Profiles of Nutrients and Chlorophyll<sub>a</sub>: Cape Columbine Transect  
 (μg at l<sup>-1</sup>)      (μg l<sup>-1</sup>)

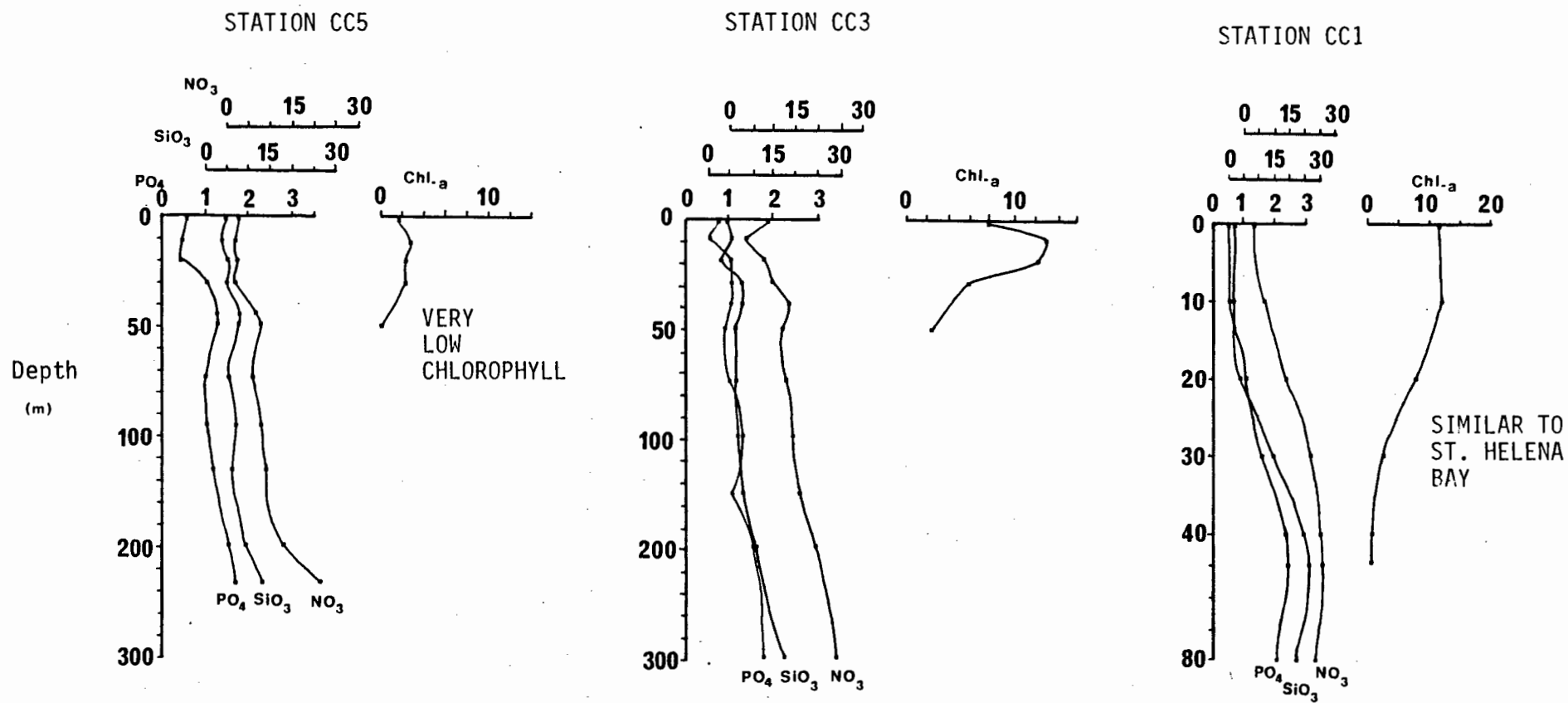


FIG. 10

Vertical Sections of Nitrate and Silicate: Cape Columbine transect.

Note the nutrient-rich waters on the inner shelf.

Nutrient units are  $\mu\text{g at l}^{-1}$

NITRATE

SILICATE

STATION NO.

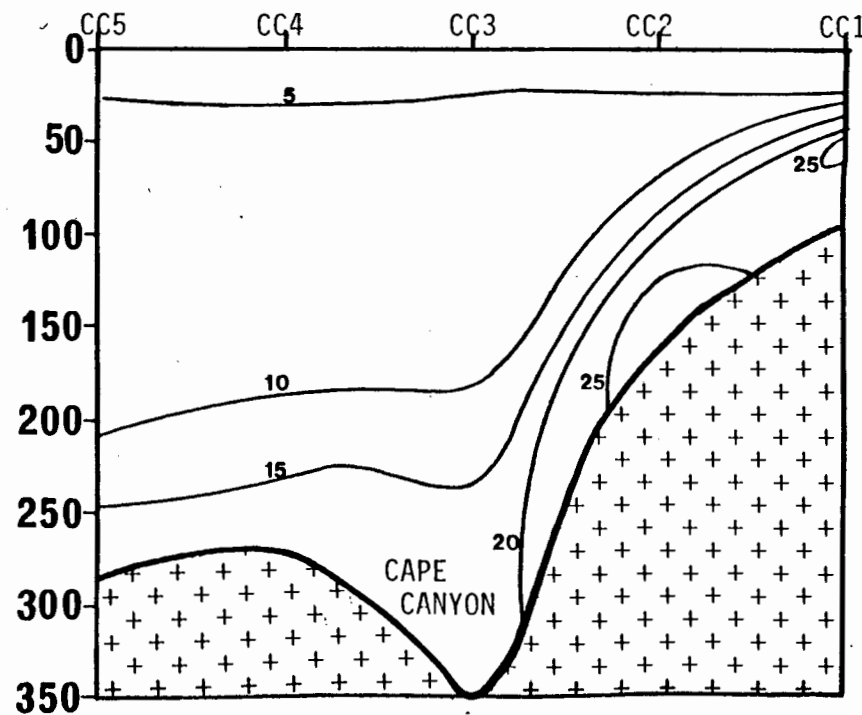
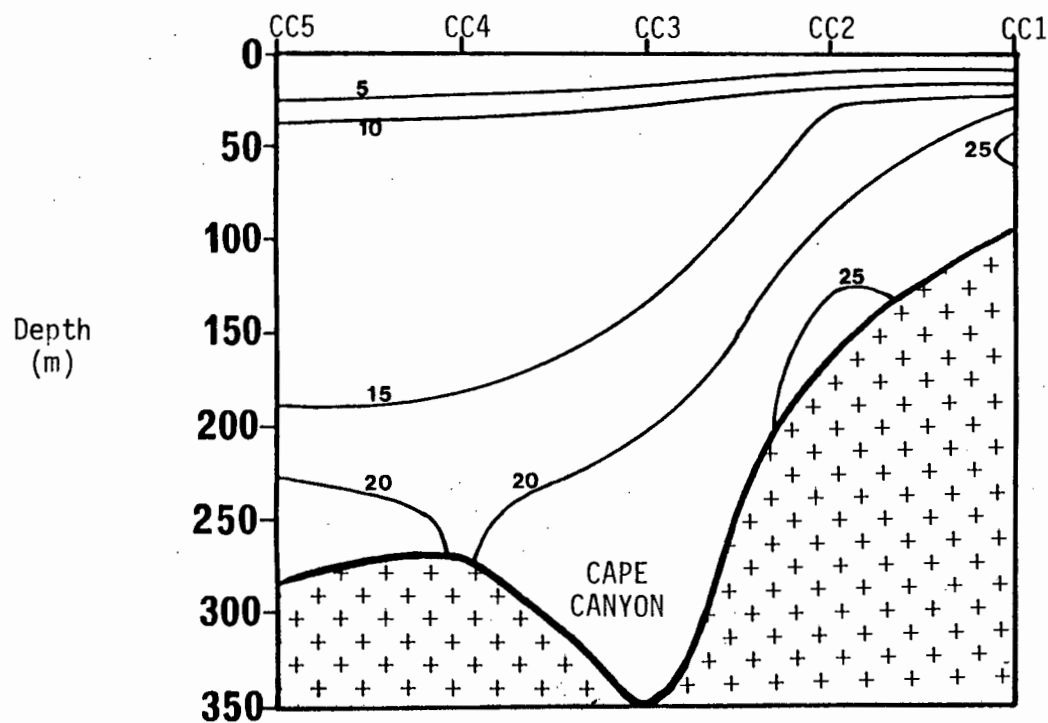


FIG. 11

Nitrite Profiles: St. Helena Bay

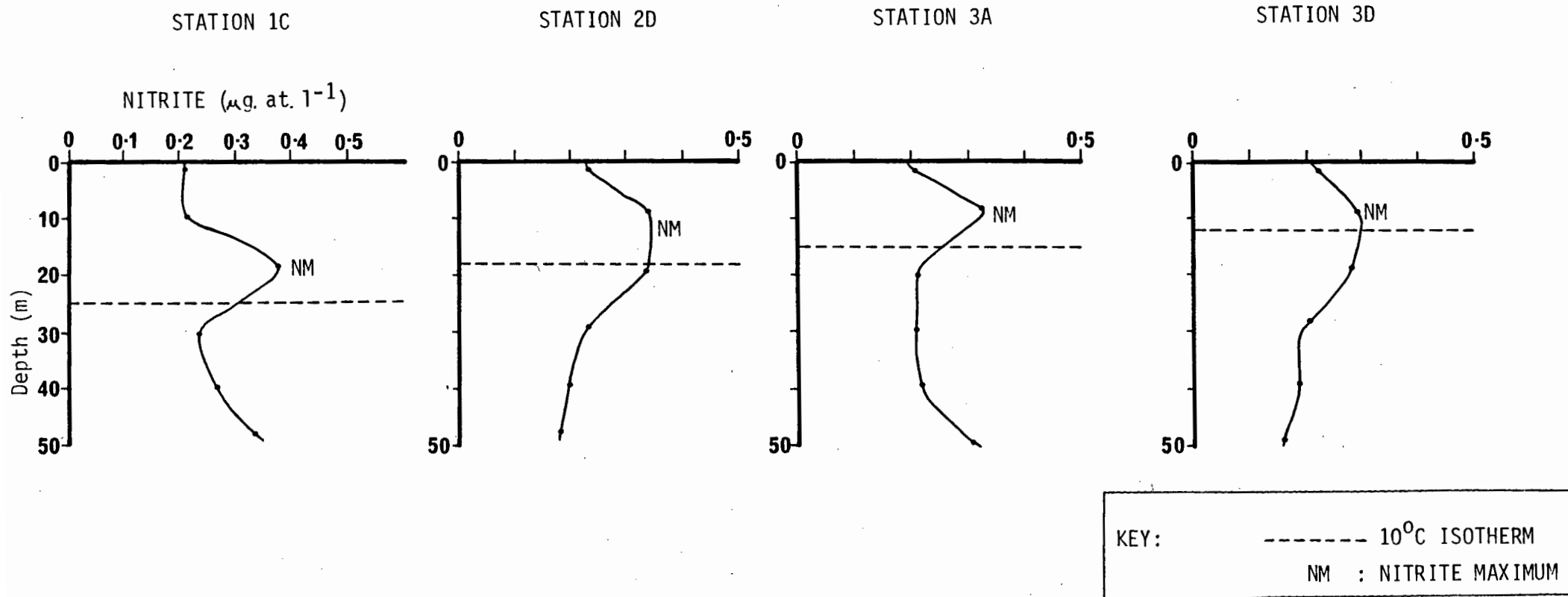


FIG. 12A

Nitrite profiles: Cape Columbine Transect

(Note the similar range of values at Station CC1 to those in St. Helena Bay (Fig. 12A))

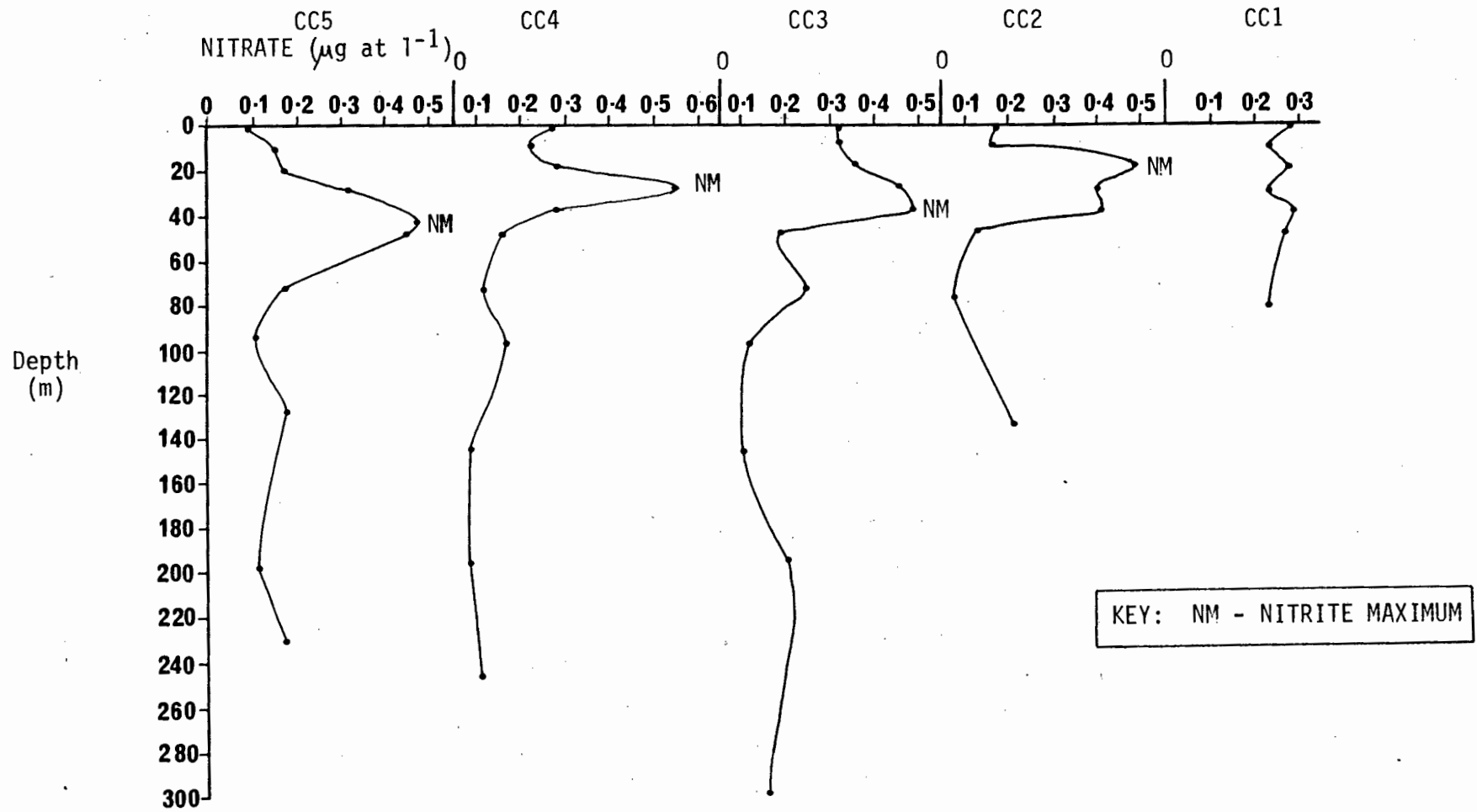


FIG. 12B

Temperature Section: Cape Columbine Transect  
shows structure during the passive phase of synoptic cycle.

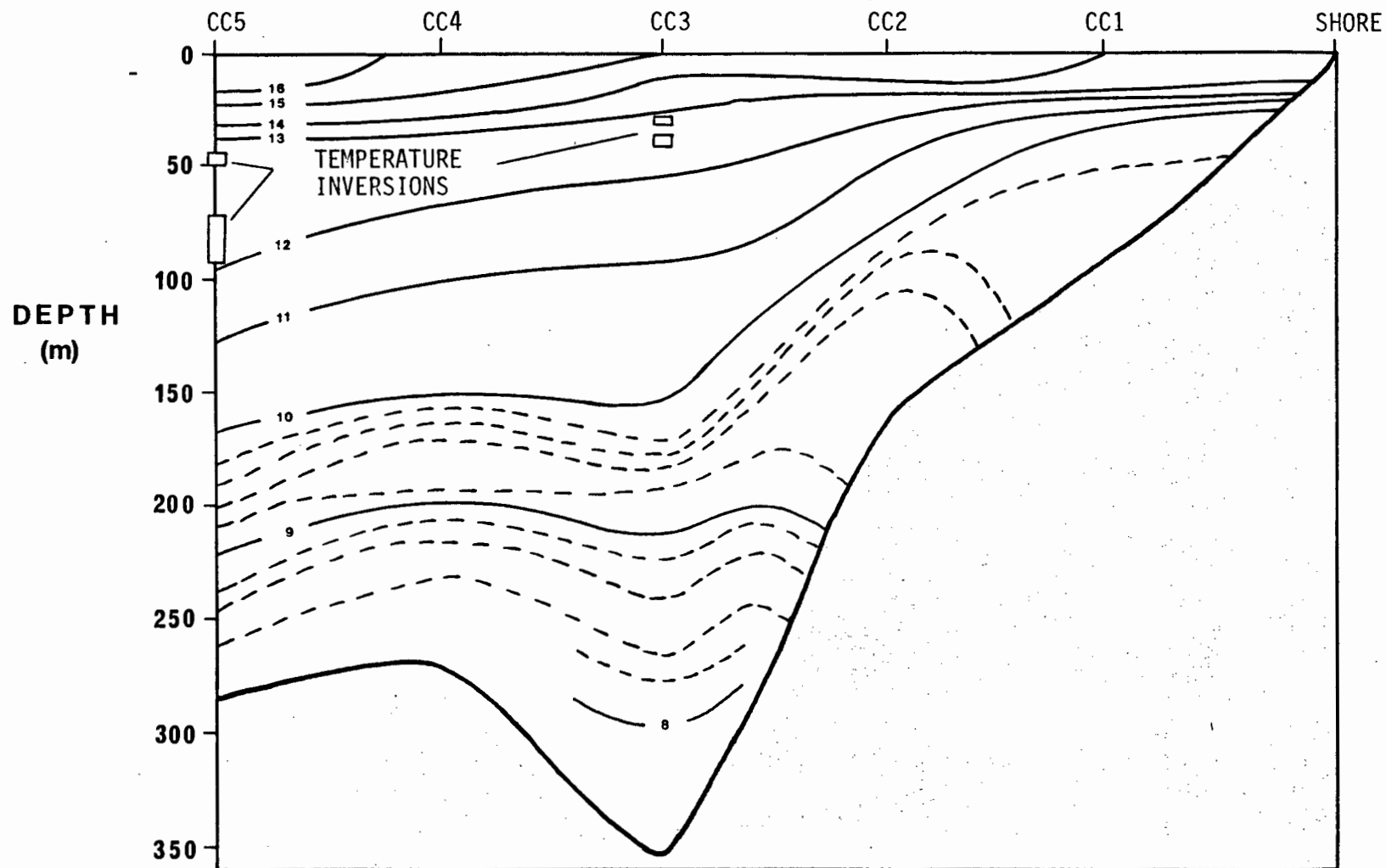


FIG. 13A

Salinity Section: Cape Columbine Transect  
Shows the offshore origins of upwelling water

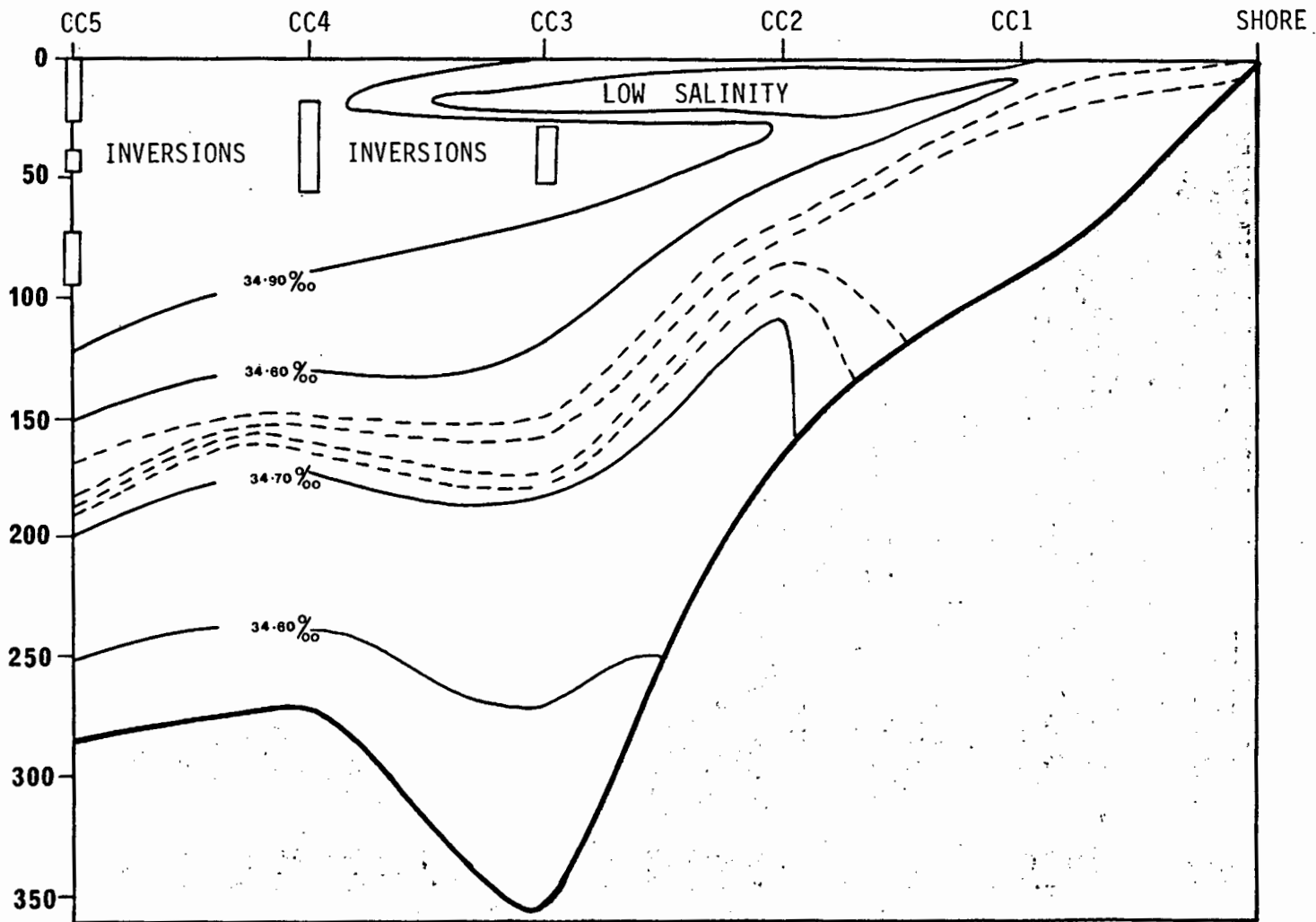


FIG. 13B

Temperature Section: St. Helena Bay

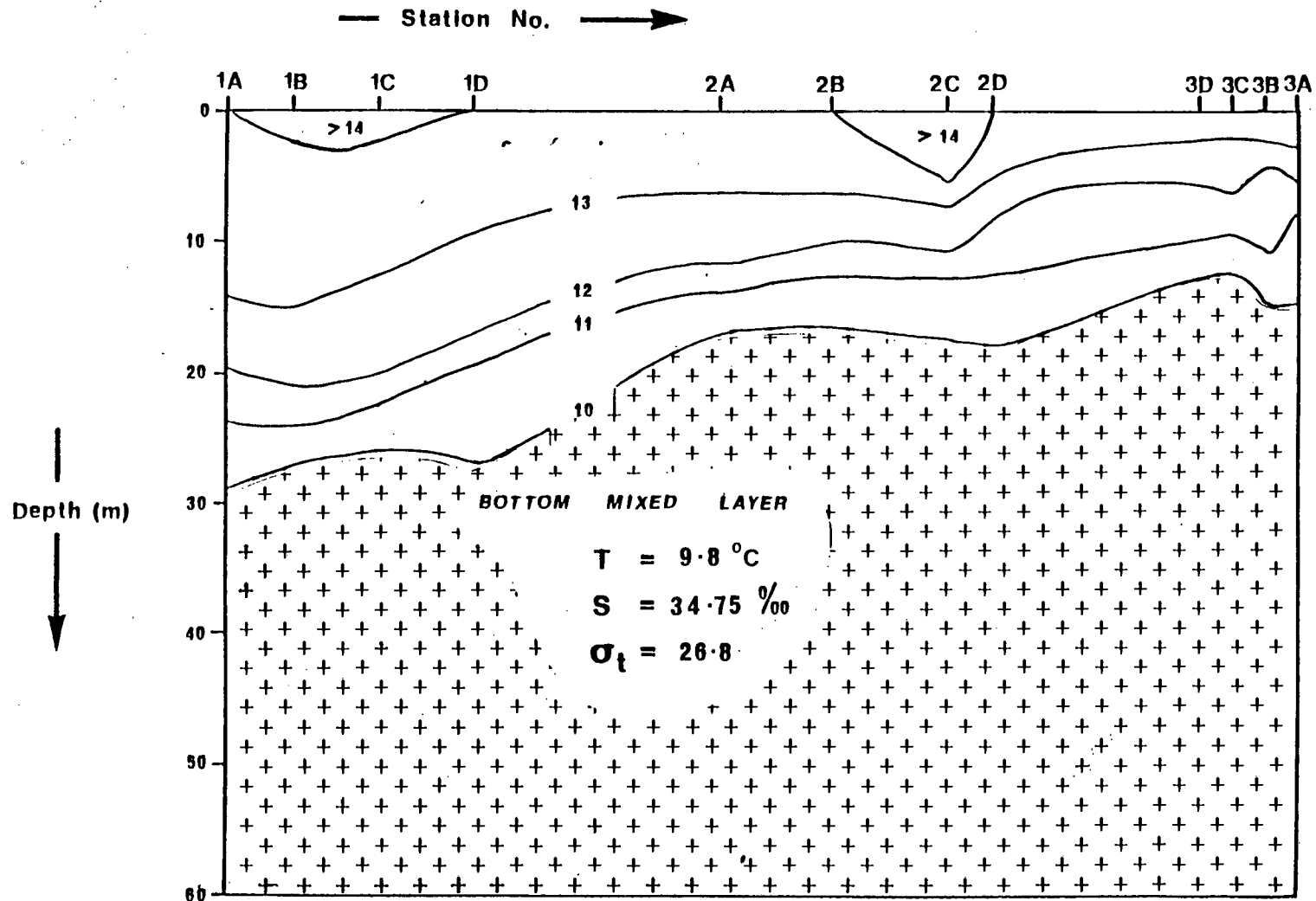


FIG. 13C

Regressions of Chlorophyll<sub>a</sub> vs Nutrients in St. Helena Bay

'Outliers' have been labelled with Station No

All outliers were found at 9 m depth

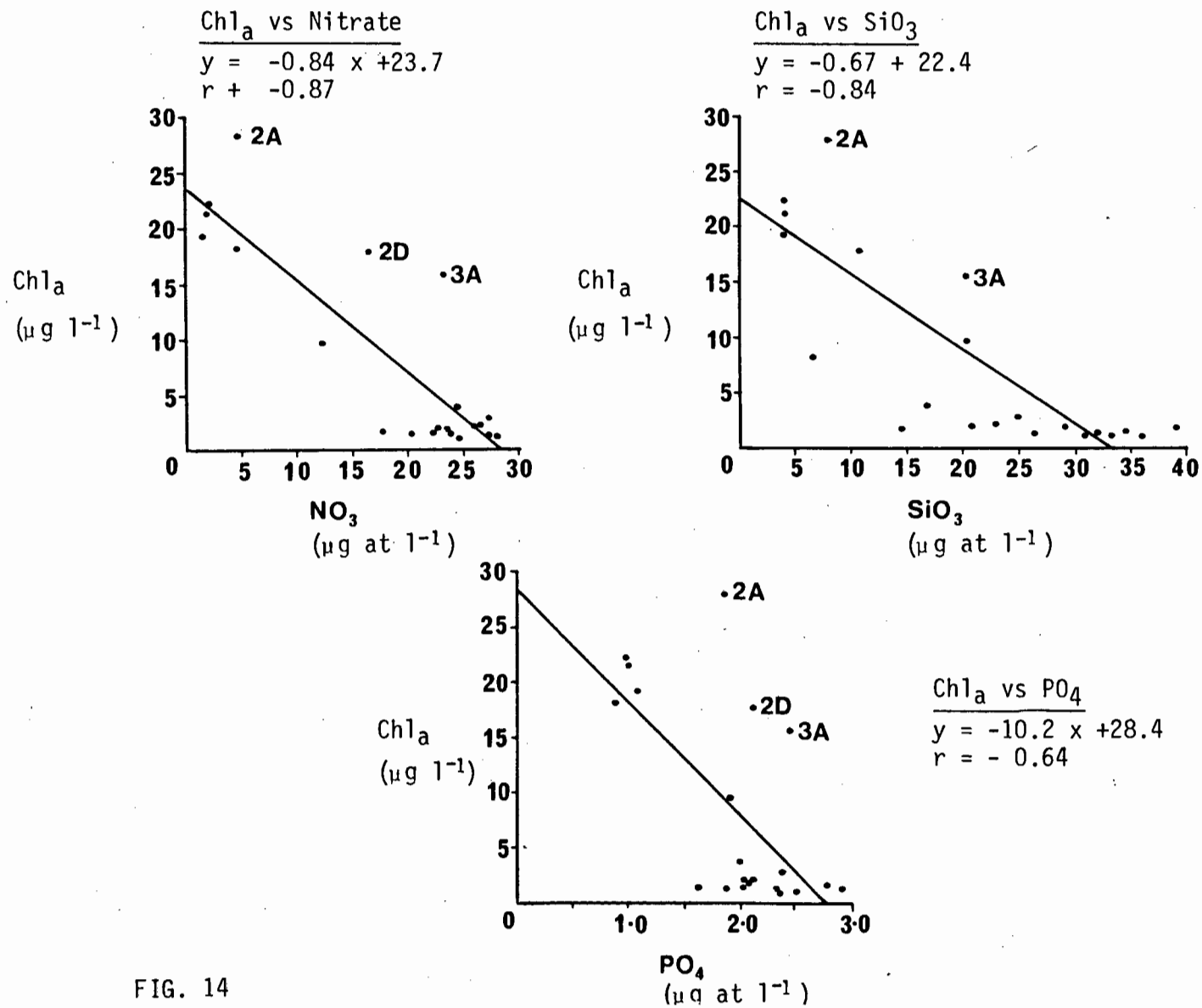


FIG. 14



Comparison of Nitrate and Nitrite profiles at two stations: St. Helena Bay and Cape Columbine Transect respectively.

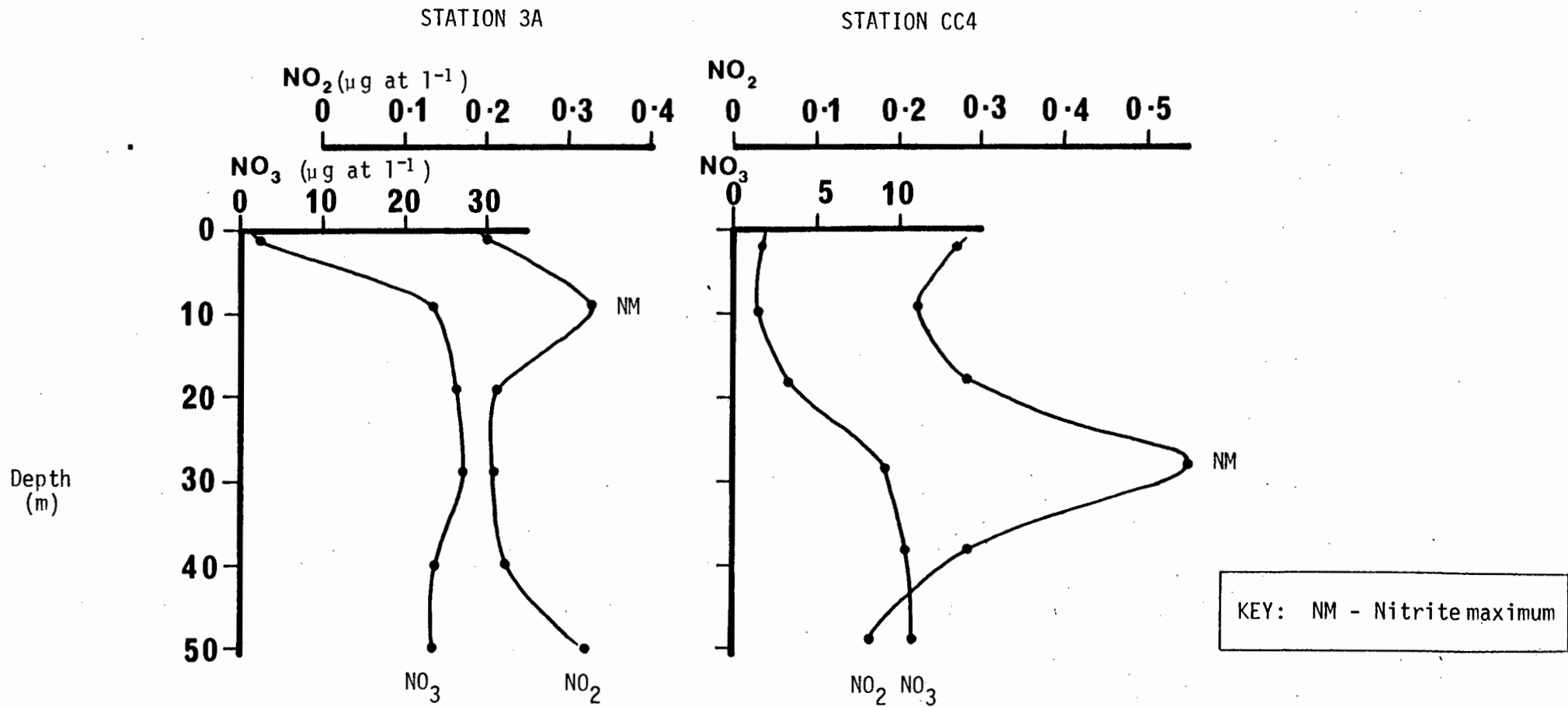
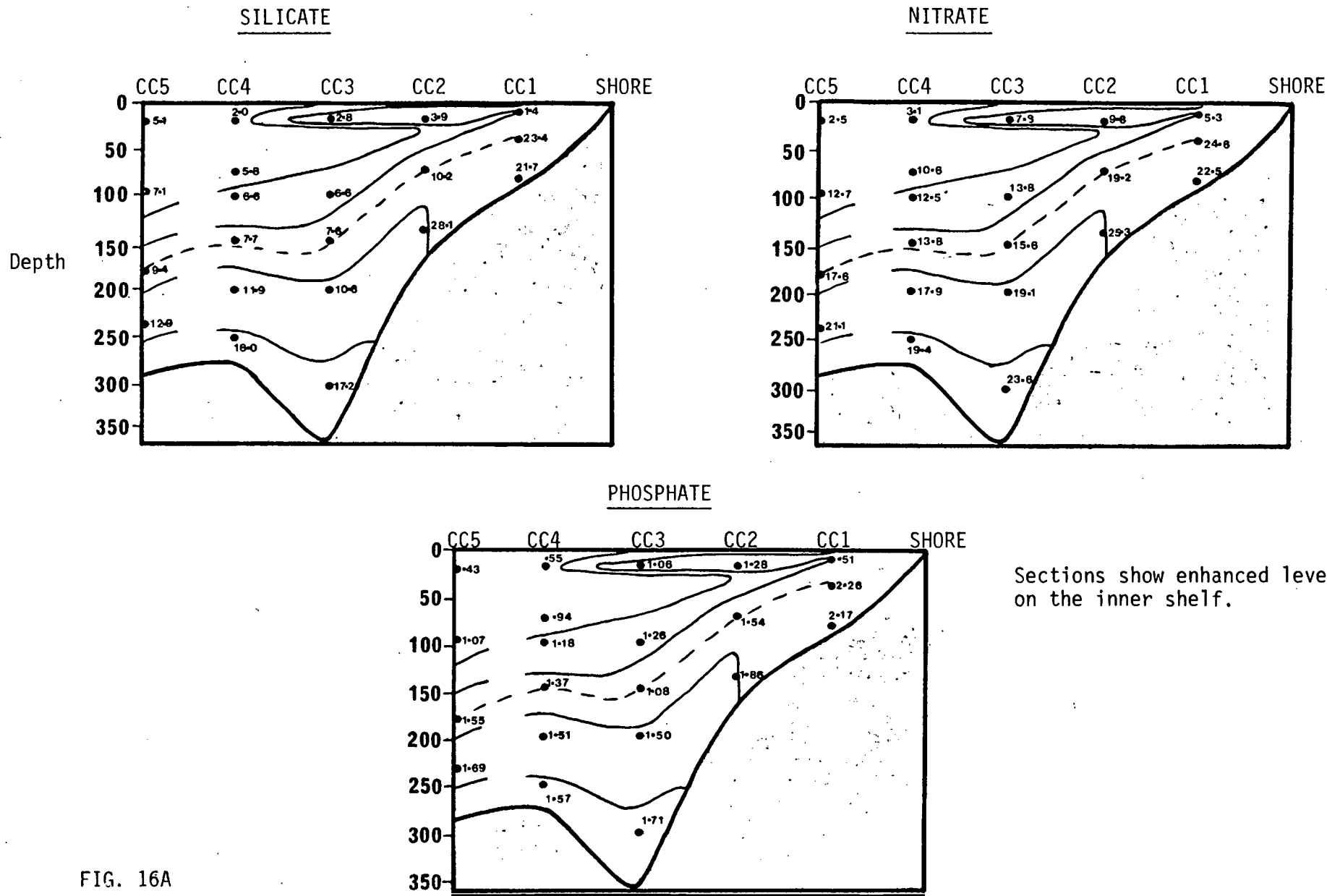


FIG. 15

Nutrient Concentrations superimposed on salinity section: Cape Columbine Transect  
 shows enhanced levels of nutrients on the inner shelf



Sections show enhanced levels of nutrients on the inner shelf.

FIG. 16A

Inter-nutrient relationships in St. Helena Bay, Bottom Layer  
and Station CC1

Ratios give an indication of the origins of the oxygen depleted layer.

Nitrate : Silicate

$$y = 0.3x + 15$$

$$r = 0.52$$

Nitrate : Phosphate

$$y = 7x + 7.6$$

$$r = 0.67$$

Silicate : Phosphate

$$y = 15.7x - 6.62$$

$$r = 0.82$$

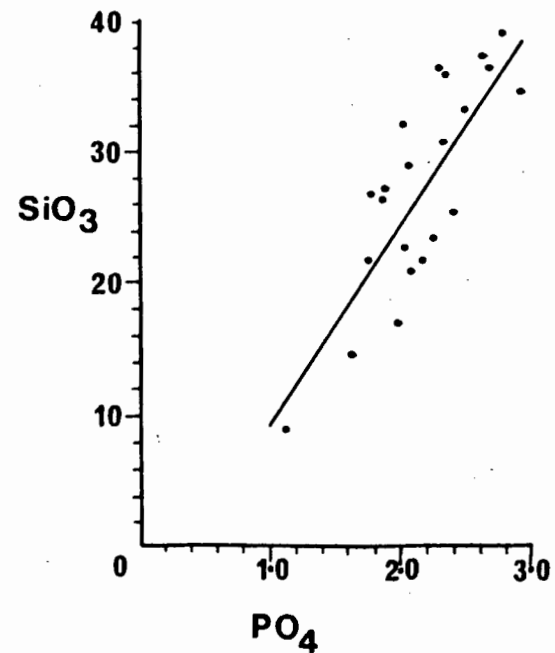
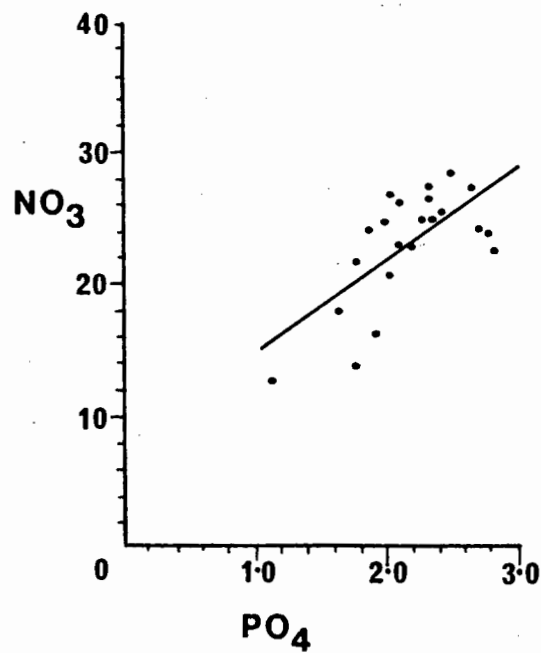
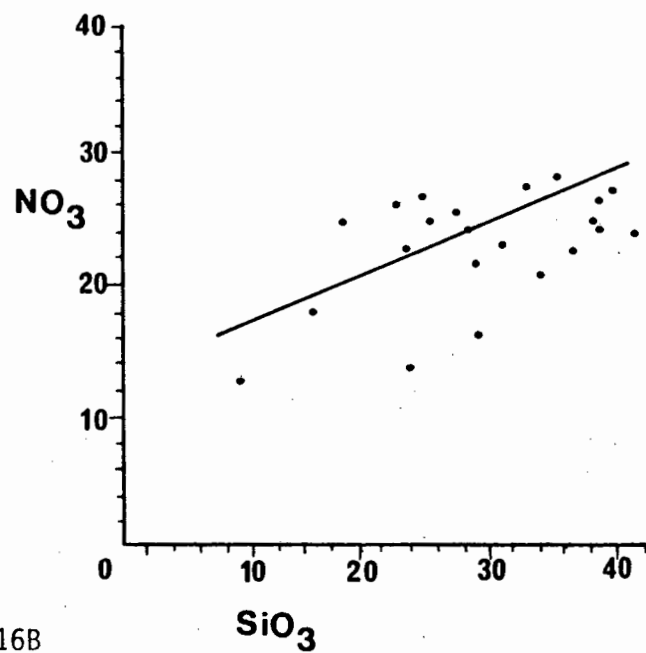


FIG. 16B

Ratio of  $\text{NO}_3$  :  $\text{SiO}_3$  in the oxygenated  
( $> 4 \text{ ml l}^{-1}$ ) bottom water of Cape  
Columbine Transect.

Gives a comparison with oxygen depleted bottom water  
( $< 2 \text{ ml l}^{-1}$ ) in St. Helena Bay.

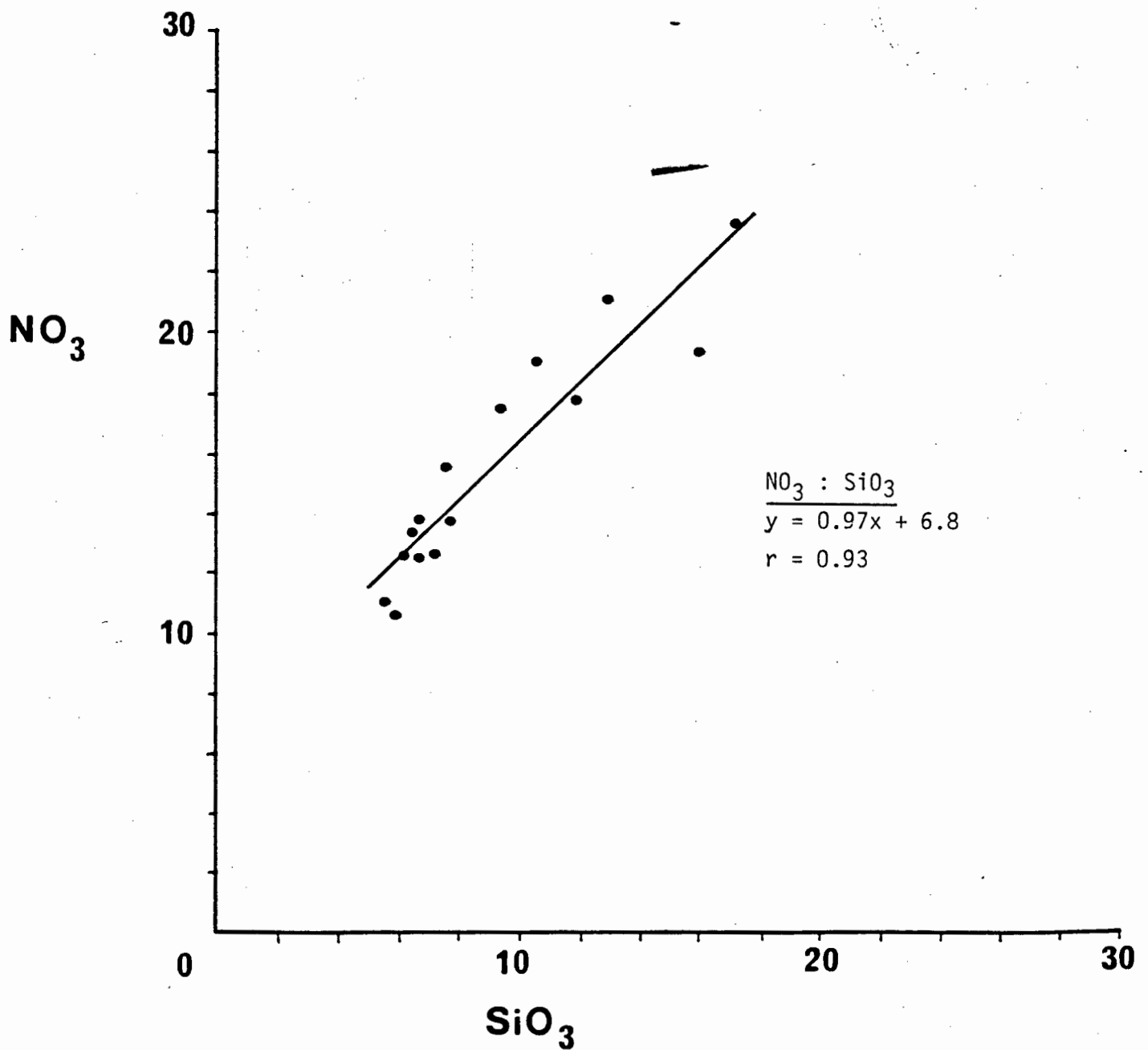


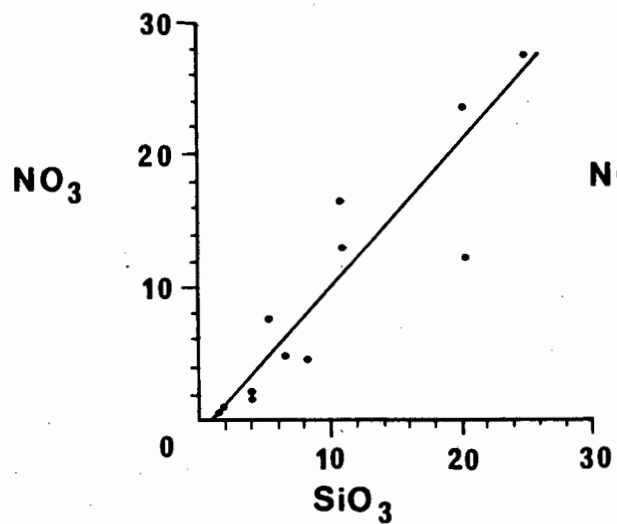
FIG. 16C

Inter - Nutrient relationships in the Surface Waters of  
St. Helena Bay, showing patterns of utilization and limitation

Nitrate : Silicate

$$y = 1.1x - 1.0$$

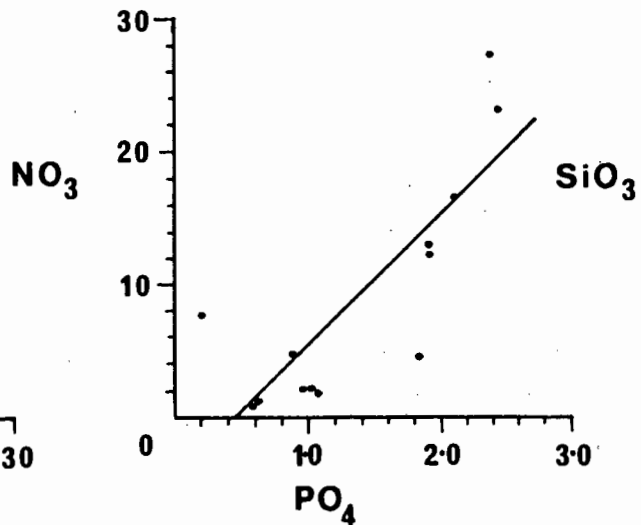
$$r = 0.92$$



Nitrate : Phosphate

$$y = 9.9x - 4.5$$

$$r = 0.82$$



Silicate : Phosphate

$$y = 8.7x - 2.6$$

$$r = 0.84$$

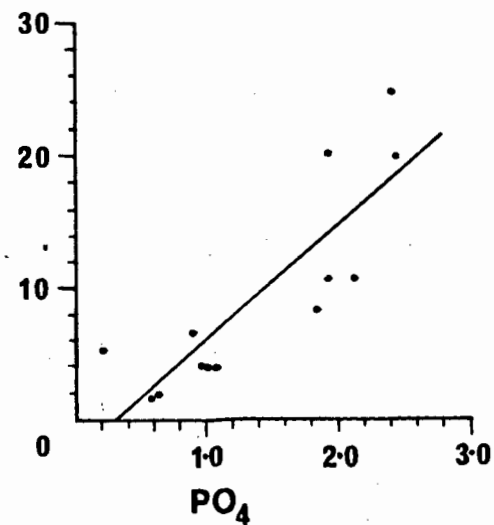


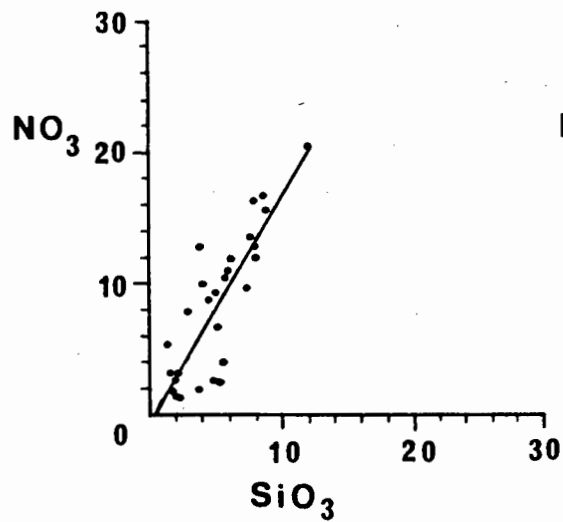
FIG. 16D

Inter-nutrient relationships in Cape Columbine Transect Surface Waters,  
showing patterns of utilization and limitation.

Nitrate : Silicate

$$y = 1.7x - 0.24$$

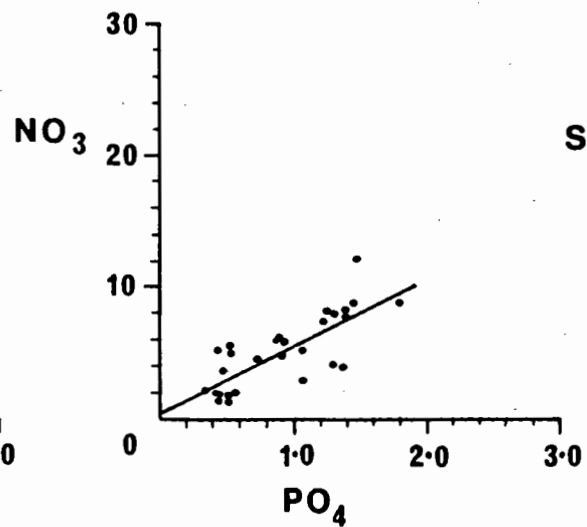
$$r = 0.85$$



Nitrate : Phosphate

$$y = 12x - 2.6$$

$$r = 0.92$$



Silicate : Phosphate

$$y = 5x + 0.5$$

$$r = 0.77$$

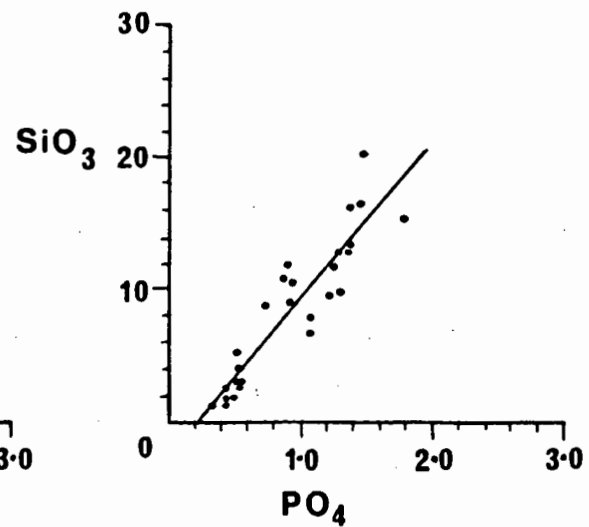


FIG. 16E

Current meter deployment and data for Ri No. Analysis

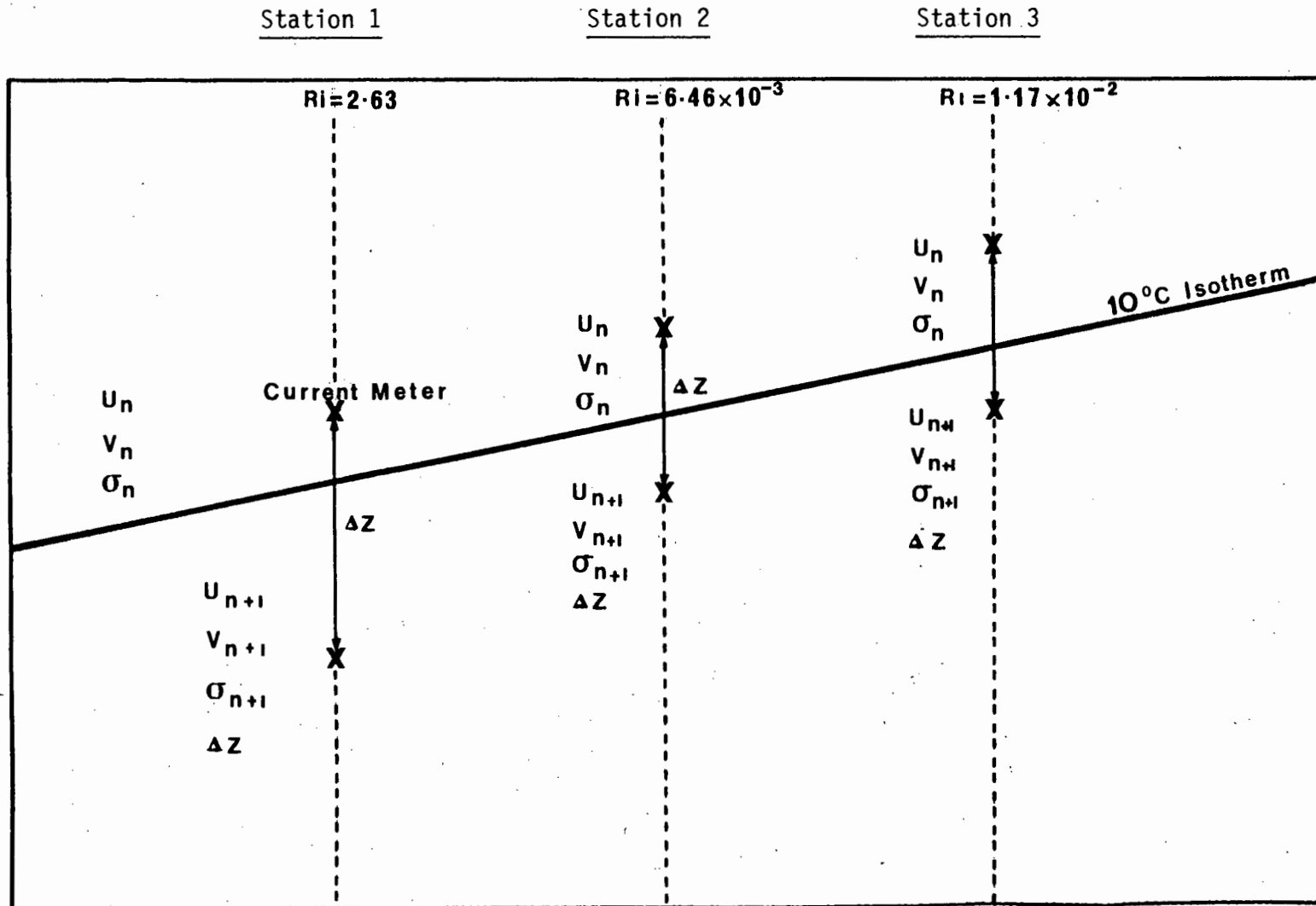
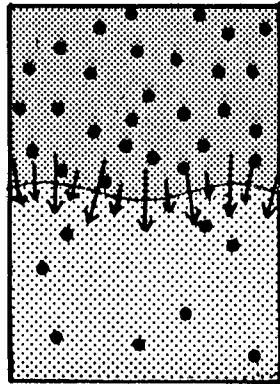


FIG. 17

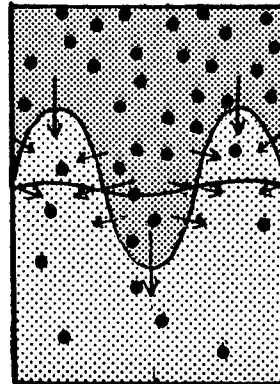
# Salt-Fingering

Hot, salty

Cold, less salty



Diffusion of Heat and Salt at different rates



Salt-fingering

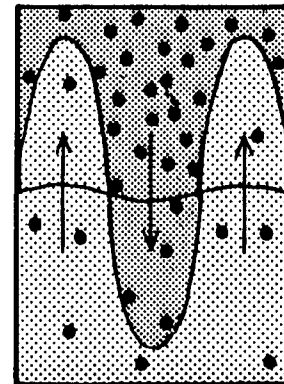


FIG. 18

From Gregg (1973)



Temperature and Salinity profiles, scaled in terms of their respective contributions to density. Shows salt-fingering layers, and the relative strength of double-diffusivity.

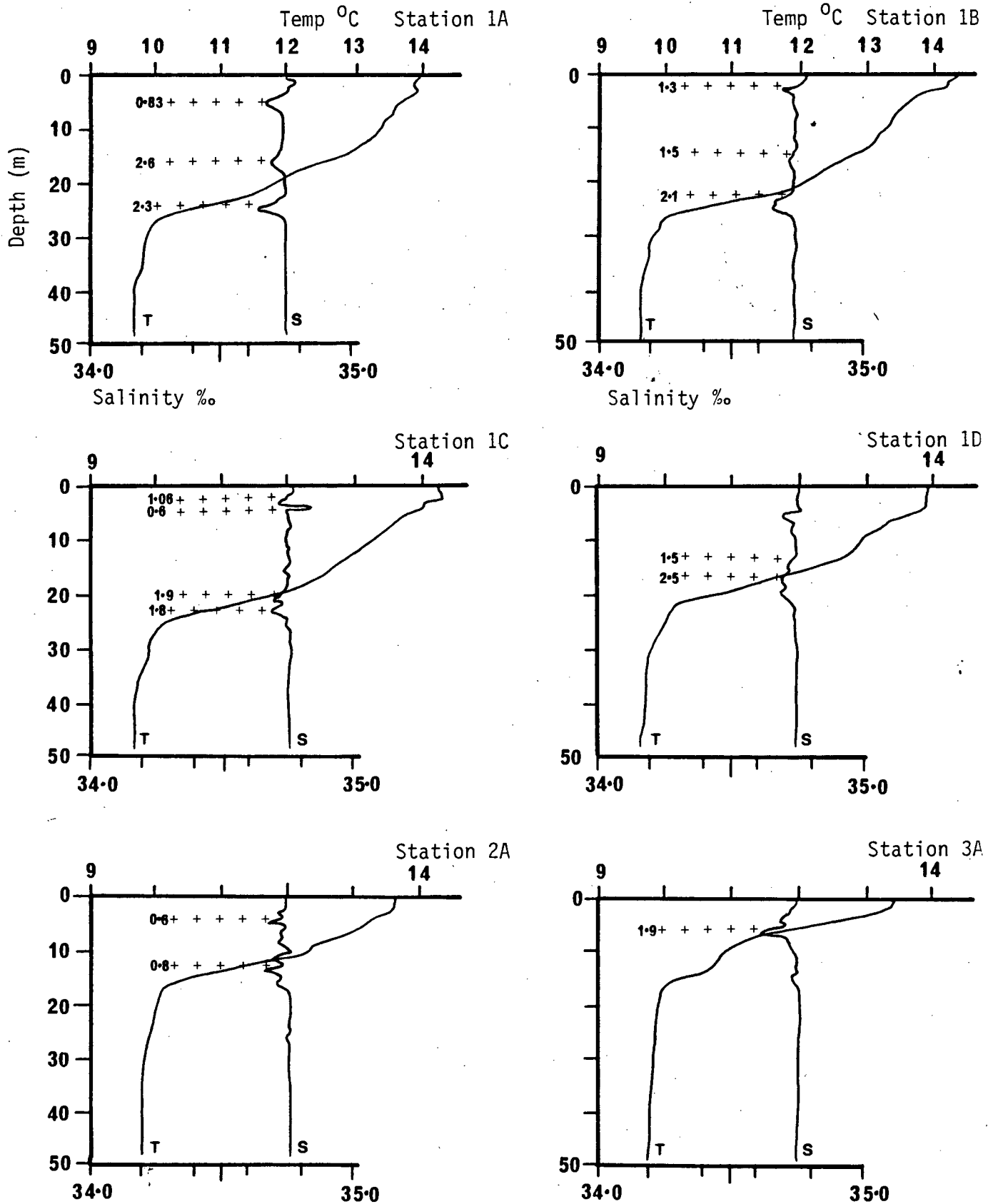
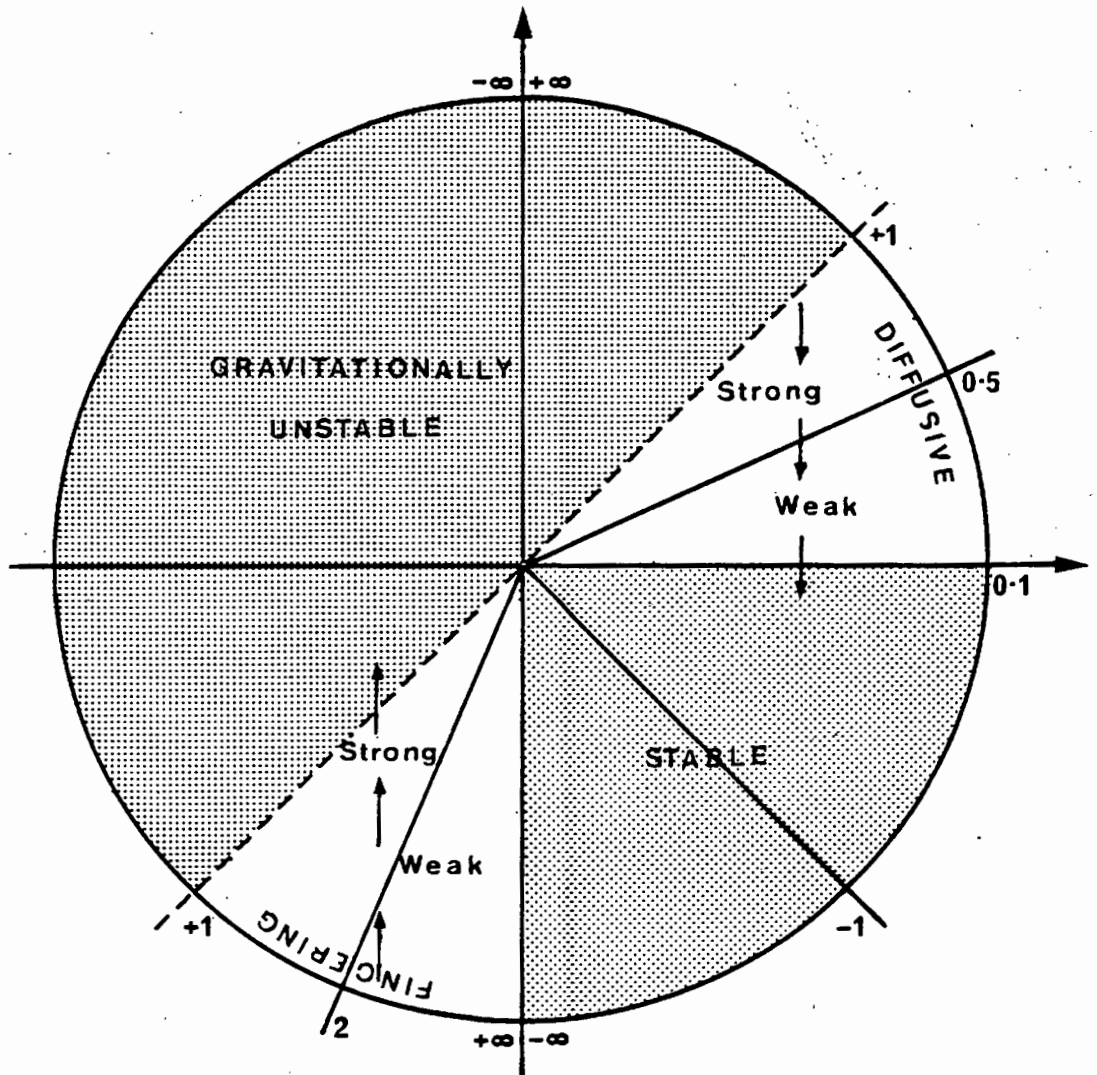


FIG. 19A

Sketch showing the regions of instability  
to double diffusive convection



From Ruddick (1983)

FIG. 19B

Evolution of Salt-Fingering Layers

Salinity profiles at adjacent stations showing  $R_\rho$  Values and  
Linked by isopycnals

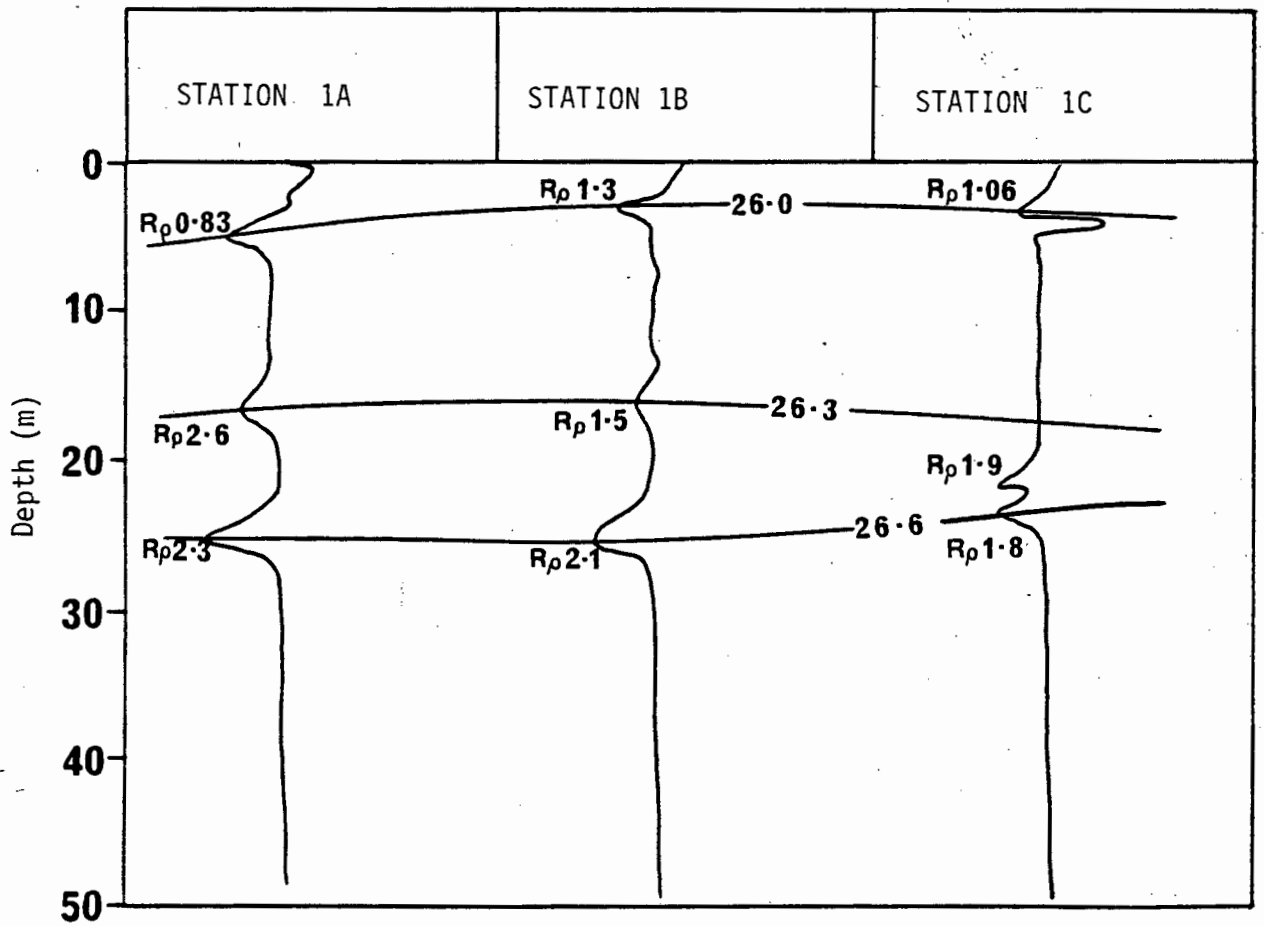


FIG. 20

Categorization of Water Types in the Cape  
Columbine upwelling area, based primarily  
on Temperature

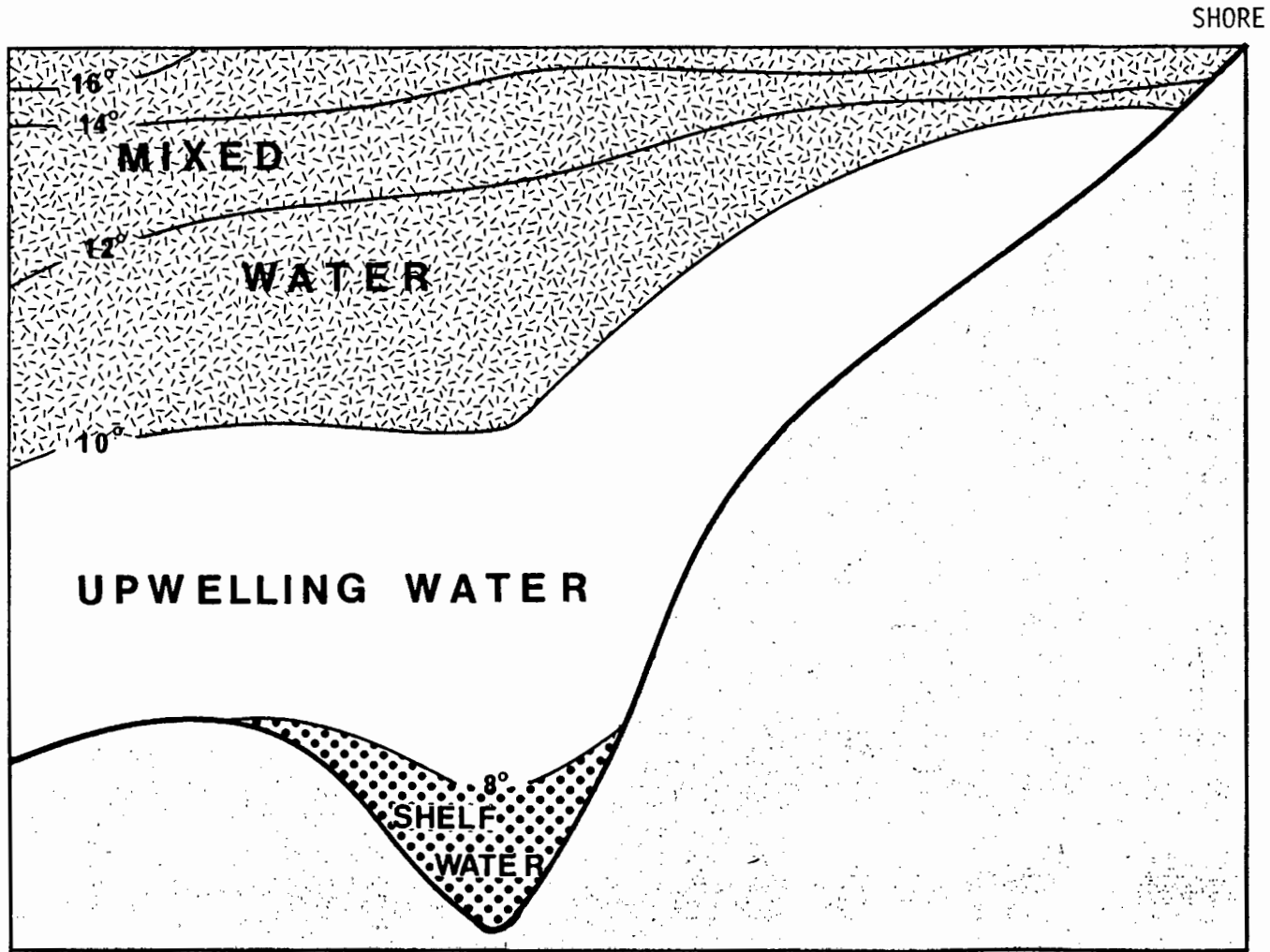


FIG. 21

Inversion Layers showing regions of potential mixing by Interleaving in the frontal zone

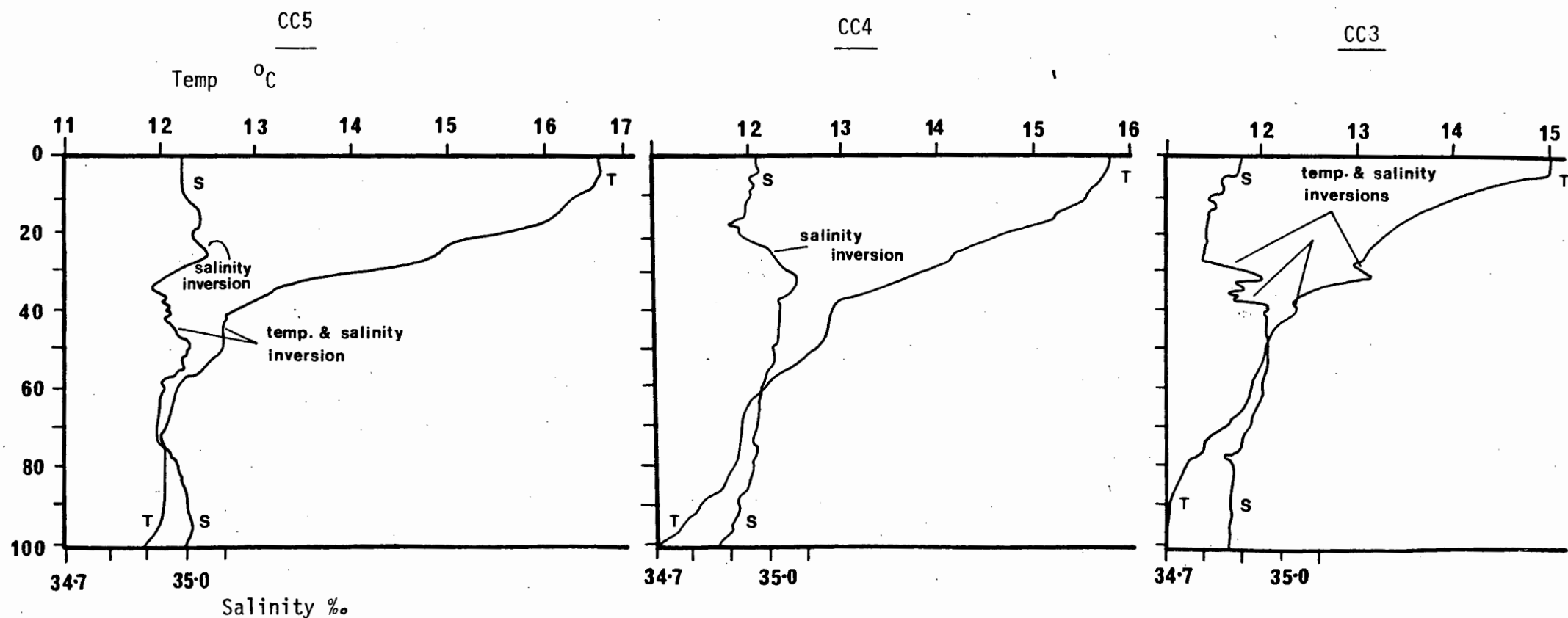


FIG. 22

Categorization of Water Types in the Cape Columbine Upwelling Area based primarily on salinity

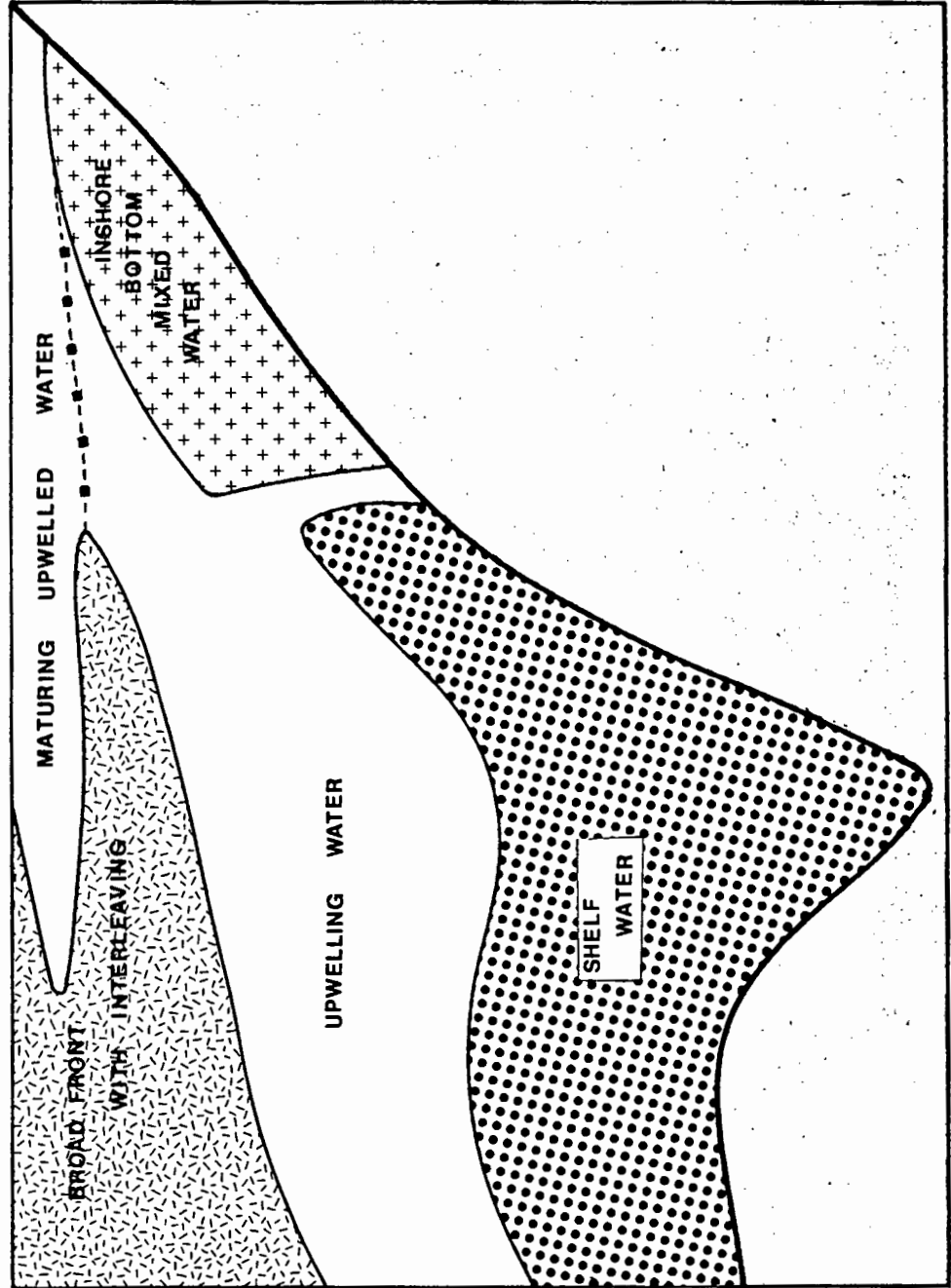


FIG. 23

Vertical Sections of nutrients - St. Helena Bay plus Station CC1

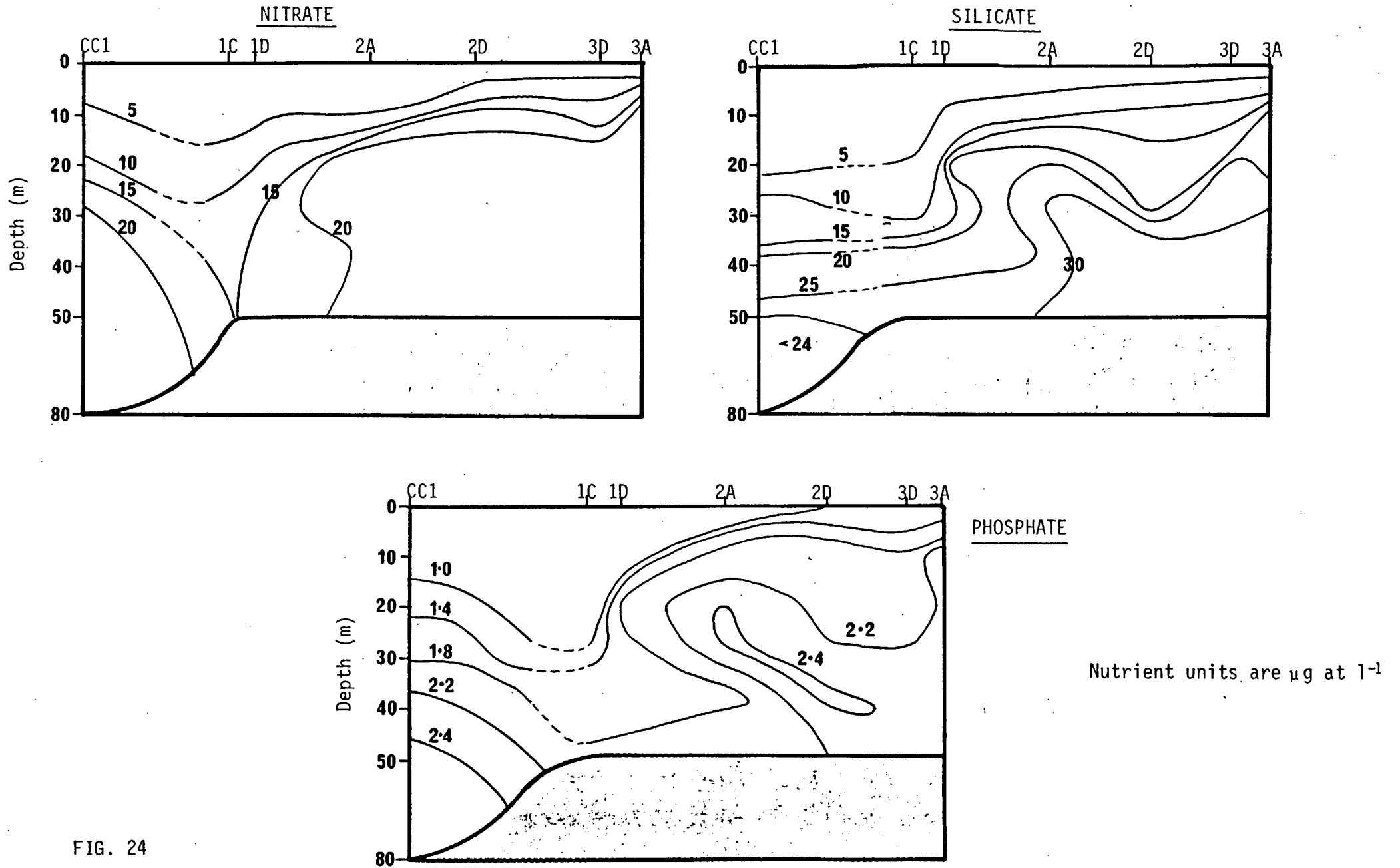


FIG. 24