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NUTRIENT DISTRIBUTIONS IN COOK STRAIT, NEW ZEALAND, DURING SUMMER

by

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List of Symbols

g = Acceleration due to gravity

f = Coriolis parameter

V = Surface velocity of geostrophic jet

P = Pressure

h = Water column depth

w = Upwelling velocity

τb = Bottom stress

τs = Surface wind stress

ρa = Density of air

ρw = Density of water

$\Delta\rho$ = Density difference over a distance interval

K_a = Dimensionless drag coefficient of air

K_w = Dimensionless drag coefficient of water

W = Wind velocity

η = Vertical displacement of the sea surface

γ = Uptake rate of the limiting nutrient

γ_{max} = Maximum uptake rate of the limiting nutrient

k_s = Concentration of the limiting nutrient at which the uptake rate is 1/2 the maximum rate

C = Concentration of the limiting nutrient

C_o = Threshold concentration of limiting nutrient

Δz = Depth interval

Δx = Distance interval perpendicular to shore

U = Onshore bottom flow

S = Stratification index

u = Amplitude of tidal streams for mean spring tide

M_2 = Principal lunar semidiurnal tidal component

σ_{ts} = (sigma-t Surface density at atmospheric pressure-1000 (kg m^{-3}).

σ_{tb} = (sigma-t) Bottom density at atmospheric pressure-1000 (kg m^{-3}).

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Chapter I

Introduction

The effects of physical mixing processes on the hydrology and biology of the central New Zealand shelf waters were investigated during two research cruises in the austral summers of 1980 and 1981. This project was part of an international multidisciplinary investigation on the effects of tidal and wind driven mixing in a shallow summer stratified sea. An integral part of the multidisciplinary investigation was the analysis of the nutrient distributions in the Cook Strait region. Little previous published data on nutrient distributions in central New Zealand coastal waters are available. In addition, no previous analysis of continuous underway nutrient measurements have been carried out in New Zealand coastal shelf waters. The results of this aspect of the research program are discussed in terms of the horizontal and vertical distributions of inorganic nutrients and their relation to physical mixing processes and biological uptake in the study area.

Nutrients are often depleted from the upper layers of a stratified water column by phytoplankton uptake. Beneath the surface mixed layer lies a region of cold, nutrient rich deep water. In addition to fresh water input and regenerative processes, surface nutrient distributions are dependent upon the supply of cold, nutrient rich deep water to the surface waters by mixing processes and subsequent uptake by phytoplankton. The nutrient data from the 1980 and 1981 cruises suggested that contributions of nitrate-nitrite to New Zealand coastal surface waters by rivers and estuaries is insignificant during the summer months. Areas that were sampled with salinities as low as 4 $^{o}/oo$ had nitrate-nitrite concentrations of less than 1 uM. Therefore, the major source of nitrate-nitrite to central New Zealand surface waters during the summer months is due to mixing of nutrient rich bottom water upwards.

The Cook Strait coastal region has several unique characteristics that contribute to its importance as an oceanographic study area. The landmass and continental shelf of New Zealand sits athwart what would otherwise be a mainly zonal flow, thus having a major influence on the circulation of the southwestern Pacific Ocean (Heath, 1971). This eastward zonal flow is an extension of the East Australian Current and is effectively split by the landmass of New Zealand with the water flowing in a clockwise direction around the northern section and counterclockwise around the southern section of New Zealand (Fig. 1). The resultant flow continues eastwards east of New Zealand (Heath, 1971). The circulation on the west coast of New Zealand is closely associated with the circulation off the east coast of Australia. As the East Australia Current is deflected eastwards it casts off anticlockwise rotating eddies that meet subantarctic water to form the Subtropical Convergence (Heath, 1971). The modified subtropical water approaches the coast of New Zealand and branches to form the Westland Current, which flows northward along the west coast of the South Island, and the Southland Current, which flows through Foveaux Strait then northwards along the east coast of the South Island (Brodie, 1960). The Westland Current branches as it approaches Cook Strait with the inshore zone rounding Cape Farewell and entering Cook Strait as the D'Urville Current. The remaining portion of the Westland Current continues northward to influence the west coast of the North Island (Brodie, 1960). Subtropical water flowing eastward meets the northern tip of New Zealand and separates to form the East Auckland Current (Brodie, 1960). The East Auckland Current, which flows southeastwards along the east coast of the

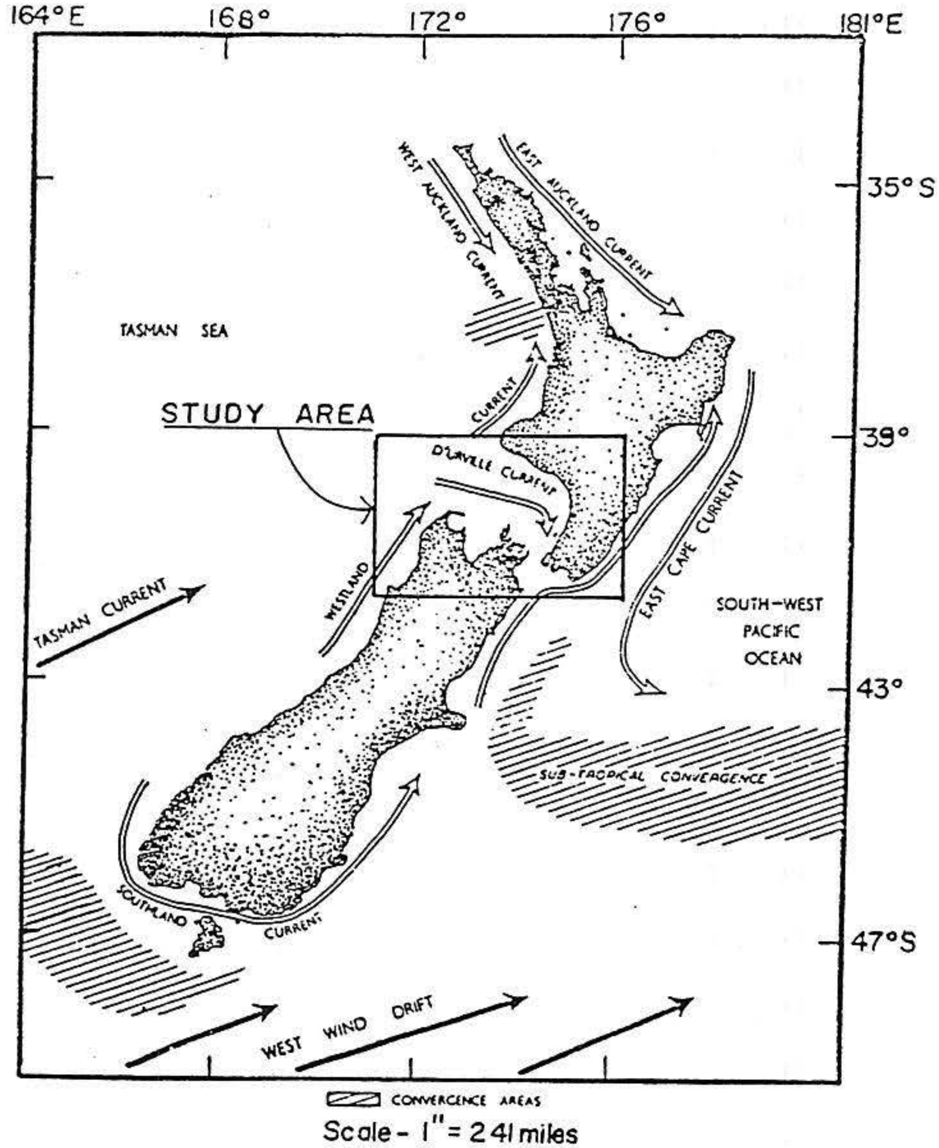

Fig. 1. General coastal circulation around New Zealand.

North Island, branches near East Cape with the main part of the flow continuing east. The remaining portion of the flow turns clockwise around East Cape and continues southwards as the East Cape Current (Heath, 1971.)

The Cook Strait shelf region is oceanographically highly variable with a large number of differing coastal regions in a relatively small area. Figure 2 illustrates locations in the Cook Strait region and the general bathymetry of the central New Zealand shelf. The coastal regimes range from the broad exposed shelf region of the South Taranaki Bight, the sheltered embayments of Tasman, Golden, and Cloudy Bays and the steep drowned river valleys of the Marlborough Sounds (Bowman et al., 1980). New Zealand's landmass is located at the center of a degenerate tidal anti-amphidrome, and as a result the M_2 semidiuranal tide forms a resonant trapped wave that rotates counter-clockwise around the New Zealand shelf. As a consequence, the tides across the east-west boundaries of the Cook Strait region are 140 out of phase, thus driving strong tidal currents up to 7 knots through the strait (Bowman et al., 1980).

The variability and strength of the winds in the

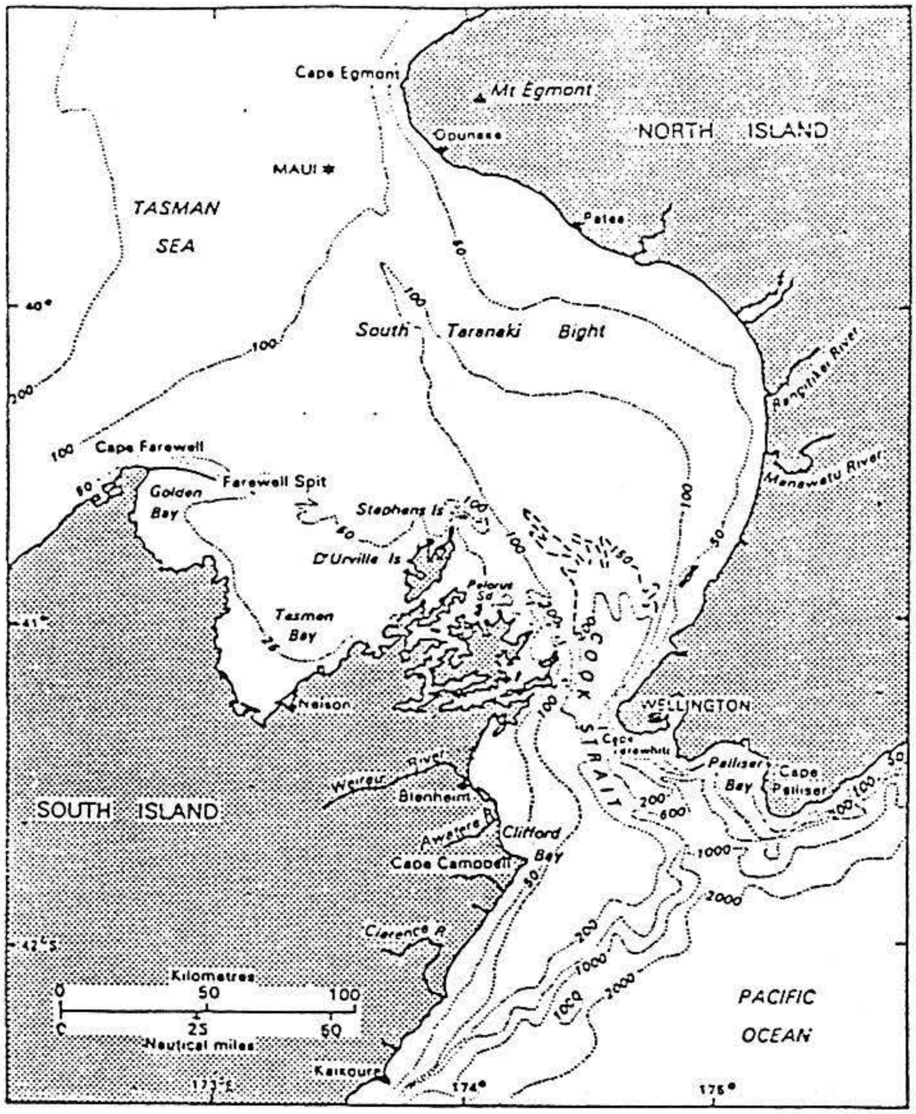

Fig. 2. Location and bathymetry map of central New Zealand with depth in meters.

central New Zealand region contribute to the importance of wind driven mixing processes and advective effects in the Cook Strait coastal shelf waters. The possible existence of a jet current and plume of cold water that flows southeastwards into oligotrophic South Pacific waters out of Cook Strait was first suggested by photographs taken by American astronauts from Skylab in 1973.

Chapter II

Summary of Cruises

The present investigation encompassed two cruises in the study area. The first cruise took place on New Zealand Oceanographic Institute's vessel R/V Tangaroa from January 9- February 4, 1980. The participating institutions on this cruise included New Zealand Oceanographic Institute, the Department of Physics at the University of Auckland and the Marine Sciences Research Center at the State University of New York. The second cruise took place on the New Zealand Naval research vessel HMNZS Tui from January 20- February 13, 1981. The participating institutions included the Departments of Botany, Geology, Physics and Zoology at the University of Auckland, the Department of Chemistry at the University of Otago, the Ministry of Agriculture and Fisheries Research Division in Wellington and the Marine Sciences Research Center at the State University of New York.

The objectives of the R/V Tangaroa cruise were a general survey of the Cook Strait region and the investigation of the possible existence of a Cook Strait plume and its properties.

The 1980 cruise on the R/V Tangaroa was divided into three parts. The first leg was from January 9-19, 1980 and was undertaken during a period of neap tides in Cook Strait. The second leg from January 26- February 4, 1980 was divided into two major surveys. The first survey from January 26- 30, 1980 was an investigation of the Strait during another period of neap tides in Cook Strait. The second survey from January 30- February 4, 1980 was designed to delineate the oceanographic properties of southeastern Cook Strait and the possible existence of a cold water plume emanating from the Strait into subtropical Pacific waters.

The 1981 cruise aboard HMNZS Tui was divided into two parts. The first leg took place from January 20-30, 1981 and was a general survey of Cook Strait again undertaken during a period of neap tides. The second leg of the HMNZS Tui cruise from February 5- 13, 1981 consisted of a series of more detailed surveys of the Cape Farewell region during a period of spring tides within Cook Strait.

The main objective of the HMNZS Tui cruise was a second general survey of the Cook Strait region with an emphasis on areas of interest indicated from the R/V

Tangaroa cruise. An additional objective was the investigation of an area of persistent upwelling and cyclogensis located in the Cape Farewell region. This part of the coast forms a convex coastal bend in the southwest approaches to Cook Strait. Cyclonic eddies were observed in unstable meanders of the upwelling frontal system and moved into the western approaches of Cook Strait.

Chapter III

Methods and Procedures

Concentrations of nitrate-nitrite, ammonium, silicate, and phosphate were measured with an Autoanalyzer system. The nitrate-nitrite method (Wood *et al.*, 1967) consists of a quantitative reduction of nitrate to nitrite by a cadmium-copper reduction column. The resultant nitrite concentration is determined by diazotization with sulphanilimide and then coupled with N-(1-Naphthyl)-ethylenediamine. A highly colored red azo dye is subsequently produced, which has an absorption maximum at 540 nm. The ammonium method (Solorzano, 1969) is dependent on the production of a blue indophenol color at high pH with an absorption maximum at 637 nm. The indophenol color at high pH is obtained by the Berthelot reaction of ammonia, phenol, and hypochlorite while buffering with sodium citrate. The phosphate method (Murphy *et al.*, 1962) relies on the production of a phosphomolybdic acid complex and its subsequent reduction in the presence of trivalent antimony. A highly colored blue solution is formed with an absorption maximum at 880 nm. The silicate method (Armstrong, 1951) is dependent upon the production of a silicomolybdic acid complex, which has a yellow color. The silicomolybdic acid complex is subsequently reduced to the heteropoly acid with stannous chloride. The result is an intensely colored blue compound with an absorption maximum at 820 nm. All of the analytical methods have been modified for use on a Technicon Autoanalyzer II system. Each of the Autoanalyzer colorimeters were equipped with 5 cm pathlength flowcells. The nitrate-nitrite Autoanalyzer channel was operated at a range of approximately 0.05-10 uM. The ammonium channel was operated at a range of approximately 0.1- 5 uM. The phosphate and silicate channels were operated at a range of approximately 0.05-5 uM and 0.1- 20 uM respectively.

The R/V Tangaroa cruise of January 9- February 4, 1980 included automated nutrient analysis for nitrate-nitrite and ammonium. Phosphate and silicate analyses of discrete samples from hydrocast stations on this cruise were carried out by the New Zealand Oceanographic Institute according to the methods of Strickland and Parsons (1968). The HMNZS Tui cruise of January 20- February 13, 1981 included automated nutrient analysis for nitrate-nitrite, phosphate and silicate.

The sampling programs for both the R/V Tangaroa and HMNZS Tui cruises included continuous underway nutrient analysis as well as nutrient analyses of discrete samples from station hydrocasts. Surface nutrient distributions were mapped as the research vessel progressed along a designated cruise track. Seawater for continuous underway nutrient analysis was supplied from a depth of 3 m by the research vessels' hull pumps. The seawater supply was subsequently circulated through a small volume seawater flowcell for sub-sampling by the Autoanalyzer probe. Seawater sampled by the Autoanalyzer probe was subsequently supplied to each of the automated chemistries by an inling stream Divider. Hydrocast stations were selected during the cruise for optimal delineation of oceanographic processes. Discrete samples from the hydrocast bottles were analyzed to produce station profiles and vertical sections along designated transects. Continuous underway measurements of temperature, conductivity (for salinity determination), and invivo Chlorophyll 'a' fluorescence according to the methods of Strickland and Parsons (1980), were obtained during the two cruises to correlate with nutrient distributions.

The research vessel positions were determined using both satellite and radar navigation. Station positions and time checks were recorded on the Autoanalyzer's chart recorder. Nutrient concentrations were subsequently digitized at 5 minute intervals on the instrument's chart recorder and transcribed to maps containing the cruise track after corrections were made for the time lag in each of the automated chemistries. Quasi-synoptic maps of nutrient distributions were then produced for each of the automated chemistries.

Contour maps of the various physical, chemical and biological properties in the Cook Strait region are not truly synoptic. A detailed survey of greater Cook Strait takes approximately seven to ten days to complete. The highly variable nature of meteorological conditions in Cook Strait inevitably results in some distortion of the distributions of properties. A quasi-synoptic representation of the oceanographic variables can be achieved by considering specific areas within Cook Strait and the meteorological conditions prior to and during sampling of these areas.

Chapter IV

Tidal Mixing in Cook Strait

IV.1 Introduction

Tidal and wind mixing are important factors controlling the extent of summer stratification in the Cook Strait region. In a shallow summer stratified sea, a bouyant stabilizing effect is produced by surface heating. Some of the turbulent kinetic energy produced by tides and winds is converted into potential energy as cold denser water is mixed upwards in the water column. The location of tidal mixing fronts can often be determined by balancing the opposing effects of these mechanisms (Simpson et al., 1978).

The semienclosed nature of the Cook Strait coastal shelf region permits the application of numerical tidal models to the area, such models have the ability to predict tidally generated currents and the degree of water column stratification. Bowman et al. (1980) applied an M_2 nonlinear numerical tidal model to the Cook Strait shelf region. An important parameter generated by this model is the stratification index $S = \log_{10} h/u^3$, where h is the depth of the water column and u is the tidal stream amplitude for a mean spring tide. According to Bowman *et al.* (1980) the inverse logarithm of the energy dissipation rate per unit mass is proportional to the stratification index S, initially derived by Simpson and Hunter (1974). Low values of the stratification index indicate regions that are well mixed and high values of the index indicate regions with strong stratification. Transitional values of the stratification index indicate frontal regions, situated between well mixed and stratified waters (Pingree *et al.*, 1978). These frontal regions, indicated by the breakdown of summer stratification due to tidal mixing, are important in determining the distribution of phytoplankton in the shallow summer stratified seas of the United Kingdom (Pingree *et al.*, 1976). Tidal mixing fronts, that are indicated by critical values of the stratification index, often have increased phytoplankton concentrations associated with these fronts.

Nutrients within the well mixed portion of a tidally mixed region tend to be an average of the surface and bottom values of the water column on the stratified side of the frontal zone. The rates at which nutrients are supplied by vertical mixing processes in these frontal regions will determine to some degree the levels attained by primary production (Pingree *et al.*, 1976).

The critical value of the stratification index for the Cook Strait region is approximately 1.5 m^{-2} sec^{3} (Bowman et al., 1980). However, winds in the Cook Strait region are highly variable and these modify the critical value of the stratification index. Orographic deflection and concentration of the winds by the mountain chains of New Zealand cause funnelling of the winds through Cook Strait (Brodie, 1960). Contours of the stratification index for Cook Strait, that are predicted by the non-linear M_2 tidal model of Bowman *et al.* (1980), are illustrated in Figure 3.

Figure 3 indicates three areas in Cook Strait where the critical value of the stratification index is attained. The first area is located in the north-western section of the Taranaki Bight off of Patea. Another area of critical values is located in a region surrounding the northern section of D'Urville Island. The third area surrounds the eastern portion of the Marlborough Sounds and extends across the narrows of Cook Strait to Cape Terawhiti. The 1.5$m^{-2}sec^{3}$ contour then returns across the narrows to the southeastern portion of the Marlborough Sounds. High values of the

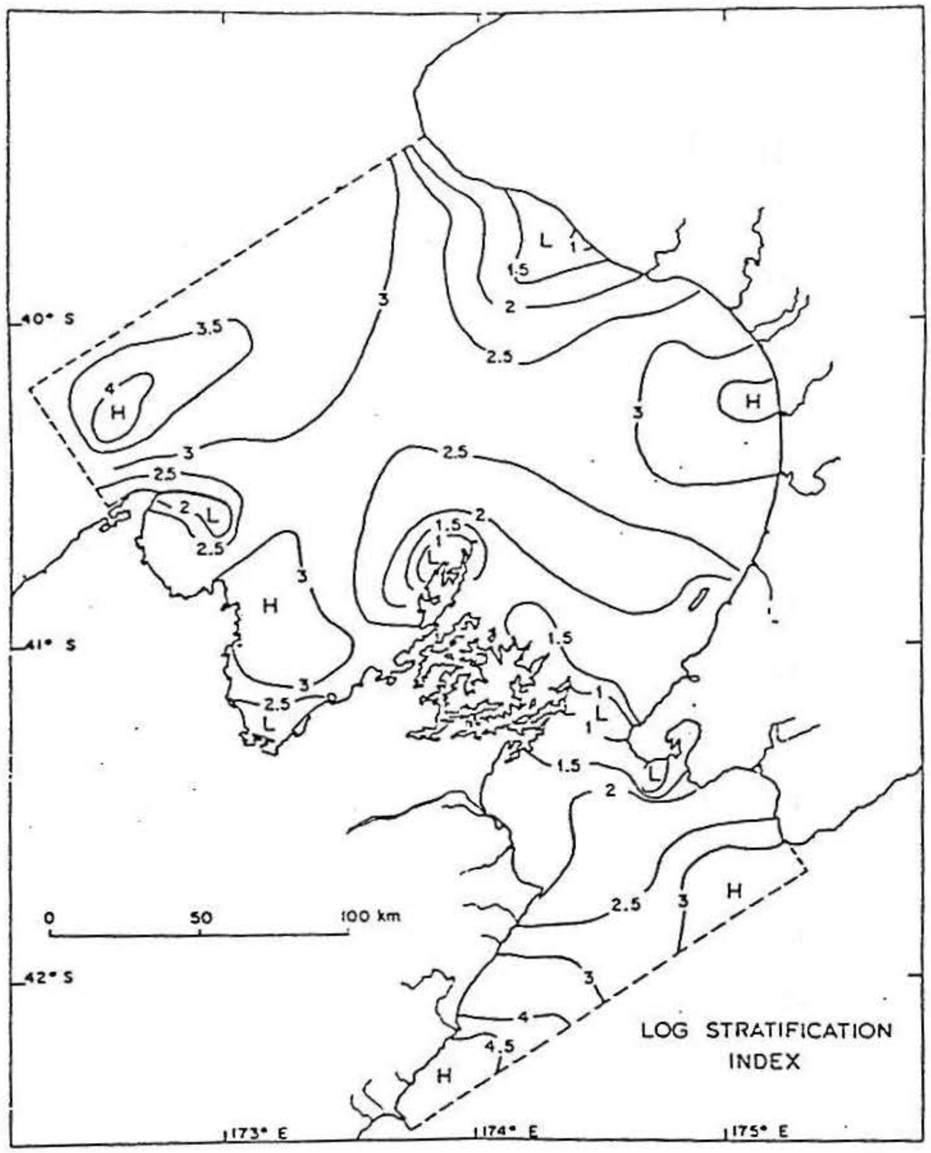

Fig. 3. Contours of the log stratification index ($m^{2}sec^{-3}$) derived from numerical model of Bowman *et al.* (1980).

stratification index, which indicate strong stratification, are located in Tasman and Golden Bays and the northeastern and central areas of the Taranaki Bight. In addition, a region of high values of the stratification index, which indicates water column stability in relation to tidal mixing, is located at the eastern approaches to Cook Strait in the area of Cook Strait Canyon and near Kiakoura.

Figure 3 also indicates some reduced values of the stratification index, that do not fall below the critical value, in the area of Cape Farewell within the southwestern approaches to Cook Strait. This suggests the possibility of some tidal influences off Cape Farewell.

IV.2 Leg 1 R/V Tangaroa 1980 Cruise

The area predicted as tidally mixed by the tidal model of Bowman *et al*. (1980) were sampled on leg 1 of the 1980 cruise during a period of generally light winds and neap tides in the strait. The cruise track for leg 1 is illustrated in Figure 4. The winds were from the southeast with a velocity of 4 m sec^{-1} or less on January 9- 10, 1980. The wind subsequently shifted to the north on January 12, 1980 and had a maximum velocity of 14 m sec^{-1}. The wind shifted to the

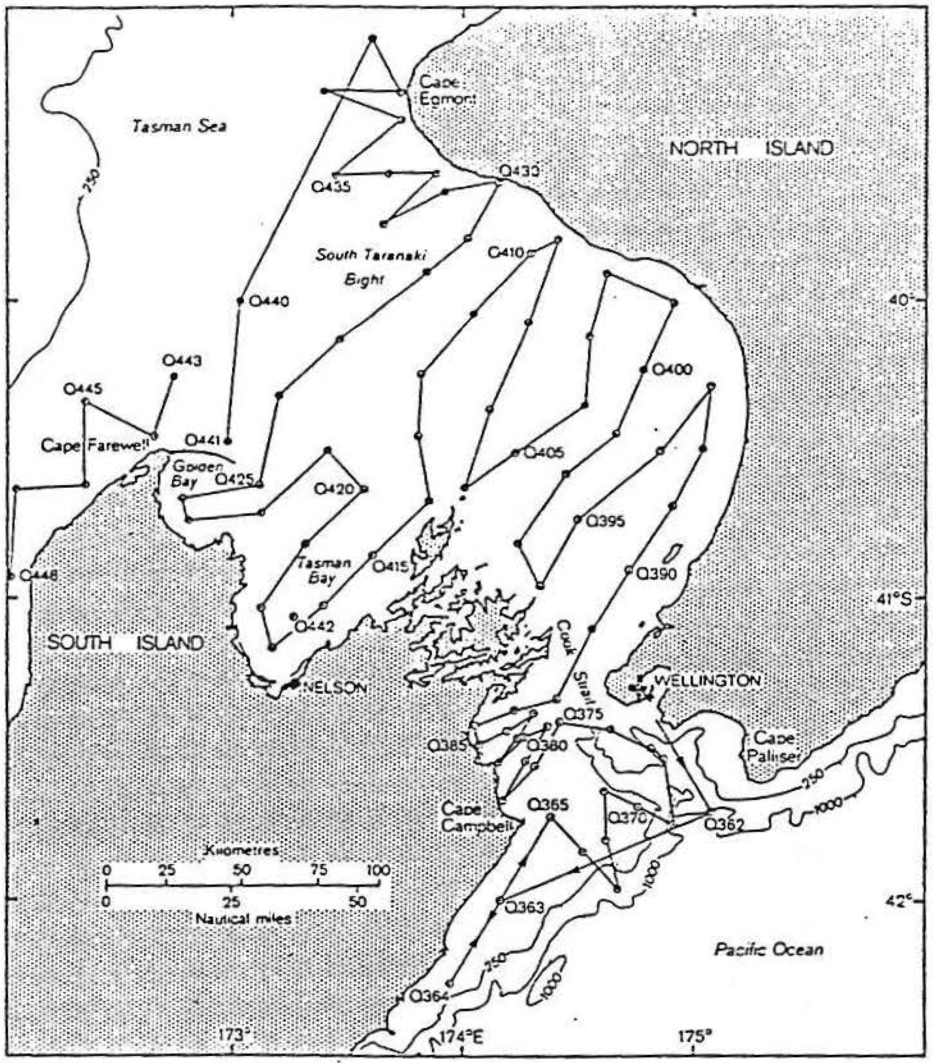

Fig. 4. Cruise track and station positions for leg 1, January 9- 19, 1980

northwest on January 13- 14, 1980 with a velocity of 10 m sec^{-1} or less. The wind vectors for leg 1 are illustrated in Figure 5.

Bulk stratification is a measure of water column stratification and is defined as the difference in density between the bottom and the surface divided by the water column depth:

Bulk stratification = $(\sigma_{tb} - \sigma_{ts})/h(10^{-3}m^{-1})$ where $_{tb}$ is the bottom density, $_{ts}$ is the surface density and h is the depth of the water column (Bowman *et al.*, 1981). Regions of low bulk stratification (Fig. 6) showed good correlation with regions less than or equal to the critical value of the stratification index (Fig. 3).

Contours of nitrate-nitrite in uM from continuous underway sampling on leg 1 are illustrated in Figure 7. Surface nitrate-nitrite distributions on the southern side of Cook Strait showed excellent agreement with predicted areas of mixing from the M_2 tidal model. The highest concentrations of nitrate-nitrite were located off D'Urville Island, the eastern to south-eastern Marlborough Sounds and in the narrows of Cook Strait. Maximum surface nitrate-nitrite concentrations were 2.7 uM off of D'Urville Island and 3.9 uM off the

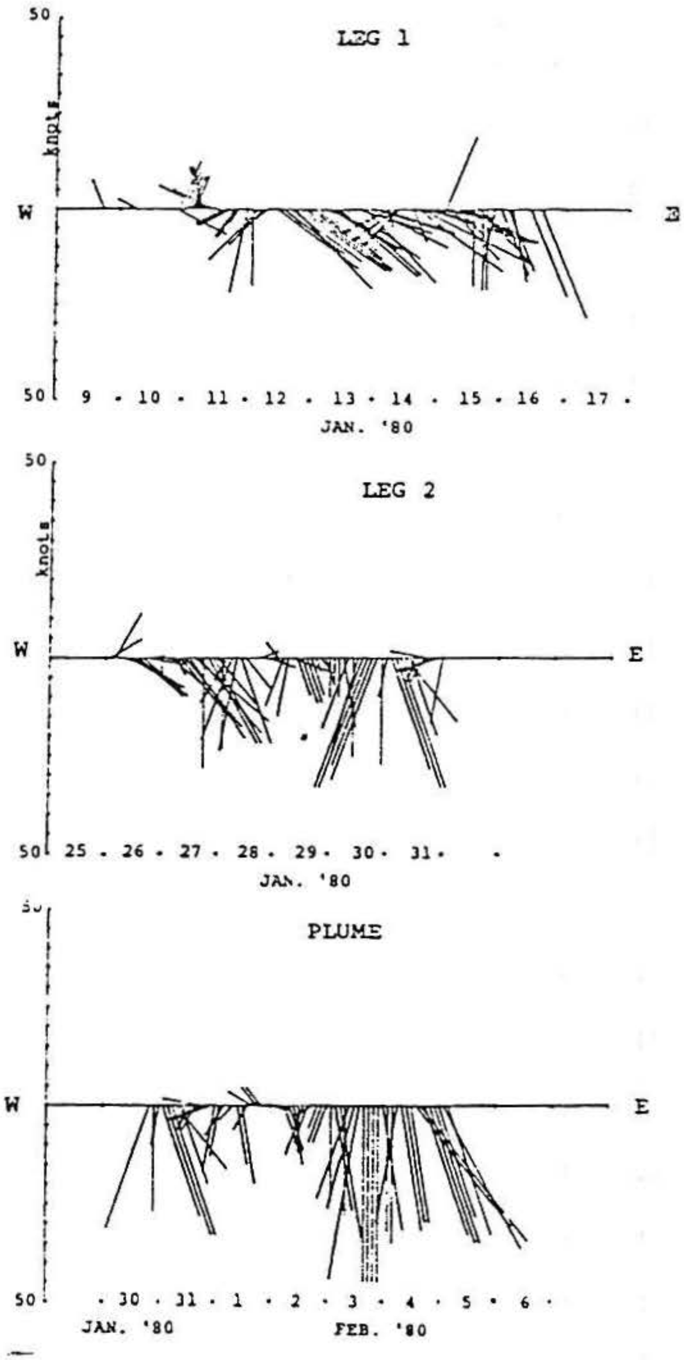

Fig. 5. Surface wind vectors for January 9-February 5, 1980 Data source: ship anemometer.

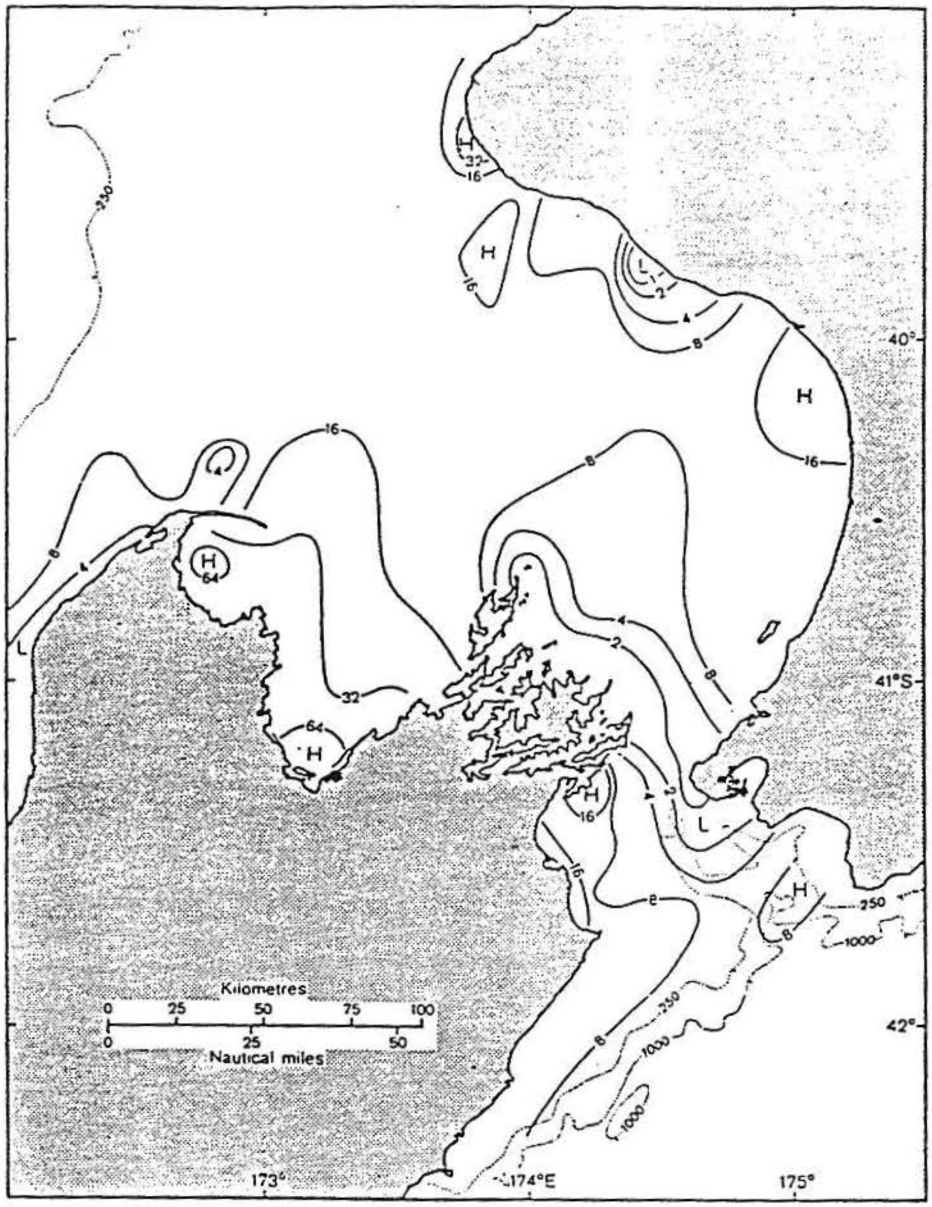

Fig. 6. Distribution of bulk stratification (X 10^{-3}) for January 9- 19, 1980, (Bowman et al., in press b).

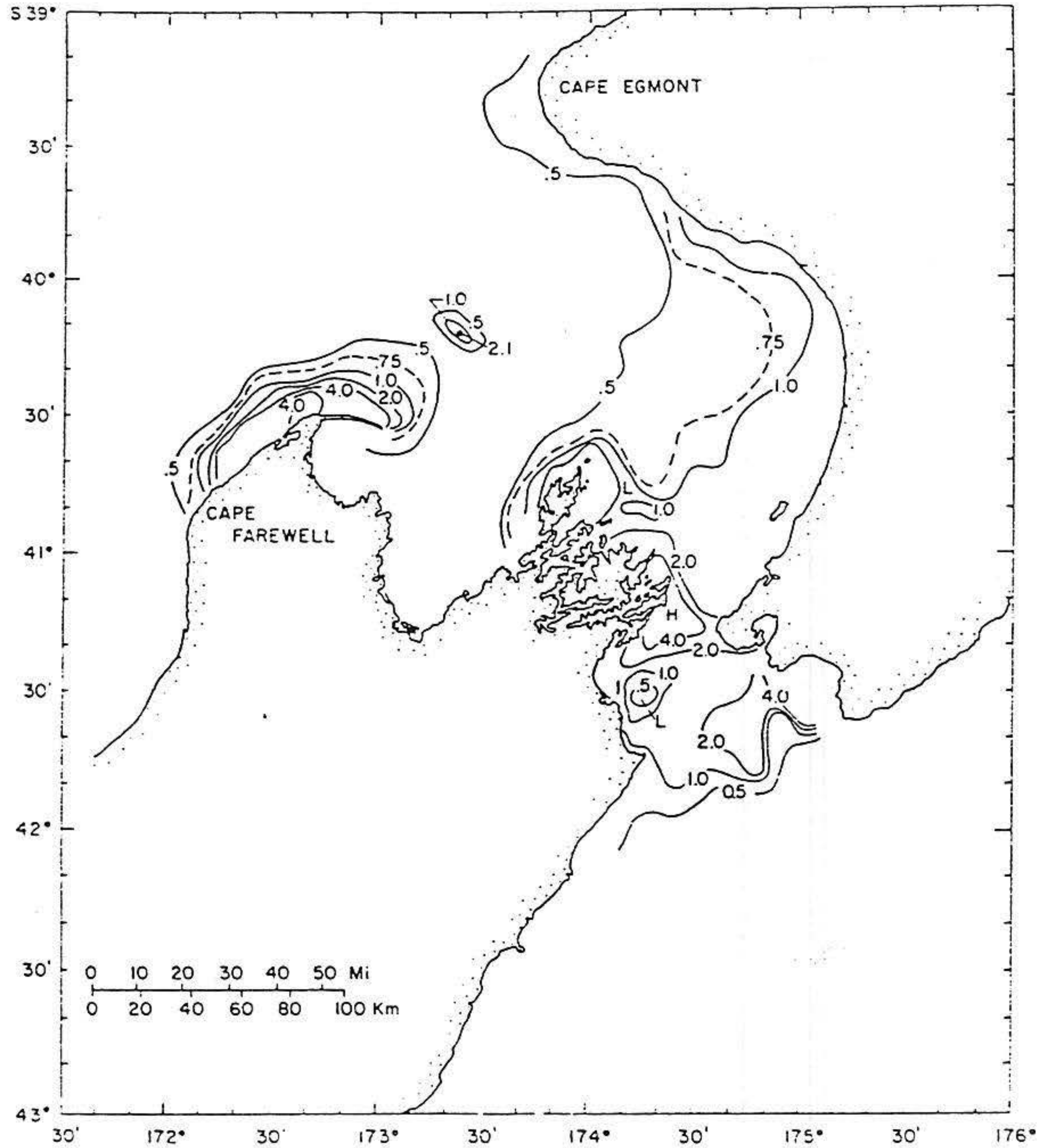

Fig. 7. Surface nitrate-nitrite distribution (uM) for leg 1 January 9- 19, 1980.

eastern to southeastern Marlborough Sounds and in Cook Strait Narrows. Surface nitrate-nitrite concentrations in the stratified waters offshore and to the west of the mixed regions was approximately 0.5 uM.

Hydrocast stations in the stratified waters in the vicinity of the mixed regions had nitrate-nitrite concentrations of 0.5 uM at the surface and 6- 8 uM in the bottom water. Since chemical and physical properties in a tidally mixed region tend to be an average of surface and bottom values in the stratified region, the expected nitrate-nitrite concentration for a tidally mixed region in Cook Strait would be 2- 4 uM. Therefore, nitrate-nitrite concentrations of 2.7 to 3.9 uM in the mixed regions off D'Urville Island, the eastern Marlborough Sounds and Cook Strait Narrows are consistent with these regions being tidally mixed.

An area of some water column stability is predicted by the model between the mixed regions off of D'Urville Island and the eastern Marlborough Sounds, in the vicinity of Pelorus Sound. A sheltering effect is provided in the Pelorus Sound area by the proximitry of D'Urville Island and the eastern Marlborough Sounds. This sheltered area corresponded to a low in nitrate-nitrite of approximately 0.6 uM indicated in Figure 7.

The surface distributions of temperature and chlorophyll 'a' for leg 1 of the 1980 cruise are shown in Figures 8 and 9 respectively. The surface temperature distribution showed good correlation with the surface nitrate-nitrite distribution in Figure 7. However, the temperature gradients were much more diffuse than the nitrate-nitrite gradients. Since nitrate-nitrite is not a conservative seawater constituent, this suggests that active uptake of nitrate-nitrite by phytoplankton was taking place in the Cook Strait region. A chlorophyll 'a' maximum of approximately 1.5 mg m^{-3} was associated with the surface nitrate-nitrite minimum in the Pelorus Sound region. This maximum was 3 to 5 times higher than chlorophyll 'a' concentrations in the surrounding areas.

Surface ammonium concentrations were generally low for leg 1 of the R/V Tangaroa cruise. Concentrations in the stratified offshore oligotrophic waters ranged from 0.2 to 0.3 uM. The tidally mixed regions in Cook Strait had slightly higher surface concentrations with values of 0.4 to 0.5 uM.

The region predicted as tidally mixed off of Patea in the northwest Taranaki Bight had low concentrations of nitrate-nitrite of approximately 0.5 uM or less.

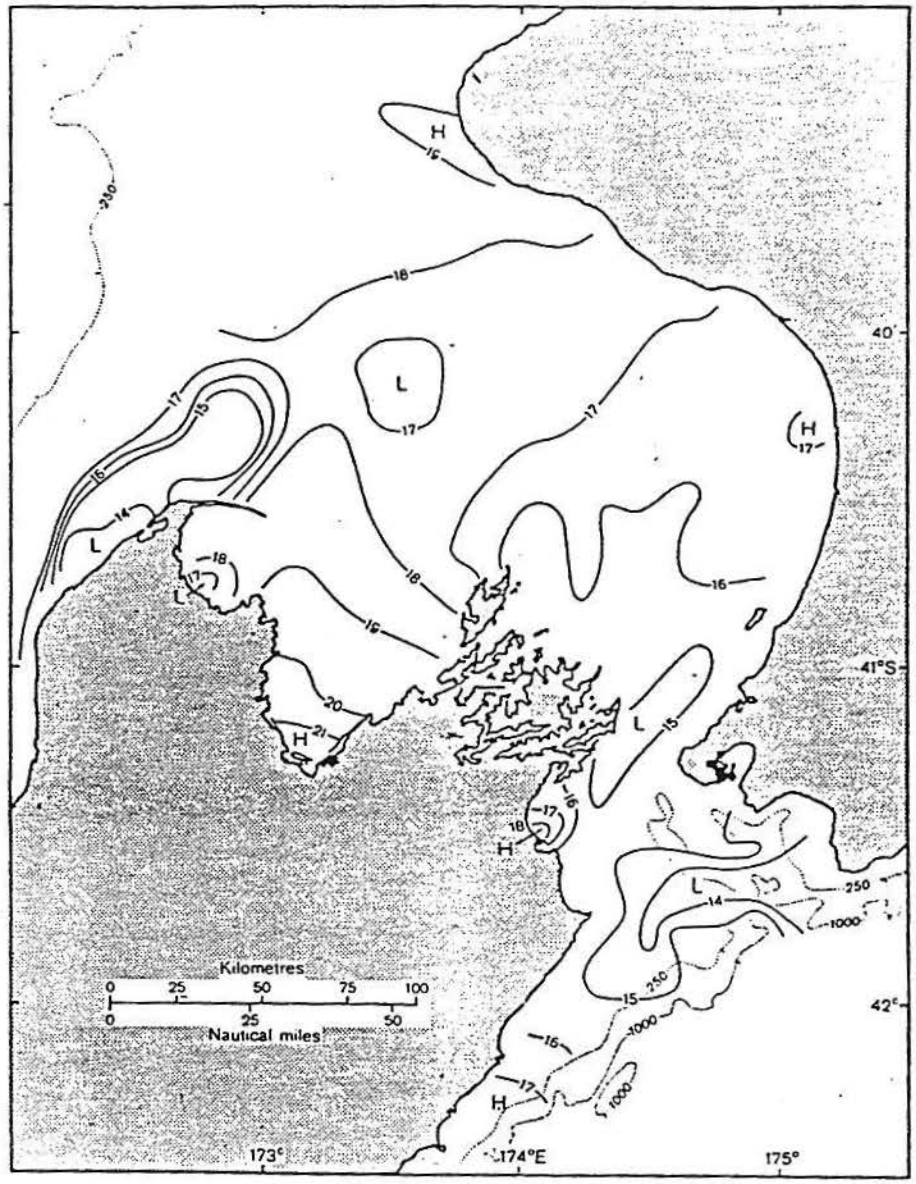

Fig. 8. Surface temperature distribution (°C) for leg 1, January 9- 19, 1980, (Bowman, et al., in press b).

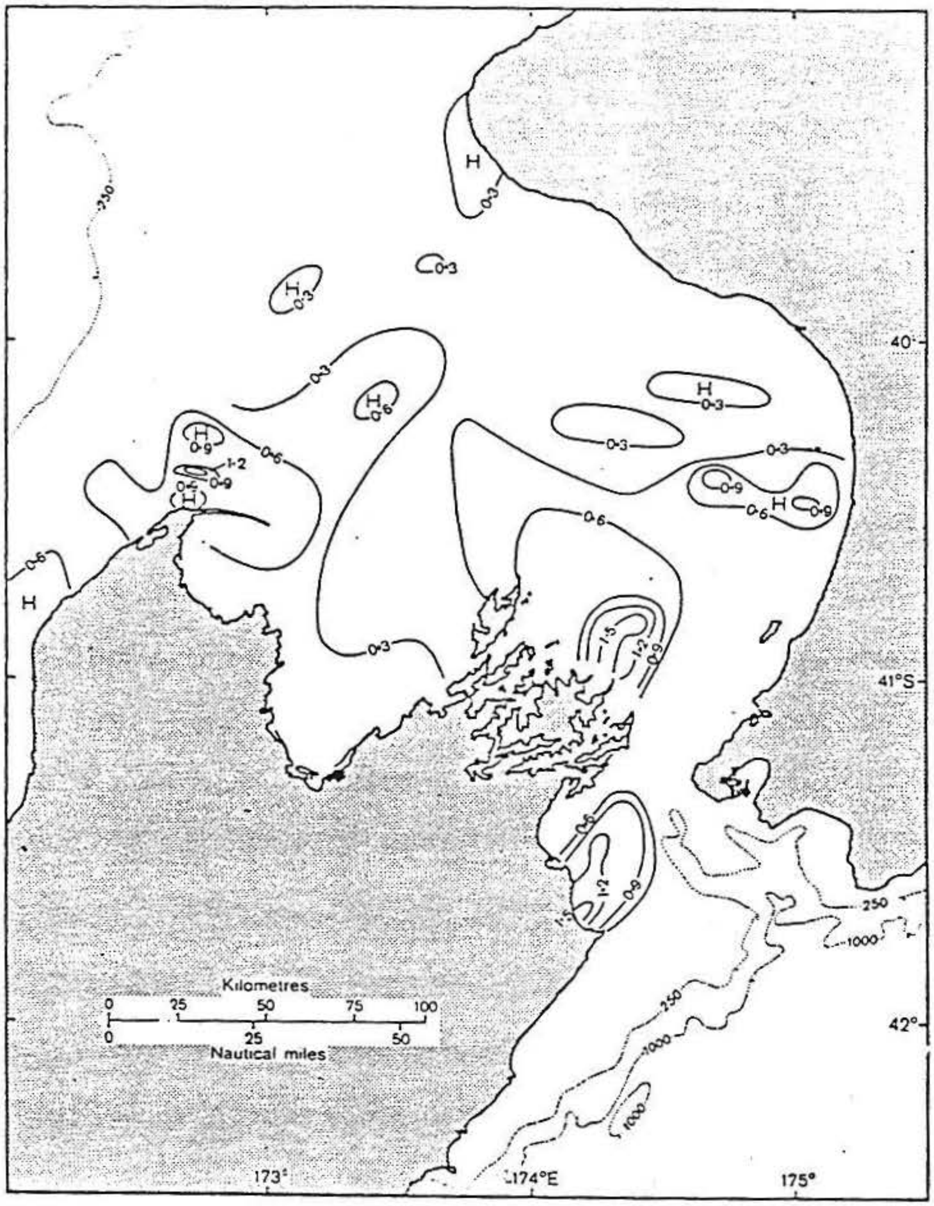

Fig. 9. Surface chlorophyll 'a' distribution (mg m^{-3}) for January 9- 19, 1980, (courtesy P. Lapennas).

Vertical profiles of temperature and sigma-t within the area indicate a well mixed, completely homogenous water column. The Patea stations had a 17.5 ^{o}C water column temperature with no significant surface to bottom temperature difference.

The region off Patea had a low in bulk stratification as predicted by the M_2 tidal model, but nitrate-nitrite and temperature values, as illustrated in Figures 7 and 8 respectively, indicated no nutrient rich cold water at the surface in this region.

The region of predicted tidal mixing off Patea coincides with a sharp rise in the bathymetry of the Taranaki Bight with an average depth in this area of 20 to 30 m. While the depth of the mixed layer in the surrounding stratified regions was 30 to 40 m for leg 1 of the 1980 cruise. As a result, this shallow water shelf off Patea intercepts the thermo-cline and there is no source of nutrient rich bottom water available on this shelf.

IV.3 Leg 2 R/V Tangaroa 1980 Cruise

The second leg of the 1980 cruise surveyed the regions predicted as tidally mixed in Cook Strait during another period of neap tides. The cruise track for the leg 2 general survey of Cook Strait is illustrated in Figure 10. A prolonged period of winds from the north and northwest preceded and coincided with the sampling of the tidal mixing regions on leg 2. The maximum wind velocity for January 26, 1980 was approximately 8 m sec^{-1}. The wind reached a maximum velocity of approximately 12 m sec^{-1} on January 27 and 28 and then subsided to a maximum of approximately 7 m sec^{-1} on January 29, 1980. The wind subsequently increased to a maximum velocity of 18 m sec^{-1} for the period of January 30- 31, 1980. A graph of the wind vectors for leg 2 are illustrated in Figure 5.

The Surface distribution of nitrate-nitrite for leg 2 is illustrated in Figure 11. The nitrate-nitrite contours indicate that the tidal mixing regions off D'Urville Island and the eastern Marlborough Sounds were much more extensive for the leg 2 survey in comparison to the leg 1 survey. The surface nitrate-nitrite concentrations in the tidally mixed regions were highest off the eastern Marlborough Sounds with a value of approximately 4.5 uM. The nitrate-nitrite concentration at the surface in the offshore stratified waters was approximately 0.3 uM.

The presence of an advective flow from west to east was suggested by the deep inflection in the

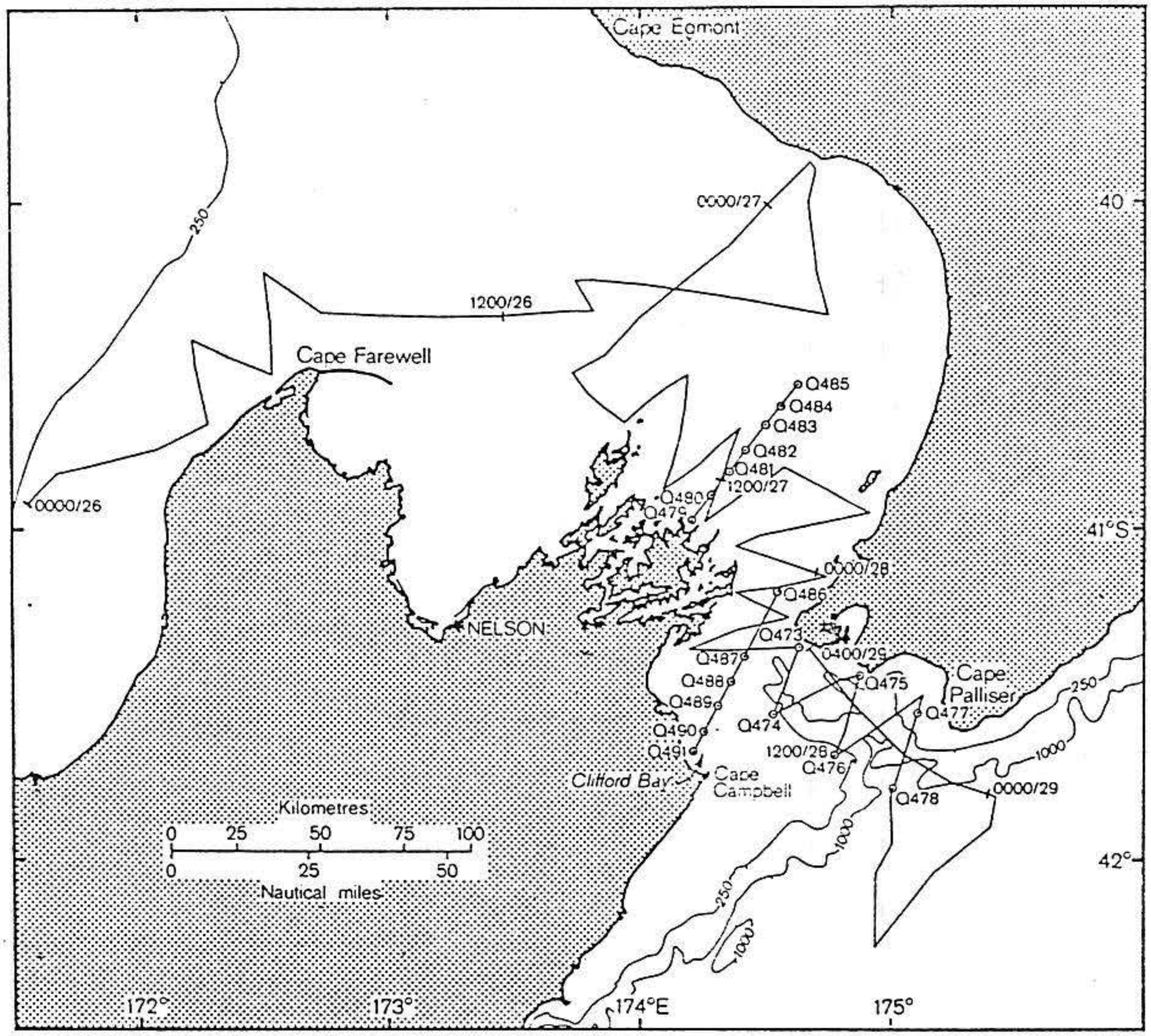

Fig. 10. Cruise track and station positions for leg 2; January 26- 31, 1980.

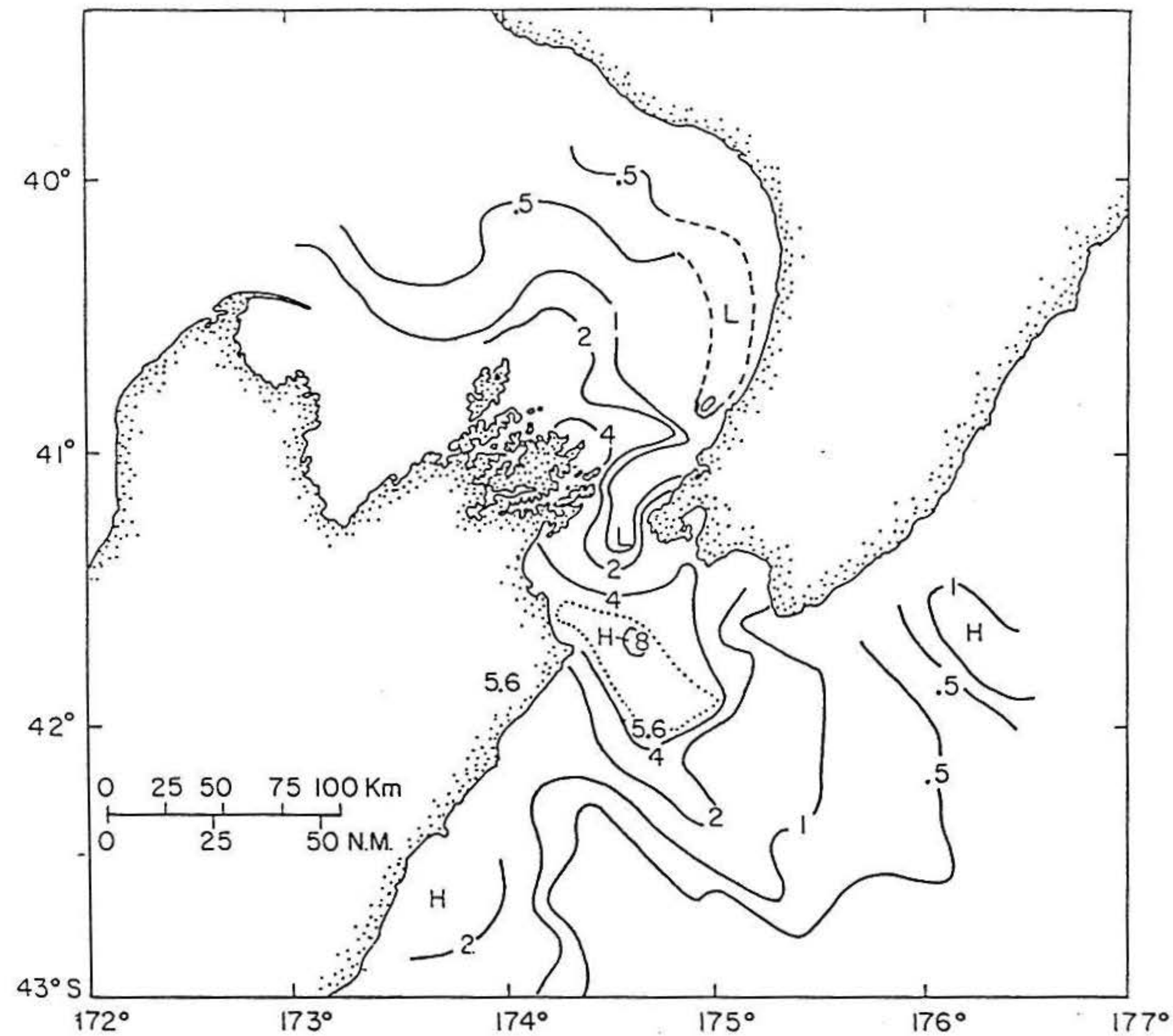

Fig. 11. Surface nitrate-nitrite distribution (uM) for leg 2, January 26- February 4, 1980.

contours of nitrate-nitrite into the narrows of Cook Strait. The prolonged period of moderate to strong winds from the north and northwest would be expected to result in a large advective flow into the western approaches to Cook Strait.

A small area with anomalously high nitrate-nitrite values of approximately 7- 8 uM was present off Arapawa Island in the eastern section of the Marlborough Sounds. Cook Strait Canyon enters the narrows of Cook Strait and turns westward into the Taranaki Bight in the vicinity of Arapawa Island, which suggests that the high nitrate-nitrite values in this area was the result of intensified upwelling from the advective flow rounding a bend in the bathymetry of the canyon.

The surface ammonium concentrations in the tidal mixing regions for leg 2 showed the same general pattern as leg 1. Ammonium concentrations were slightly higher for the mixed regions, with values of 0.4 to 0.6 uM and a small patch of water off the eastern Marlborough Sounds with a value of 0.8 uM. Ammonium concentrations in the offshore stratified regions were 0.2- 0.3 uM, which were similar to leg 1.

The surface temperature distribution in Figure 12 showed good correlation with the nitrate-nitrite

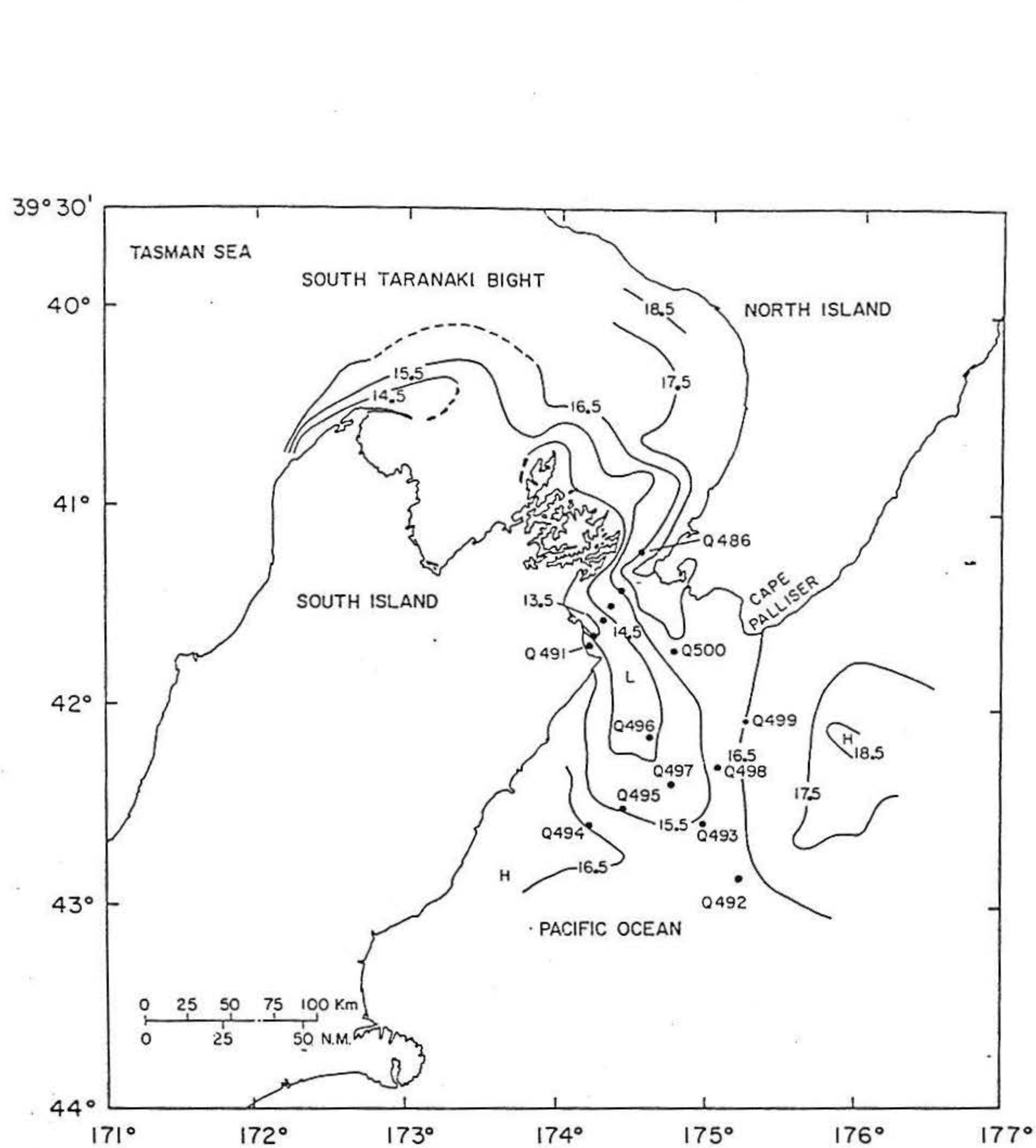

Fig. 12. Surface temperature distribution (°C) for January 26- February 4, 1980, (Bowman et al., in press c).

distribution with an inverse relationship between temperature and nitrate-nitrite values. The temperature distribution also indicated a more extensive region of tidal mixing than the previous leg 1 survey. The surface temperature in the tidally mixed regions had a minimum temperature of approximately 14.5 ^{o}C. The temperature in the surface stratified waters offshore of the mixed region was approximately 18 ^{o}C. The surface temperature distribution also indicated the advective intrusion of warm surface water into Cook Strait Narrows.

The surface chlorophyll 'a' distribution for leg 2 of the 1980 cruise (Fig. 13) showed a chlorophyll 'a' maximum of approximately 1.5 mg m^{-3} that corresponded to the area off Pelorus Sound. Figure 13 also showed that chlorophyll 'a' increased in the area of the front off the tidal mixing region.

Leg 2 of the 1980 cruise included a transverse vertical section of the tidal mixing region and the frontal boundary off Pelorus Sound. The transect was made up of Stations Q479- Q485 and the station locations are illustrated in Figure 10. Vertical sections of the physical and chemical properties of the transect are illustrated in Figures 14a to f. The vertical

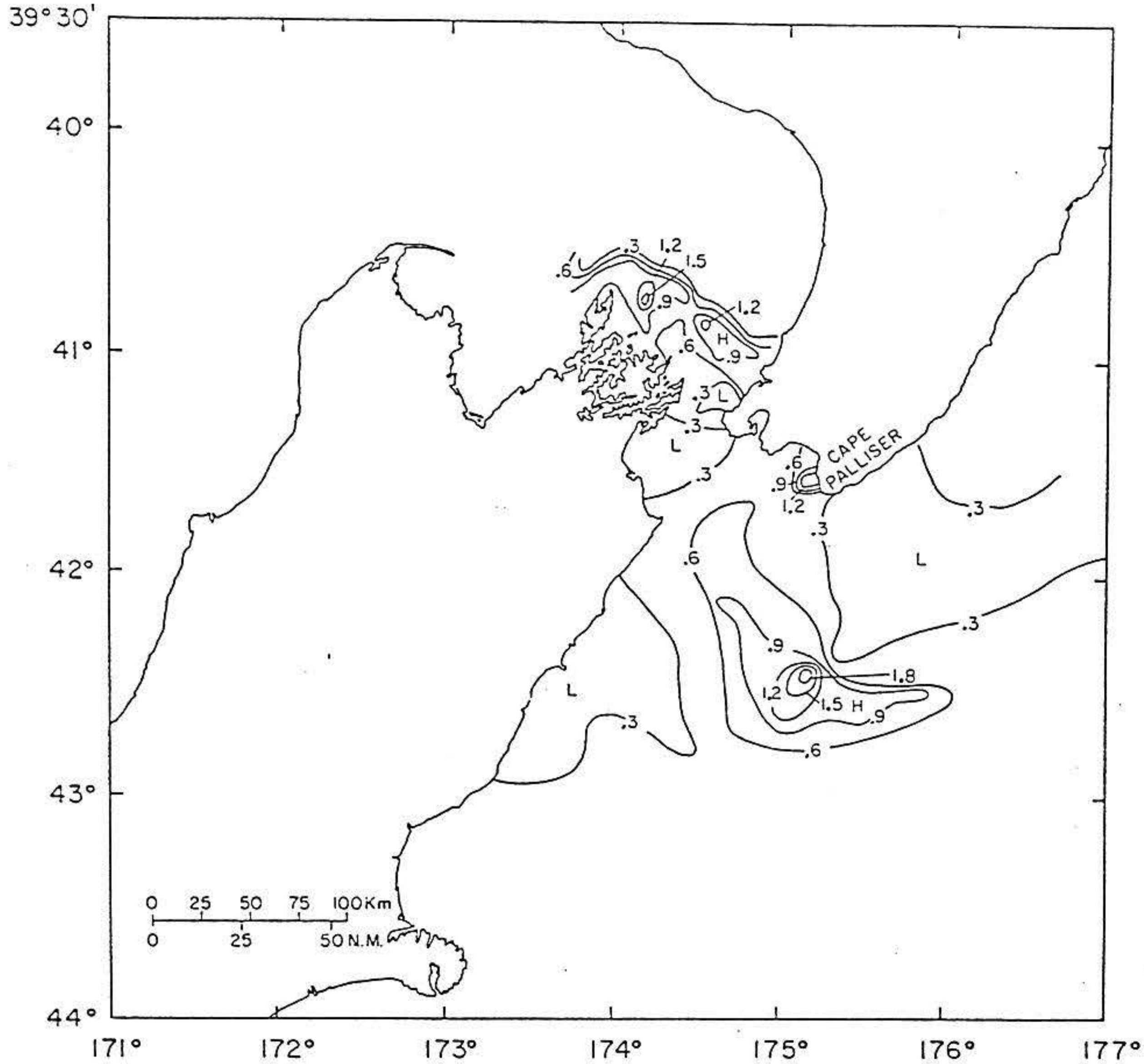

Fig. 13. Surface chlorophyll 'a' distribution (mg m^{-3}) for January 27- February 4, 1980, (courtesy P. Lapennas).

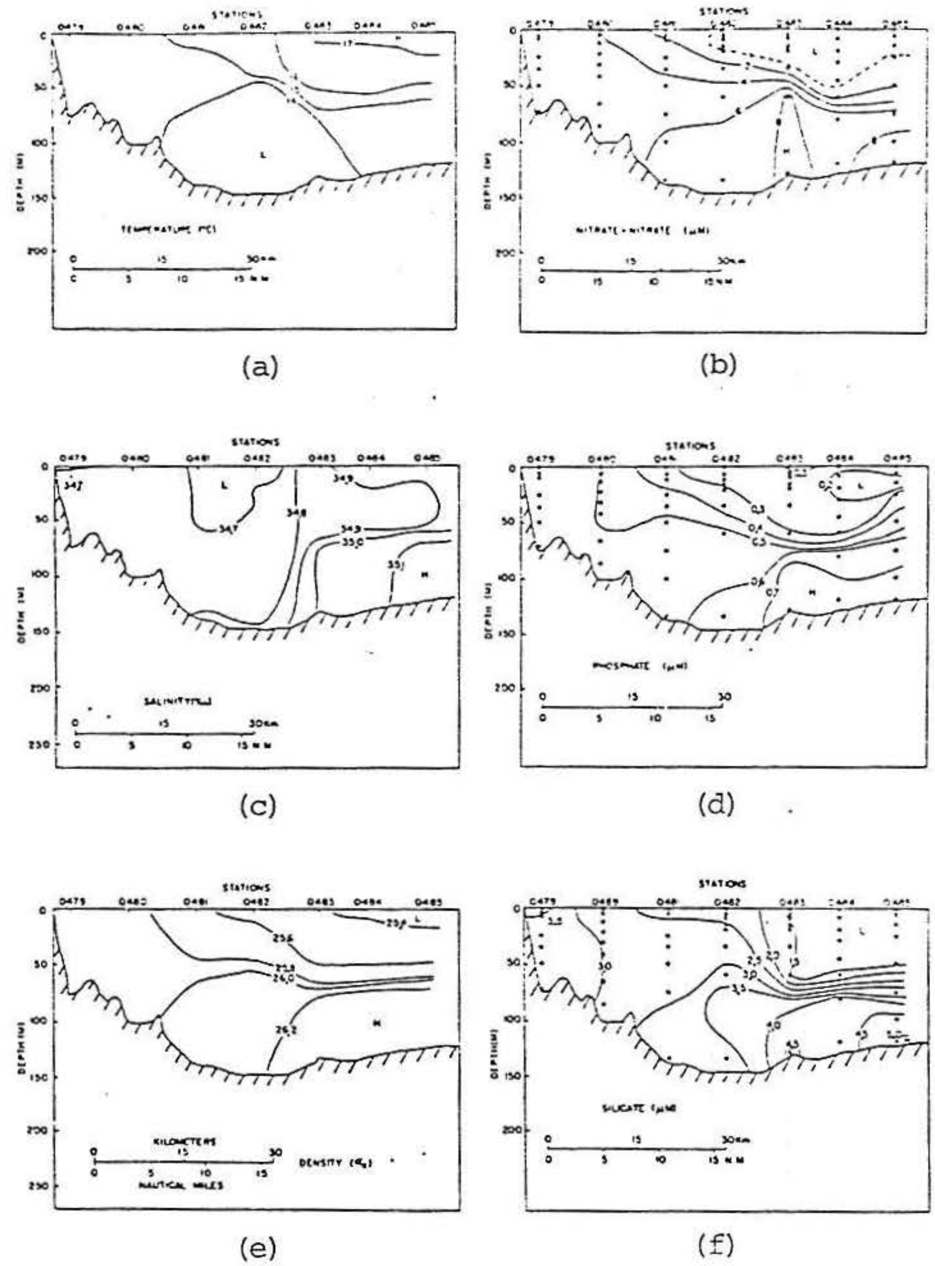

Fig. 14. Vertical distribution of physical and chemical properties for Pelorus Sound transect: a) temperature (^{o}C), b) nitrate-nitrite (uM), c) salinity ($^{o}/oo$), d) phosphate (uM), e) density (σ_t), f) silicate (uM).

distribution of the physical and chemical properties (Fig. 14a to f) showed the classical structure of a tidal mixing system as described by Pingree et al. (1976). Figures 14a to f indicated that the tidal mixing front was located between Stations Q480 and Q481.

The nitrate-nitrite concentrations for the transect (Fig. 14b) are in the range of 4- 4.5 uM in the nearshore mixed region and less than 0.5 uM in the surface offshore stratified region. The maximum concentration in the bottom water of the offshore stratified region was approximately 8 uM.

The phosphate concentrations for the transect (Fig. 14d) indicated the same general distribution as nitrate-nitrite with phosphate values of 0.5- 0.6 uM in the nearshore mixed region and 0.2- 0.3 uM in the surface stratified region offshore. The maximum phosphate concentration was approximately 0.7 uM in the bottom water of the stratified region.

The silicate concentrations for the transect (Fig. 14f) correlated well with the nitrate-nitrite and phosphate distributions. The silicate concentration in the mixed region was 2.5- 3.0 uM. However, the concentrations increased to greater than 3.5 uM within the tidally mixed region as the coastline was approached.

Silicate is one of the most variable of the nutrients with high inputs from rivers and silica dissolution from nearshore sediments (Dugdale, 1976). A silicate concentration of 25- 30 uM was sampled in an area with a salinity of 4 ‰ on the west coast of South Island. This suggests that the higher nearshore silicate concentrations were due to coastal inputs. The silicate concentration was approximately 1.2 uM in the surface offshore stratified region. The maximum concentration in the bottom water of the stratified region was between 4.5- 5.0 uM.

The nitrate-nitrite to phosphate ratio was approximately 10:1 in the tidally mixed region. The stratified offshore region had a nitrate-nitrite to phosphate ratio of 2:1 in the surface waters and 11:1 in the bottom waters. The nitrate-nitrite to silicate ratio was approximately 1.7:1 in the inshore tidally mixed region. The stratified offshore region had a nitrate-nitrite to silicate ratio of approximately 0.4:1 in the surface waters and a ratio of approximately 1.9:1 in the bottom waters.

The biological parameters of chlorophyll 'a' and primary production for the Pelorus Sound section are illustrated in Figures 15a and b. Low chlorophyll 'a'

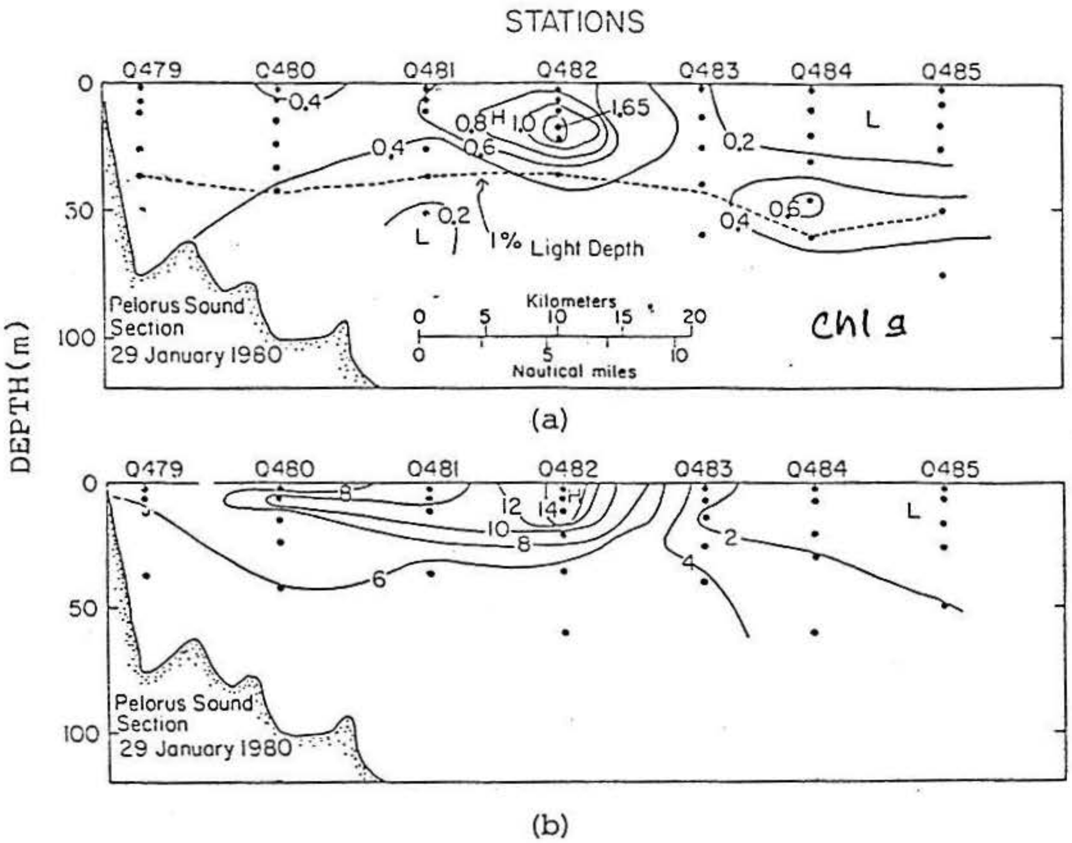

Fig. 15. Vertical distribution of biological properties for Pelorus Sound transect: a) chlorophyll 'a' (mg m^{-3}), b) primary production (mg C $m^{-3}hr^{-1}$), (courtesy P. Lapennas).

concentrations of 0.3- 0.4 mg m^{-3} are present in the tidally mixed region. Nutrient levels are sufficient for net growth in the well mixed region but light is expected to be a limiting factor in this region because of the depth of mixing. In the surface waters of the well stratified region, nutrients become depleted and are expected to be a limiting factor to phytoplankton growth (Pingree et al., 1976). Figures 14b, 14d and 14f show the low surface nutrient levels at stations in the stratified region. Figure 15a shows a low surface chlorophyll 'a' concentration of less than 0.2 mg m^{-3} for stations in the stratified region, that corresponded to the low nutrient levels. In addition, Figure 15a indicated that there were increased chlorophyll 'a' concentrations near the depth of the thermocline in the stratified regions. The phytoplankton associated with this chlorophyll 'a' increase are first in line to utilize nutrients mixed up from the bottom layer and still maintain enough stability to prevent sinking into the bottom layer (Pingree et al., 1976).

The maximum chlorophyll 'a' concentrations (Fig. 15a) were found in the marginally stratified water on the offshore side of the frontal boundary in the area of Station Q482. The chlorophyll 'a' maximum 1.65

mg m^{-3} at Station Q482 was approximately 8 times the concentration found in the surface stratified region. The chlorophyll 'a' maximum on the stratified side of the tidal mixing front was due to a sufficient supply of nutrients from the adjacent mixed region and the increased stability (Pingree et al., 1976).

The primary productivity maximum at Station Q482 (Fig. 15b) corresponded to the chlorophyll 'a' maximum (Fig. 15a). The high rate of primary production in Figure 15b corresponded to a relatively low chlorophyll 'a' maximum indicating that phytoplankton losses due to advection and herbivore grazing were significant in the area of this tidal mixing front.

IV.4 Leg 1 HMNZS Tui 1981 Cruise

The tidally mixed region around D'Urville Island and the eastern Marlborough Sounds was surveyed on leg 1 of the 1981 HMNZ Tui cruise, during a period of neap tides in Cook Strait. The cruise track and station positions for leg 1 is illustrated in Figure 16. The survey of the tidal mixing regions on leg 1 occurred during a period of moderate northerly to westerly winds in Cook Strait. A wind vector diagram for the 1981 cruise is illustrated in Figure 17.

The surface distribution of nitrate-nitrite for leg 1 is illustrated in Figure 18. Figure 18 indicated

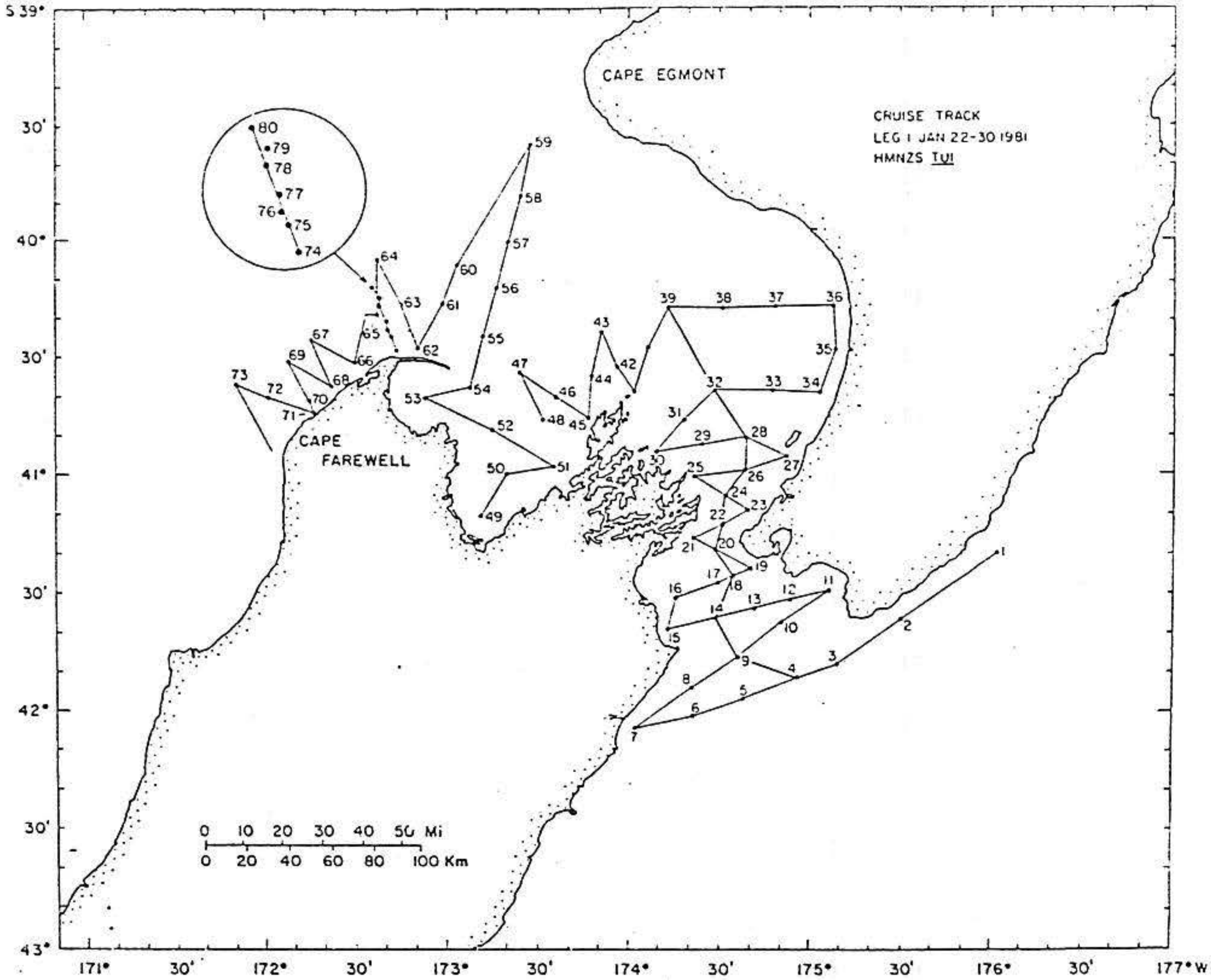

Fig. 16. Cruise track and station positions for leg 1, January 22- 30, 1981.

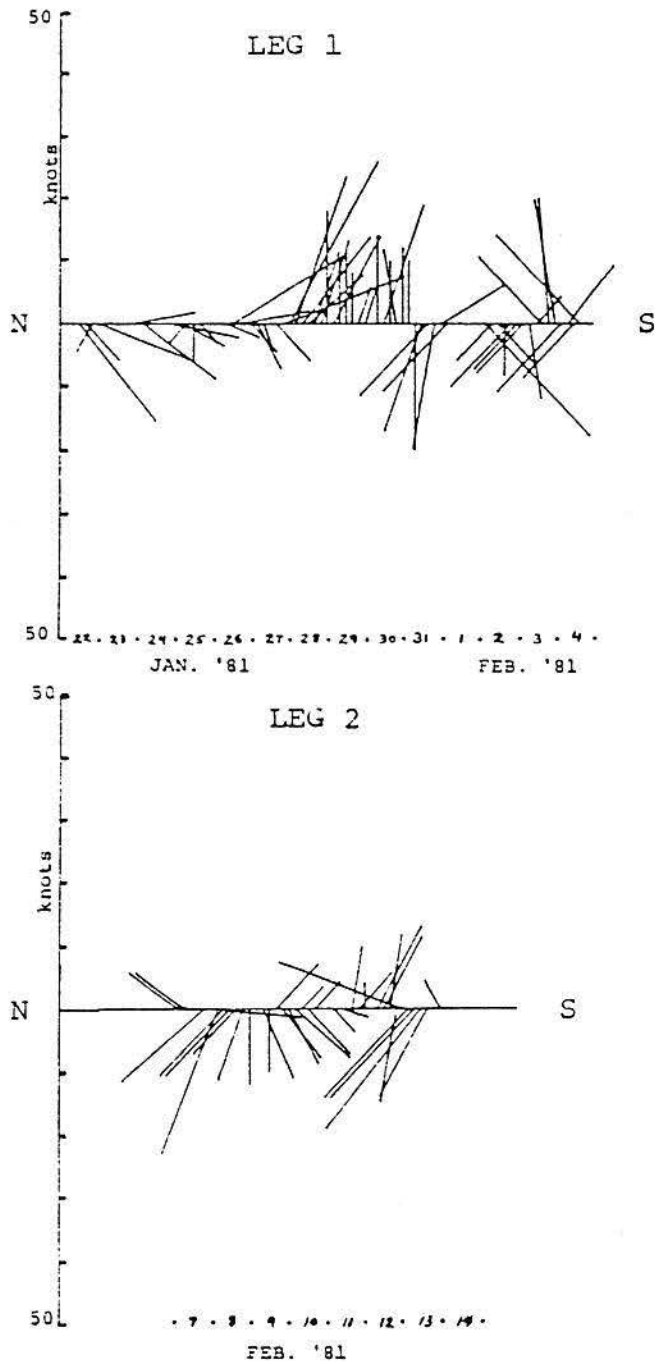

Fig. 17. Surface wind vectors diagram for January 22-February 14, 1981 Data source: ship anemometer.

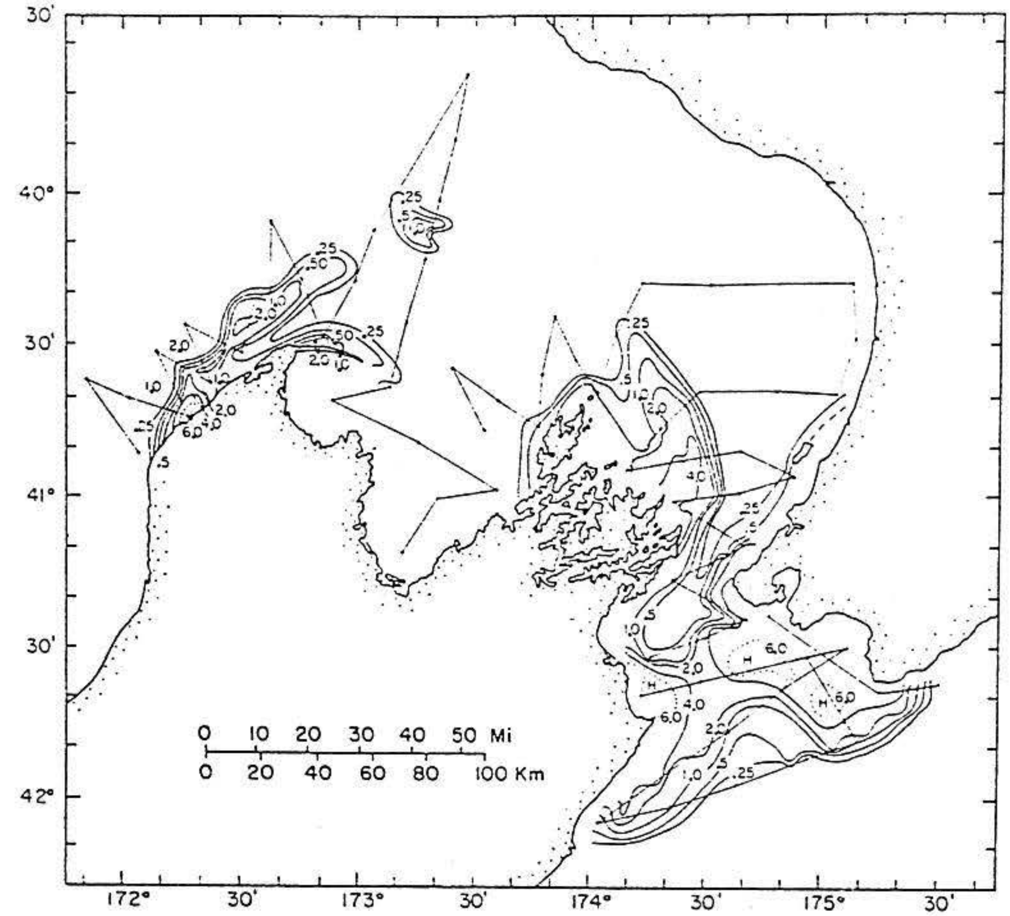

Fig. 18. Surface nitrate-nitrite distribution (uM) for leg 1, January 22- 30, 1981.

that the nitrate-nitrite distribution was similar in shape and extent to leg 2 of the 1980 cruise. The highest nitrate-nitrite concentration for the tidally mixed regions occurred in the area off the eastern Marlborough Sounds with a value of approximately 4.9 uM. Concentrations of less than 0.25 uM were found in the surface stratified waters seaward of the mixing front. The surface nitrate-nitrite distribution indicated the increased stability of the Pelorus Sound area by the inflection of the contours of the frontal boundary indicating lower values in this area.

The surface distribution of silicate for leg 1 is illustrated in Figure 19. The surface silicate distribution showed the same general pattern as the nitrate-nitrite distribution. The surface contours of silicate indicated that the gradients in concentration were not as sharp as the surface gradients of nitrate-nitrite. The highest concentrations of silicate in the tidally mixed regions were located off the eastern Marlborough Sounds with values between 4.0- 4.5 uM. The silicate concentration in the surface stratified waters offshore of the frontal boundary was approximately 0.7- 0.8 uM.

Contributions of silicate from rivers along the coast of the northeastern Taranaki Bight can be seen

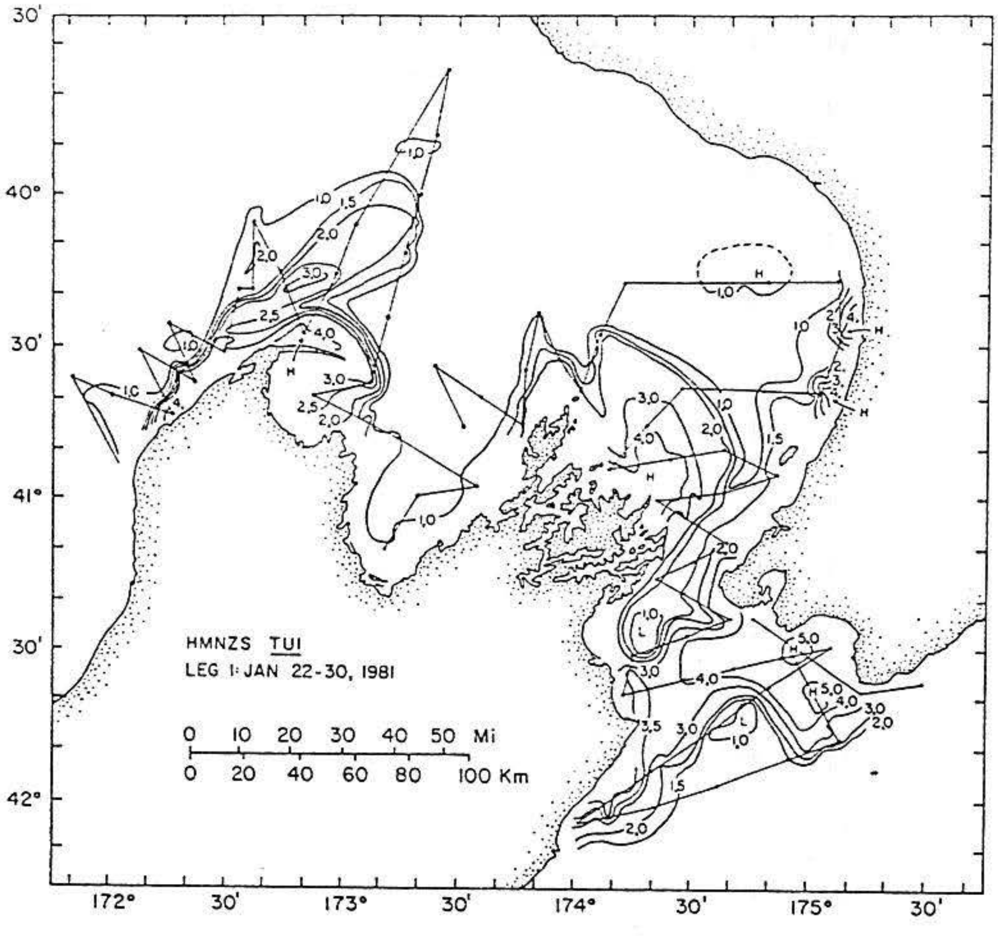

Fig. 19. Surface silicate distribution (uM) for leg 1, January 22- 30, 1981.

as two plumes of elevated silicate values with maximum concentration of 4.5- 5.0 uM and no corresponding increased nitrate-nitrite values.

The surface distribution of phosphate for leg 1 of the 1981 cruise is illustrated in Figure 20. Due to instrumental problems very little data is available on the surface phosphate distribution for the tidal mixing region. However, the available data on the phosphate distribution appears to follow the nitrate-nitrite distribution closely.

The temperature distribution for leg 1 of the 1981 cruise is illustrated in Figure 21. The temperature values are inversely related to the nutrient concentrations and showed good correlation with the nutrient distributions. The lowest temperatures for the tidal mixing regions were found off the eastern Marlborough Sounds. A temperature of 14.6 ^{o}C corresponded to the high values of nitrate-nitrite and silicate in the area of the eastern Marlborough Sounds.

The surface chlorophyll 'a' distribution for leg 1 of the 1981 cruise is illustrated in Figure 22. The highest concentrations of chlorophyll 'a' in the area of the tidal mixing regions occurred off the Pelorus Sound area with values greater than 1 mg m^{-3}.

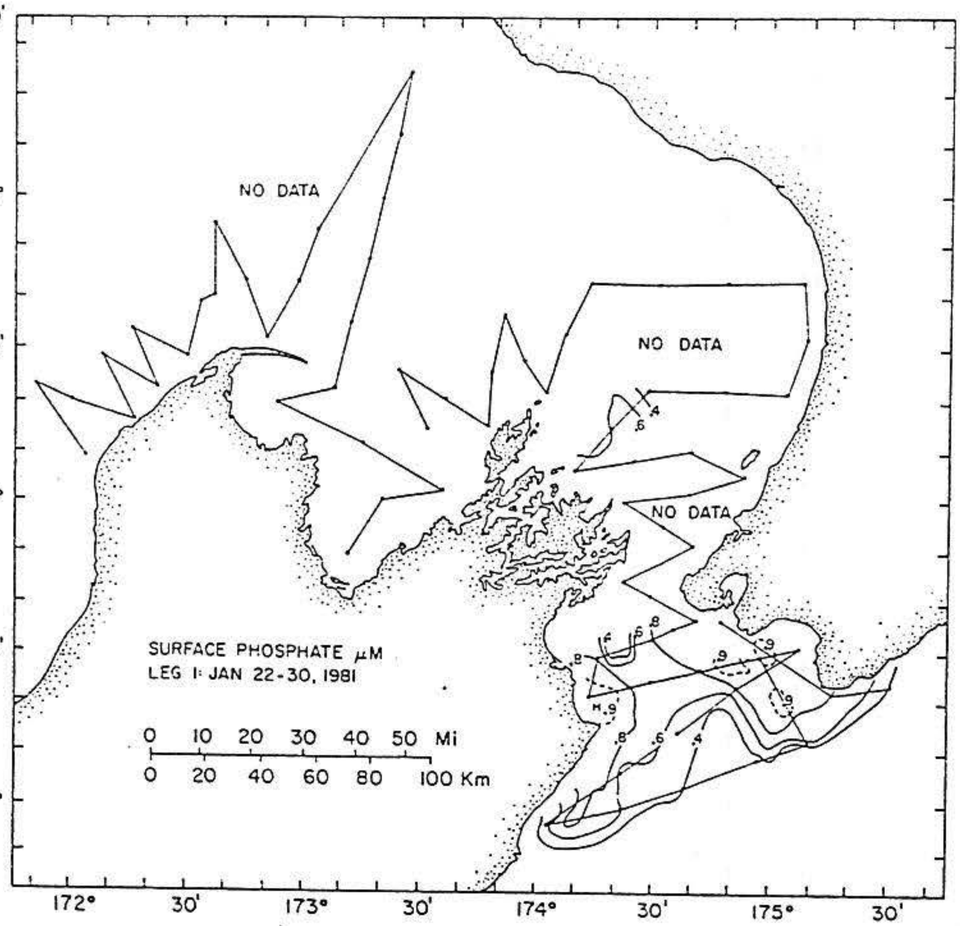

Fig. 20. Surface phosphate distribution (uM) for leg 1, January 22- 30, 1981.

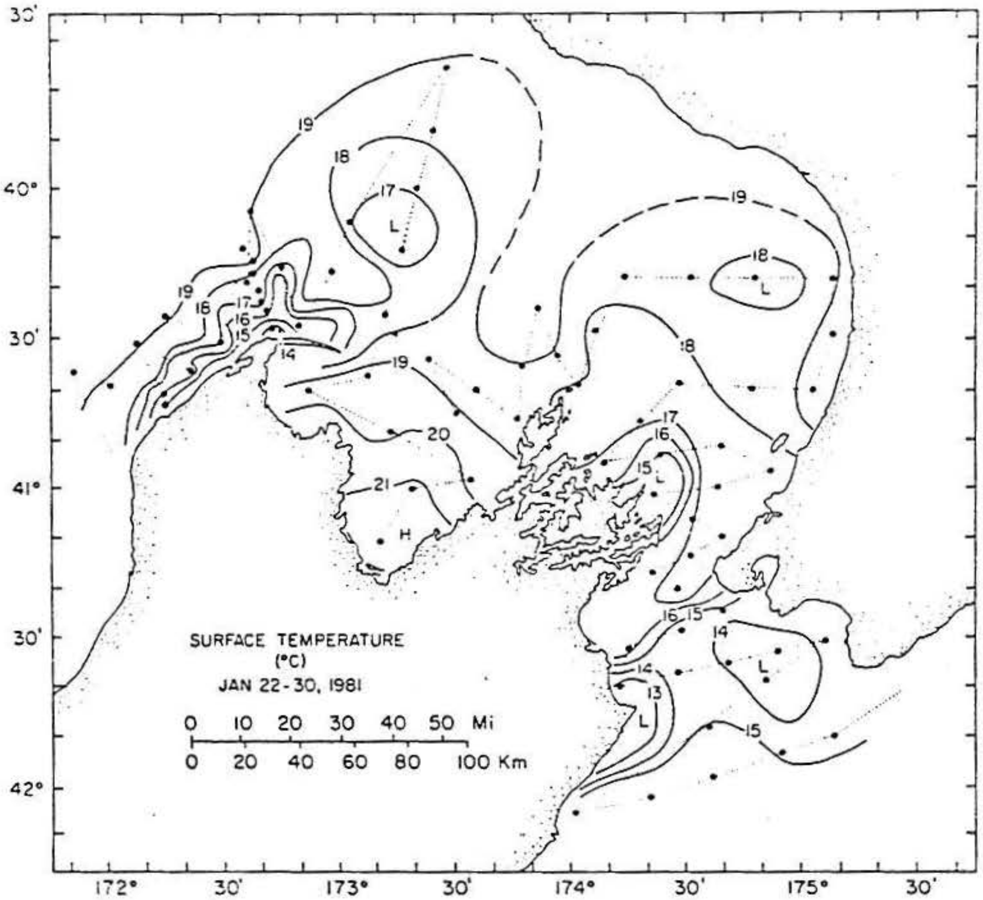

Fig. 21. Surface temperature distribution (°C) for leg 1, January 22- 30, 1981, (Bowman et al., in press b).

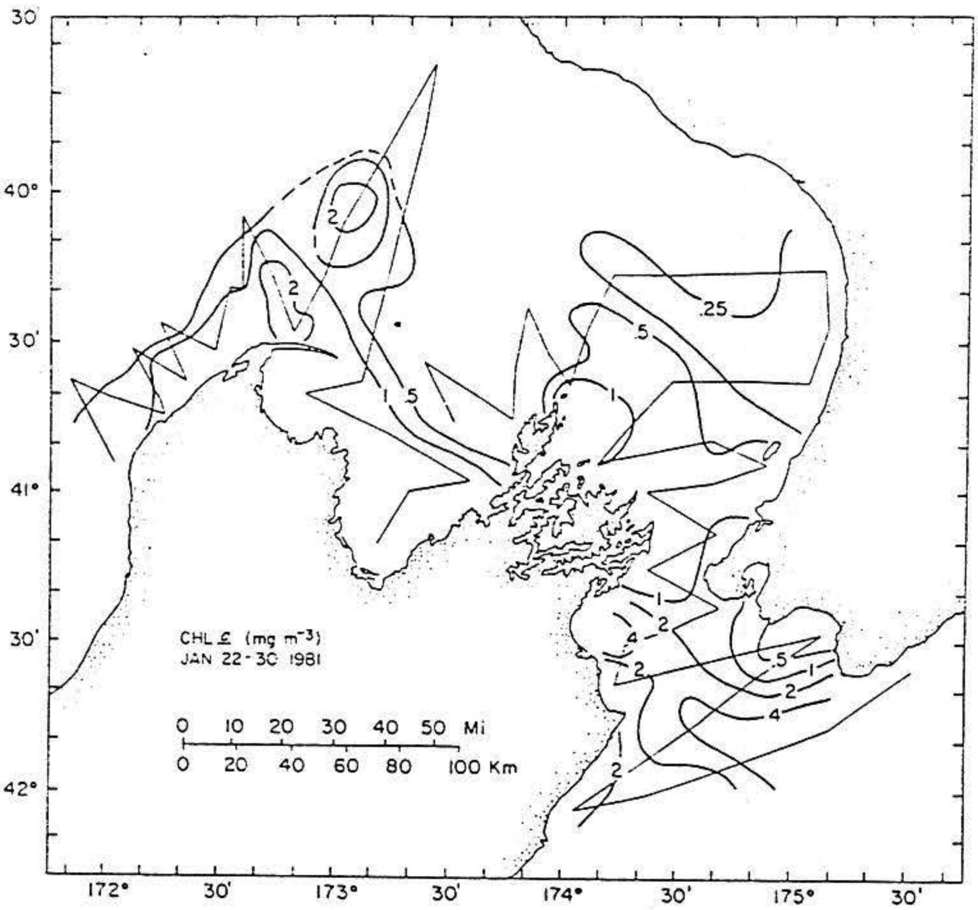

Fig. 22. Surface chlorophyll 'a' distribution (mg m^{-3}) for January 22- 30, 1981, (courtesy P. Lapennas).

IV.5 Discussion

The nutrient and temperature distributions for leg 1 of the 1980 cruise showed excellent agreement with the regions that are predicted as tidally mixed by the non-linear M_2 tidal model of Bowman et al. (1980), except for the area off Patea. Vertical profiles of nutrient and temperature in the area off Patea indicate that there was no source of cold, nutrient rich bottom water to mix upward on the shallow shelf off Patea. The nutrient and temperature data indicated that the major mechanism effecting these distributions within Cook Strait during the period of southerly winds on leg 1 was tidal mixing.

The greater extent of the tidal mixing region on leg 2 of the 1980 cruise compared to leg 1, despite the fact that both legs of the cruise occurred at the same state of neap tides, indicated that the advective flow had a large influence on the extent of the mixed region. Since the turbulent energy dissipation rate per unit mass is inversely proportional to the depth divided by the velocity cubed, a change in the mean velocity due to advection will influence the extent of a mixed region.

In addition to the modifications in the extent of the mixed region due to the advective flow, there are possible influences from wind induced upwelling. However, although the extent of the mixed region was much greater for leg 2 compared to leg 1, the absolute values of the nitrate-nitrite concentrations were similar for both surveys. The nitrate-nitrite concentrations ranged from 2- 4 uM in the well mixed regions off D'Urville Island and the eastern Marlborough Sounds and approximately 0.5 uM in the stratified waters offshore of the frontal boundary (Fig. 11). These concentrations suggest that tidal mixing modified by an advective flow was the predominant mechanism supplying nutrients to the surface layers, as opposed to wind induced upwelling with expected nitrate-nitrite concentrations of 6- 8 uM. The nitrate-nitrite concentrations in the tidal mixing regions of Cook Strait are similar to the range in concentrations reported by Pingree et al. (1978) for the tidal mixing regions on the northwest European shelf.

A vertical section of the tidal mixing front was sampled off Pelorus Sound on leg 2 of the 1980 cruise. The vertical distributions of the physical and chemical properties indicated the classical structure of a tidal mixing system. The vertical section of chlorophyll 'a' for Pelorus Sound indicated that the chlorophyll 'a' maximum was found in the marginally stratified water on the offshore side of the frontal zone.

A supply of silicate is required by diatoms to synthesize their frustules (Davis et al., 1978). The high nitrate-nitrite to silicate ratio in the well mixed region and the sharp gradient in the nitrate-nitrite to silicate ratio in the region of the tidal mixing front suggests that diatoms were important contributors to the species composition in the well mixed and frontal regions. The low nitrate-nitrite to silicate ratio in the surface stratified region suggests that small flagellated forms, which do not require silicate, are the most abundant phytoplankton in the stratified region. Simpson et al. (1979) and Pingree et al. (1978) found a similar distribution of phytoplankton species in corresponding tidal mixing regions on the western European shelf.

The front in the Pelorus Sound transect was more diffused than other areas in the tidal mixing region, as indicated in Figure 11. This was consistent with the fact that the M_2 tidal model of Bowman et al. (1980) predicts this as an area of marginal stability, between the well mixed regions off D'Urville Island and the eastern Marlborough Sounds. Consequently changes in the tidal streaming and advective flow will result in large onshore-offshore movements of the frontal boundary in the Pelorus Sound area. Simpson _et al_. (1978) state that areas of intermittent stability with large movements in the frontal zone could be important in the biological process. The periodic release of nutrients from mixing and subsequent stability is important in phytoplankton growth (Pingree _et al_., 1977). This is consistent with the fact that the surface chlorophyll 'a' distribution (Fig. 12) indicated a chlorophyll 'a' maximum off Pelorus Sound and the eastern Marlborough Sounds in a region of intermittent stability with large movements in the frontal zone.

The tidal mixing front represents a strongly baroclinic zone in approximate geostrophic balance (Simpson, 1976). The degree to which the system is in geostrophic balance is not fully known but friction does play some part and the velocities calculated along frontal zones will be somewhat over estimated (Simpson _et al_., 1974). The baroclinic jet derived from the geostrophic balance will flow parallel to the tidal mixing front. However, the frictional damping will produce an unbalanced pressure field and sets up a circulation perpendicular to the front. The result is an upwelling and divergence on the well mixed side in the area of the front and with a downwelling and convergence on the stratified side in proximity to the front (Simpson, 1976).

The existence of a phytoplankton patch at the front must be considered in terms of achieving a balance between loses from dispersal plus grazing and enhanced growth from increased nutrients plus aggregation due to a convergence (Pingree *et al.*, 1976).

The magnitude of the geostrophic shear across the front can be calculated using the thermal wind equation:

$$\Delta V = g/f\rho \cdot \Delta\rho/\Delta x \cdot \Delta z$$

where g is gravity, f is the coriolis parameter, ρ is the density, Δz is the depth interval, and $\Delta\rho/\Delta x$ is the horizontal density gradient (Simpson *et al.*, 1979).

The geostrophic velocity across the frontal boundary can be calculated from the density section for the Pelorus Sound transect (Fig. 14e). This flow, estimated as 6 cm sec^{-1}, flows parallel to the front and is directed towards Cook Strait Narrows. This relatively weak baroclinic zone was a consequence of the diffuse frontal boundary off Pelorus Sound. Areas with stronger baroclinic zones such as the eastern Marlborough Sounds, would be expected to possess stronger geostrophic velocities parallel to the front. As a comparison, Simpson et al. (1974) have calculated geostrophic velocities of approximately 30 cm sec^{-1} for tidal mixing fronts on the western European shelf.

The ammonium distributions for leg 2 of the 1980 cruise indicated generally low values of ammonium at the surface with slightly higher values for the mixed regions. The main pathway of nitrogen utilization in surface stratified oligotrophic waters is considered to be recycled ammonium (Lorenzen, 1976). The recycled ammonium is quickly utilized by the phytoplankton maintaining low ambient concentrations in the upper layers of the water column (Lorenzen, 1976).

Vertical profiles of ammonium in stratified regions of Cook Strait generally indicate low concentrations below the thermocline. In stratified regions at depths below the thermocline most of the ammonium is oxidized to nitrate, which forms the major inorganic nitrogen reservior (Redfield et al., 1963). Ammonium concentrations in some of the vertical profiles for the stratified regions indicated a subsurface maximum of approximately 1.2 uM at about

30 m. Walsh et al. (1974) also observed a subsurface ammonium maximum and attributed this maximum to a possible balance between excretion by herbivores and light limited uptake by phytoplankton. In addition, some elevated ammonium values were encountered in nearshore areas adjacent to estuaries and in samples taken close to the bottom. The elevated ammonium values in these areas are probably due to increased biological activity and flux of ammonium from the sediments.

The surface nutrient distributions for leg 1 of the 1981 cruise (Fig. 18, 19, and 20) and the surface temperature distribution (Fig. 21) all had deep inflections in the contours into the narrows of Cook Strait indicating an advective flow from west to east on leg 1 of the 1981 cruise. The tidal mixing region on leg 1 of the 1981 cruise was much more extensive than the tidal mixing region on leg 1 of the 1980 cruise, similar to leg 2 of the 1980 cruise.

One of the factors influencing the fluctuations in the extent of the tidal mixing region with changes in the mean velocity is the bathymetry of the region. There is no significant change in the bathymetry for a large distance seaward of the tidal mixing regions off D'Urville Island and the eastern Marlborough Sounds, except for the upper reaches of the Cook Strait Canyon that extends into the Taranaki Bight. The position of the tidal mixing front and therefore, the extent of the tidally mixed region is inversely proportional to h/u^3. When there is no slope to the bottom then the depth h is a constant and any changes in the velocity u will result in large fluctuations in the extent of the tidally mixed region (Pingree et al., 1978). In addition, gradients in the contours of the stratification index are widely spaced off the eastern Marlborough Sounds indicating the potential for large movements in the frontal boundary. Therefore, due to a gentle slope in the bathymetry (Fig. 2) and wide gradients in the stratification index (Fig. 3), the extent of the tidal mixing region off the eastern Marlborough Sounds will have large fluctuations with changes in the tidal streaming and advective flows.

The surface chlorophyll 'a' distribution for leg 1 of the 1981 cruise (Fig. 22) indicated that the chlorophyll 'a' maximum was located in the area of intermittent stability off Pelorus Sound in agreement with the previous chlorophyll 'a' data. This maximum corresponded to an area of lower nutrient values indicated by an inflection in the nutrient contours of the tidal mixing front.

Chapter V

Upwelling in Cook Strait

V.1 Introduction

Coastal upwelling can occur as the result of several physical mechanisms: as a compensatory flow of cold bottom water upward when surface water is transported offshore by the wind, when water flows over a region of decreasing depth, or flows around a promontory. The highly variable nature of the winds and topography of the central New Zealand coastal shelf suggests the importance of upwelling in these waters. Upwellings in the Cook Strait area have been discussed by Stanton (1971) and Heath (1971). A combination of temperature, salinity, and nutrient data was utilized on the 1980 and 1981 cruises to delineate the sources and extent of upwelling in Cook Strait.

V.2 Leg 1 R/V Tangaroa 1980 Cruise

A period of strong southerly winds preceded leg 1 of the 1980 cruise. The winds reached a velocity of 25 m sec^{-1} on January 3, 1980 (J. Bradford, Pers. Comm.). During the beginning of leg 1 the wind continued to blow from a southerly direction until January 12, 1980 with a velocity of approximately 5 m sec^{-1} or less. The wind vectors for leg 1 are illustrated in Figure 5 and the cruise track has already been illustrated in Figure 4.

The surface distribution of nitrate-nitrite for leg 1 (Fig. 7) indicated that there was no intrusion of oligotrophic water from the Taranaki Bight. This suggests that there was no advective flow from west to east in Cook Strait at this time. The surface distribution of nitrate-nitrite within Cook Strait on leg 1 appeared to be mainly determined by tidal mixing. However, a region of elevated nitrate-nitrite values was observed off Cape Palliser in the eastern approaches to Cook Strait. The nitrate-nitrite concentration in the upwelling region off Palliser Bay ranged from 4.0 to 5.0 uM. The nitrate-nitrite concentration in the oligotrophic surface waters to the east of Palliser Bay was less than 0.3 uM.

The ammonium concentration in the upwelling region off Palliser Bay was slightly higher than the surrounding oligotrophic waters. Ammonium concentrations in the upwelling region was approximately 0.4 to 0.5 uM, while the ammonium concentrations in the surface oligotrophic waters to the east of the upwelling region off Palliser Bay was approximately 0.2 to 0.3 uM.

The surface temperature distribution for leg 1

(Fig. 8) indicates a temperature minimum corresponding to the region of high nitrate-nitrite values off Palliser Bay. Figure 8 indicates a surface water temperature 13- 14 °C in the upwelling region and a surface temperature of approximately 17 °C in the oligotrophic water to the east of Cape Palliser. The salinity was approximately 34.5 ‰ in the surface water of the upwelling region corresponding to the lowest temperatures and highest nitrate-nitrite values.

A combination of the temperature, salinity and nitrate-nitrite data indicated that the source of the upwelling off Palliser Bay was Southland Current water. The temperature and salinity characteristics of Southland Current water as described by Heath (1975) and represented by Station D860 is illustrated in Figure 23.

V.3 Leg 2 R/V Tangaroa 1980 Cruise

The second leg of the 1980 cruise took place subsequent to and during a period of strong north to northwesterly winds. Winds from a northerly to westerly direction are recorded as present 41% of the days in the central New Zealand region (Brodie, 1960). The wind velocity was approximately 6 m sec^{-1} on January 26 and increased to approximately 13 m sec^{-1}

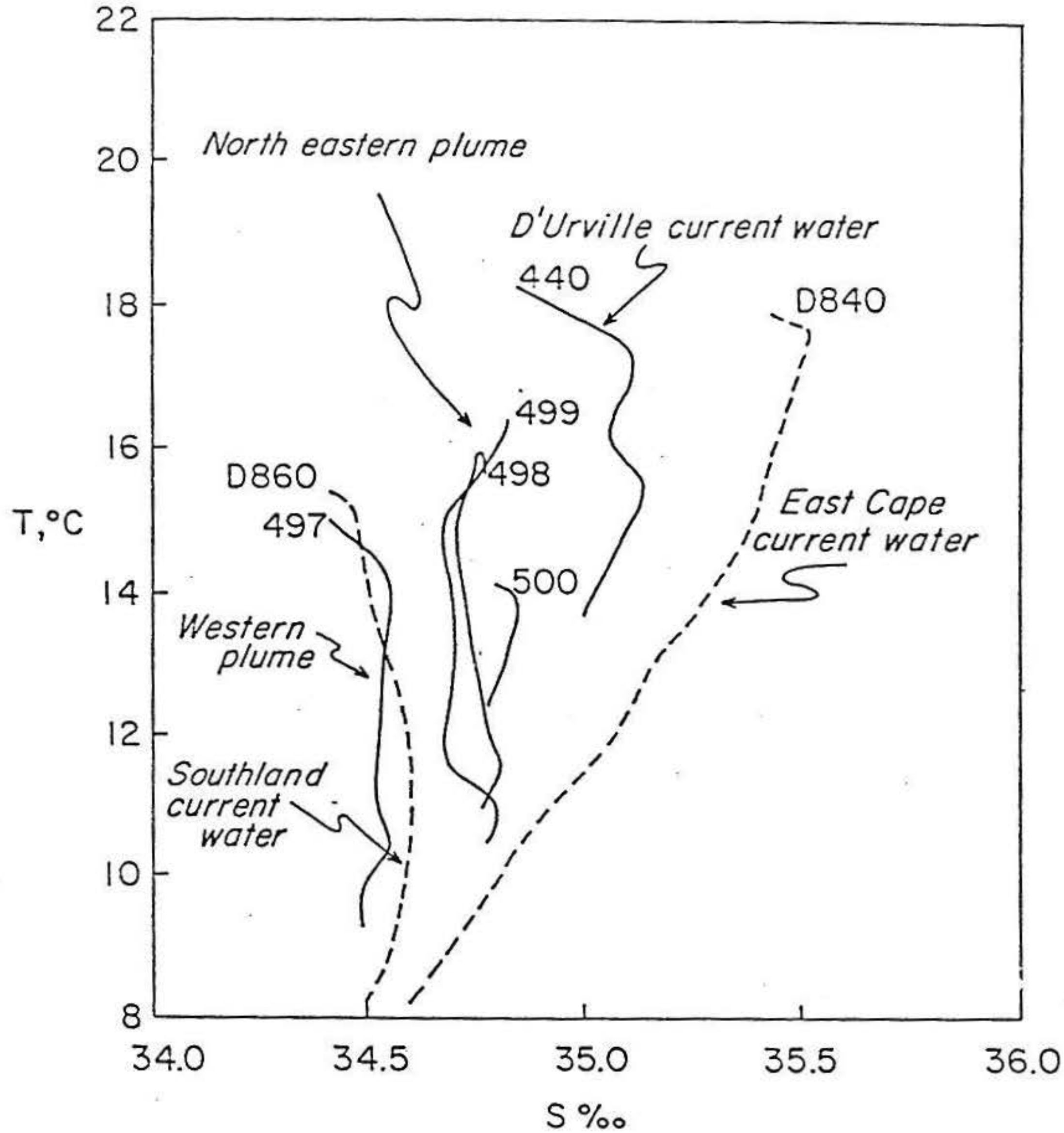

Fig. 23. Temperature-salinity diagram for the north-eastern section of the plume, January- February, 1980, (Bowman et al., in press c).

on January 27 and 28, 1980. The wind velocity subsided to approximately 6 m sec^{-1} on January 29 and then increased to a maximum velocity of 17 m sec^{-1} on January 30 and 31, 1980. The cruise track for leg 2 is illustrated in Figure 10.

Contours of surface nitrate-nitrite values for this survey are illustrated in Figure 11. The deep inflection in the contours of nitrate-nitrite into the narrows of Cook Strait from the west indicated that strong advective flow from west to east was taking place in Cook Strait. Nitrate-nitrite concentrations of 0.5- 0.75 uM indicated an intrusion of oligotrophic waters from the Taranaki Bight through Cook Strait Narrows. Contours of nitrate-nitrite values (Fig. 11) showed steep gradients on both sides of Cook Strait Narrows. Values decreased by 4 uM in a distance of 3.5 km offshore from the western side of Cook Strait Narrows. These steep nitrate-nitrite gradients are associated with the largest currents resulting from the advective intrusion of oligotrophic waters into the narrows.

The surface temperature distribution for leg 2 (Fig. 12) indicated the intrusion of high temperature (approximately 17 ^{o}C) oligotrophic water with corresponding low values of nitrate-nitrite into the narrows.

Drogue experiments carried out by B. Sanderson gave further confirmation of the presence of the advective flow from west to east in Cook Strait during this period. Drogue trajectories from leg 2 are illustrated in Figure 24. The velocities of the drogues that passed through Cook Strait Narrows were averaged over a 14 day period. Each drogue trajectory is represented by a relatively straight line between the starting point and the pickup point. Therefore, surface water velocities calculated from these trajectories are an underestimate of the actual velocities. A velocity of 26 cm sec^{-1} was calculated from the trajectory of drogue number 28 that passed through Cook Strait Narrows.

A series of hydrostations were sampled on leg 2 forming a transect from Cook Strait Narrows to Clifford Bay. The transect included Stations Q486-Q491 and the locations are illustrated in Figure 10. Vertical sections of the physical and chemical properties for this transect are illustrated in Figures 25a to f. The figures show that all the isopleths bend upward toward the surface indicating that upwelling was taking place.

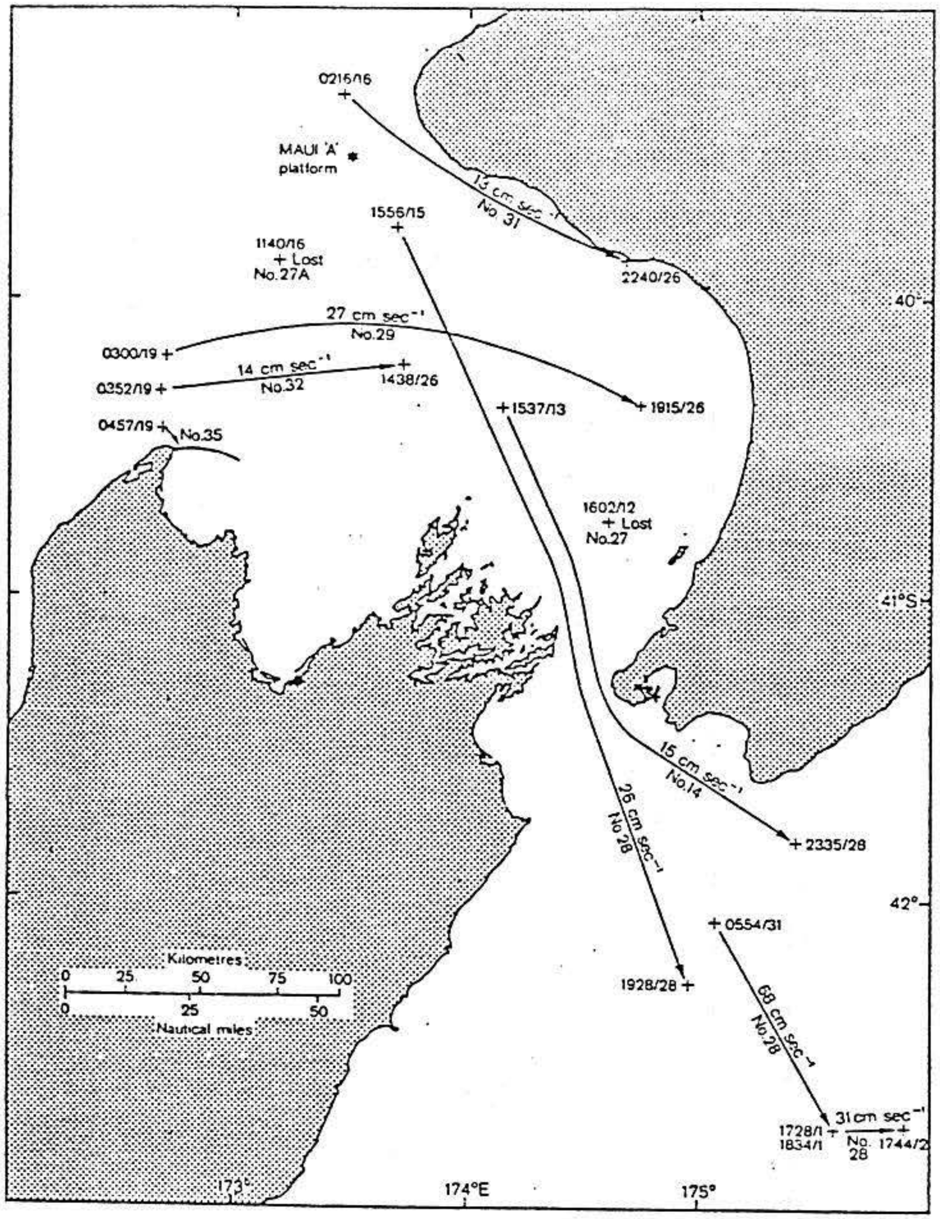

Fig. 24. Hypothetical drogue trajectories January 15- February 2, 1980, (Bowman _et al._, in press c).

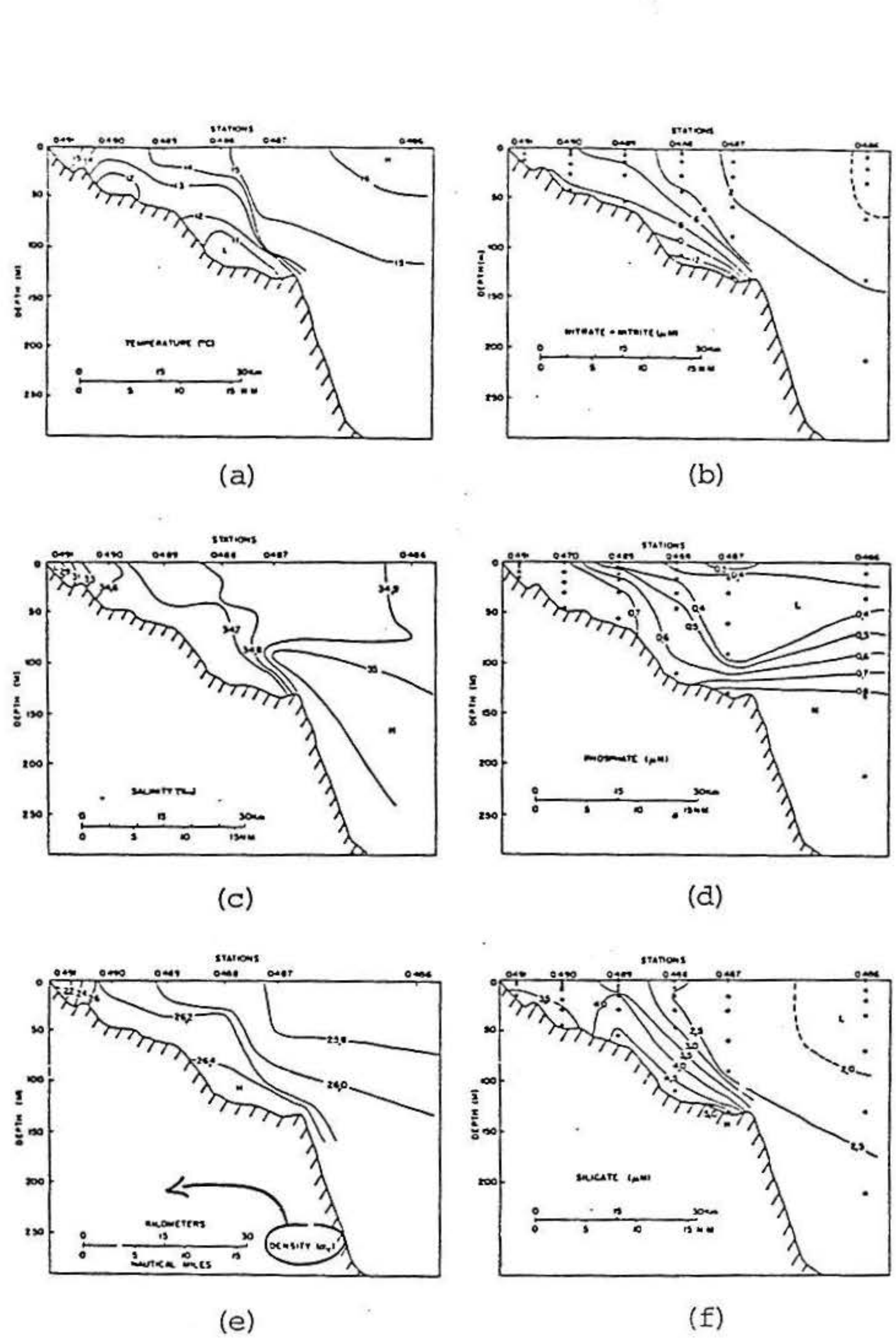

Fig. 25. Vertical distribution of physical and chemical properties for Clifford Bay transect on 1980 cruise: a) temperature (^{O}C), b) nitrate-nitrite (uM), c) salinity (o/oo), d) phosphate (uM), e) density (σ_{τ}), f) silicate (uM).

The vertical section of nitrate-nitrite values (Fig. 25b) indicated a maximum value of 6.5 uM at the nearshore Stations Q491 and Q490. The nitrate-nitrite concentrations decreased to a minimum of approximately 0.5 uM at Station Q486 in Cook Strait Narrows.

The vertical distribution of phosphate (Fig. 25d) showed good correlation with the nitrate-nitrite distribution. The maximum phosphate value of 0.74 uM occurred at Stations Q491 and Q490 and the minimum phosphate value of 0.33 uM for the transect was located at Station Q486.

The vertical silicate distribution (Fig. 25f) is similar to the nitrate-nitrite and phosphate distributions with a nearshore maximum of 3.8 uM off Clifford Bay and a minimum for the transect of 1.9 uM in Cook Strait Narrows.

The ammonium concentrations were highest for the nearshore stations of the Clifford Bay transect. The maximum ammonium concentration of approximately 2.0 uM at a depth of 5 m was sampled at Station Q491. The ammonium values decreased to less than 0.4 uM at the offshore stations in Cook Strait Narrows.

The temperature and sigma-t values for the

Clifford Bay transect (Fig. 25a and 25e respectively) showed excellent correlation with the nutrient values. The temperature distribution was inversely related to the nutrient distributions with high temperatures corresponding to low nutrient and low temperatures corresponding to high nutrient values. Sigma-t values have a direct relationship to the nutrient values with increasing values of sigma-t corresponding to increasing nutrient values.

Chlorophyll 'a' concentrations in mg m^{-3} and primary production in mg C m^{-3} hr^{-1} for the Clifford Bay transect are illustrated in Figures 26a and b respectively. Figure 26a indicates that chlorophyll 'a' values were relatively low for the entire transect. A slight increase in chlorophyll 'a' and primary production is indicated in the nearshore stations of Clifford Bay. The decrease in the depth of mixing in the shallow water stations of Clifford Bay permitted some net accumulation of phytoplankton despite strong transport of water eastward out of the bay.

The presence of Southland Current water on the shelf off Clifford Bay is readily indicated in Figures 25a to f by the temperature, salinity, and nutrient characteristics of the water mass. The water below

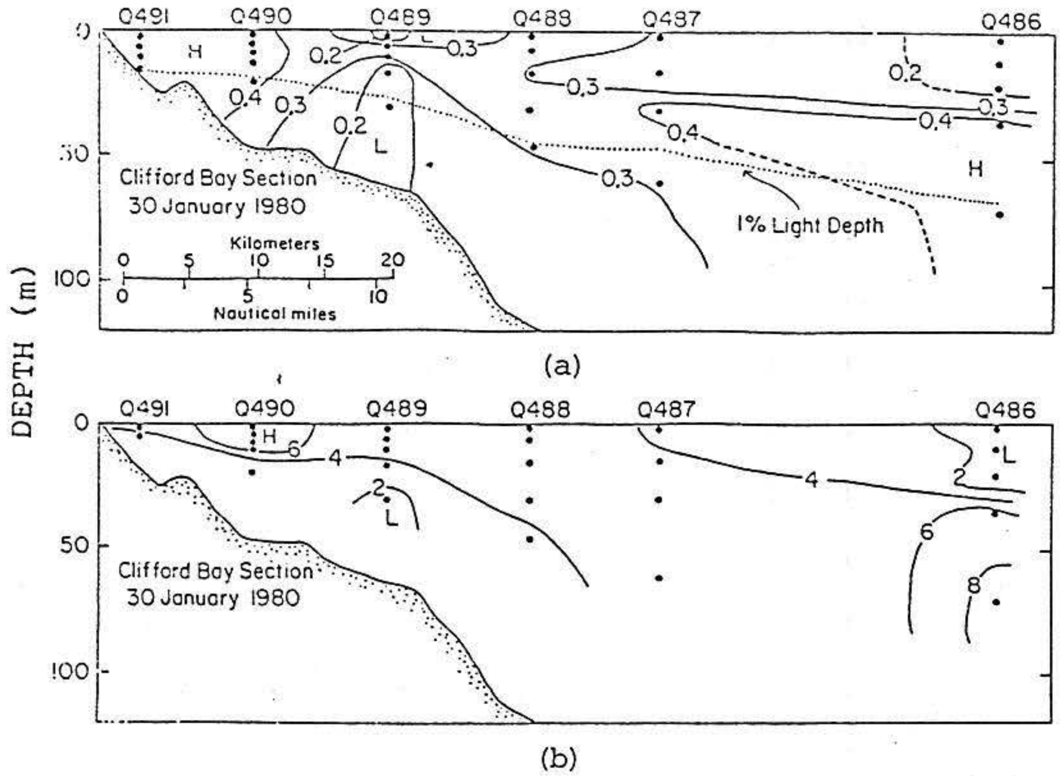

Fig. 26. Vertical distribution of biological properties for Clifford Bay transect: a) chlorophyll 'a' (mg m^{-3}), b) primary production (mg C $m^{-3}hr^{-1}$), (courtesy P. Lapennas).

70 m on the Clifford Bay shelf had a salinity of 34.6 ^{o}/oo or less, and a temperature that ranged from 12^{o} C to less than 11^{o} C. The nitrate-nitrite values associated with this salinity and temperature regime ranged from 10.0 uM to approximately 12.0 uM at 100 m. Water of D'Urville Current origin is approximately 35.0 ^{o}/oo and 13^{o} C at 130 m with a nitrate-nitrite concentration of approximately 8.0 uM. East Cape Current water at a depth of 130 m has a salinity of approximately 35.3 ^{o}/oo and a temperature of approximately 13^{o} C. However, Southland Current water with a salinity of 34.6 ^{o}/oo has a relatively shallow thermocline and nutricline. At a depth below 60 m Southland Current water has a temperature of less than 11^{o} C and nitrate-nitrite values greater than 10 uM. In addition, the nitrate-nitrite to silicate ratio of 3.2 for Southland Current water at a depth of 130 m is more representative of the 2.7 nitrate-nitrite to silicate ratio of the water at 130 m on the shelf off Clifford Bay than the 1.7 ratio of D'Urville Current water at 130 m in the Taranaki Bight. As a result, the temperature, salinity, and nutrient data indicated that the bottom water on the shelf off Clifford Bay is of Southland Current origin.

V.4 Leg 1 HMNZS Tui 1981 Cruise

A general survey of Cook Strait was undertaken on leg 1 of the 1981 HMNZS Tui cruise. The cruise track and station locations from January 22 to January 30, 1981 is illustrated in Figure 16. The survey occurred during a period of moderate northerly to westerly winds with a maximum wind speed of approximately 15 m sec^{-1} between January 22 and January 27, 1981. A wind vector diagram for the 1981 HMNZS Tui cruise is illustrated in Figure 17.

Contours of surface nitrate-nitrite values for leg 1 are illustrated in Figure 18. The nitrate-nitrite distribution indicated that advection from west to east was taking place in Cook Strait Narrows during the period of northerly and westerly winds. An intrusion of oligotrophic water from the Taranaki Bight with a nitrate-nitrite concentration of approximately 0.25 uM is indicated in Figure 18. The presence of oligotrophic water in Cook Strait Narrows is also indicated in the surface distribution of silicate and phosphate illustrated in Figures 19 and 20 respectively. Concentrations in the water passing through Cook Strait Narrows were approximately 1.0 uM for surface silicate and 0.3 uM for surface phosphate.

The surface nitrate-nitrite distribution (Fig. 18) indicated that the maximum nitrate-nitrite concentrations were located nearshore off Clifford Bay. The maximum surface nitrate-nitrite value in the upwelling region was 7.3 uM. The surface silicate and phosphate distributions (Fig. 19 and 20 respectively) showed good correlation with the nitrate-nitrite distribution. The maximum concentrations of phosphate and silicate in the upwelling region were approximately 1.0 uM and 3.7 uM respectively. The surface nitrate-nitrite values indicated increased surface concentrations in two regions within the eastern approaches of Cook Strait located just south of the North Island. One region was located off Wellington and the other region was located off Cape Palliser. The two regions had surface nitrate-nitrite concentrations of 6.5 uM to 7.0 uM. The corresponding surface silicate concentrations in the regions were 4.8 uM to 5.0 uM and the surface phosphate concentrations were approximately 0.95 uM.

The surface temperature distribution illustrated in Figure 21 showed good correlation with the nutrient distributions. Figure 21 indicated the intrusion of

17.5 °C water in Cook Strait Narrows. Areas of lowest water temperature were associated with the highest nutrient values. The upwelling region off Clifford Bay had surface water temperatures of approximately 12.4 °C. The two high nutrient regions between Cape Terawhiti and Cape Palliser had low temperatures of less than 13.5 °C in conjunction with the increased nutrient values.

The surface chlorophyll 'a' distribution for leg 1 of the 1981 cruise is illustrated in Figure 22. The chlorophyll 'a' concentrations were comparatively low in the upwelling regions. The upwelling region off Clifford Bay had a chlorophyll 'a' concentration of approximately 0.8 mg m^{-3}. The two upwelling regions between Cape Terawhiti and Cape Palliser also had low surface chlorophyll 'a' values of approximately 0.8 mg m^{-3}. Figure 22 indicates that the chlorophyll 'a' concentrations increased to approximately 2.0 mg m^{-3} moving toward the deeper areas in the middle of eastern Cook Strait. The chlorophyll 'a' concentration increased to greater than 4.0 mg m^{-3} in the eastern approaches of Cook Strait with a maximum of approximately 6.8 mg m^{-3} beyond the coastal shelf.

The warm water advected into Cook Strait Narrows had a surface chlorophyll 'a' concentration of approximately 0.7 mg m^{-3}. Figure 22 indicated that the oligotrophic water in the northwestern Taranaki Bight with a surface temperature greater than 18 ^{o}C had a chlorophyll 'a' concentration of less than 0.25 mg m^{-3}.

A longitudinal section of Cook Strait was produced from hydrostation data with the vertical sections of the physical, chemical and biological properties illustrated in Figures 27 a to f. The vertical distribution of nitrate-nitrite (Fig. 27b) indicated that deep water in Cook Strait Narrows between 50 m and 200 m at Station 22 was relatively homogenous. The distribution of silicate values (Fig. 27d) was consistent with the nitrate-nitrite distribution indicating that the deep water in Cook Strait was relatively homogenous compared to the surrounding water masses. Vertical distributions of temperature and sigma-t (Fig. 27a and 27e respectively) showed good correlation with the nutrient distributions. The temperature and sigma-t data for the transect also indicated comparatively homogenous water beneath the surface at Station 22 in Cook Strait Narrows.

The temperature, salinity and nutrient data combined indicate that the source of this comparatively homogenous water was the area near Station 23 shown

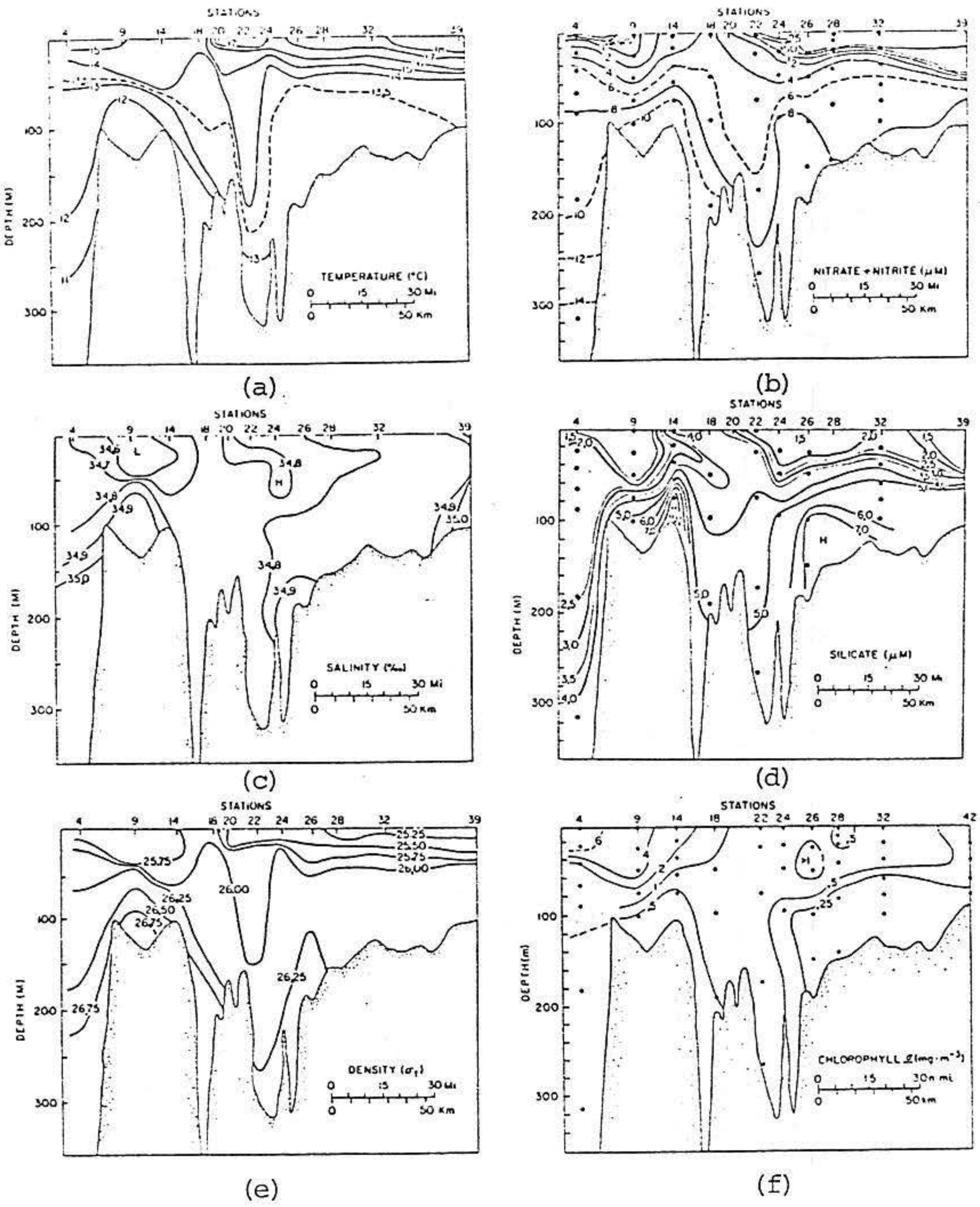

Fig. 27. Vertical distribution of physical, chemical and biological properties for the longitudinal section of Cook Strait, Jan. 22- 30, 1981: a) temperature (°C), b) nitrate-nitrite (uM), c) salinity (°/oo), d) silicate (uM), e) density (σ_t), f) chlorophyll 'a' (mg m^{-3}).

in Figure 16. The slope current produced from northerly winds in the Cook Strait region advected D'Urville Current water into the narrows along the northeastern Taranaki Bight. Downwelling of this water occurred in the proximity of Station 23, which lay just north of Cape Terawhiti at the entrance of Cook Strait Narrows. The downwelled water was introduced into Cook Strait Canyon in the central region of the Narrows near Station 22. The data suggests that this water was mixed in the narrows and subsequently advected southward.

The vertical distribution of chlorophyll 'a' for the longitudinal section of Cook Strait is illustrated in Figure 27f. Figure 27f indicates low surface chlorophyll 'a' values were present in the western Taranaki Bight. The highly stratified region in the Taranaki Bight is represented by Station 39 with a surface chlorophyll 'a' value of 0.18 mg m^{-3}. In addition, Station 39 had a high subsurface chlorophyll 'a' maximum of 2.7 mg m^{-3} associated with the base of the thermocline and a strong gradient in nutrients at 50 m. Surface chlorophyll 'a' concentrations increased to approximately 0.7 mg m^{-3} eastward toward Cook Strait Narrows. The chlorophyll 'a' values for the mixed area in Cook Strait Narrows is represented by Station 22.

Chlorophyll 'a' concentrations at Station 22 indicated small variations from the surface to a depth of 275 m. The surface chlorophyll 'a' concentration at Station 22 was approximately 0.7 mg m^{-3} and approximately 0.6 mg m^{-3} at 275 m. The phaeo-pigment concentration increased in the deep water to almost 50% of the chlorophyll 'a' value. The chlorophyll 'a' data substantiated the chemical and physical data and indicated that the water at Station 22 was downwelled into a poor light regime.

The eastern approaches of Cook Strait are represented by Stations 9 and 4 in Figure 27f. The increased stability in this region permitted the accumulation of phytoplankton biomass. The chlorophyll 'a' concentration increased to 4.7 mg m^{-3} at the surface of Station 9 and was approximately 6.8 mg m^{-3} at the surface of Station 4.

V.5 Discussion

The eastern approaches to Cook Strait is a complex region that is influenced by interactions between several water masses. Water of D'Urville Current origin flowing from west to east through Cook Strait Narrows interacts with East Cape Current water and Southland Current water to the east. The extent of the influence of each of these water masses and current systems on the circulation in eastern Cook Strait is dependent upon previous wind and weather conditions. The prolonged period of strong to moderate winds from a southerly direction prior to and during the first part of leg 1 of the 1980 cruise would not be conducive to an advective flow from west to east through Cook Strait Narrows. This is substantiated by the surface nutrient and temperature distributions, which indicated that no advective flow was taking place in Cook Strait Narrows during the period of sampling on leg 1. The major influence on the distribution of nitrate-nitrite in Cook Strait Narrows and off the Marlborough Sounds for leg 1 appeared to be tidal mixing.

The Southland Current flows northward along the east coast of South Island passing through the Mernoo Gap approximately 200 km south of Cape Cambell. The current divides near Kaikoura with one component continuing northward to influence the eastern approaches of Cook Strait and the other component meandering eastward to combine with the East Cape Current. The strength of these various components of the Southland Current are influenced by the wind and by interactions with other water masses, such as the D'Urville Current and East Cape Current in the eastern approaches of Cook Strait. As a result, the strength of the Southland

Current off any particular section of the coast will be highly variable (Heath, 1972).

Wind driven transport alters the slope of the sea surface and as a result, the barotropic component of the current velocity is also altered. Southerly winds will increase the barotropic velocity of the Southland Current by increasing the slope of the sea surface (Heath, 1970). Brodie (1960) states that strong southerly winds minimize the indraught of the D'Urville Current into Cook Strait and extends the Westland Current to the north. The period of strong to moderate southerly winds at the beginning of leg 1 resulted in abatement of the advective flow of the D'Urville Current through Cook Strait Narrows. In addition, the southerly winds reduced the transport of the East Cape Current and decreased its influence on the eastern approaches of Cook Strait. The increased transport and influence of the Southland Current in the eastern approaches of Cook Strait resulted in the encroachment of the Southland Current onto the steep shallow shelf off Palliser Bay. The upwelling that occurred off Palliser Bay on leg 1 was caused by water flowing over a decreasing depth.

The surface nitrate-nitrite distribution for leg 1 of the 1980 cruise (Fig. 7) indicated a region of depleted nitrate-nitrite values off Clifford Bay. This region of low nitrate-nitrite values corresponded with a region of high chlorophyll 'a' concentration (Fig. 9). The minimum nitrate-nitrite concentration in the depleted region was approximately 0.3 uM, which corresponded to a chlorophyll 'a' value of approximately 1.2 mg m^{-3}. This distribution of nitrate-nitrite and chlorophyll 'a' on leg 1 was probably the result of increased stability in the Clifford Bay region during a period of inappreciable advection through Cook Strait Narrows. A previous upwelling event during advection through the narrows would supply nutrients to the Clifford Bay region. Subsequent stability in the region during a period of no advection through the narrows would result in nutrient depletion and accumulation of phytoplankton biomass.

The chemical and physical data for leg 2 of the 1980 cruise indicated that water from the Taranaki Bight was advected into Cook Strait Narrows. This southward directed advective flow was the result of the barotropic and baroclinic components of the pressure gradient during the period of northerly winds. The water advected into the narrows was subsequently mixed with the deep water residing in Cook Strait Canyon.

The resultant water mass was transported towards the steep shelf off Clifford Bay. The upwelling that resulted was the consequence of water flowing onto a decreasing depth. The upwelled water mixed with water of Southland Current origin that was present on the Clifford Bay shelf as the result of a branch of the Southland Current flowing around Cape Cambell and entering Cook Strait. This Southland Current water was mainly confined to the shelf near Clifford Bay (Heath, 1972). The upwelled water was subsequently transported eastward from the Clifford Bay region.

Drift card releases in the western approaches of Cook Strait in 1953 and 1954 described by Garner (1955) and Heath (1969) indicated an advective flow from west to east in Cook Strait during this study period. Calculations of Current velocities from drift card studies are dependent upon recovery of the cards from strandings. Drift card studies probably underestimate current velocities because the detail of the drift paths is not known and the cards may be stranded for a length of time before recovery. The largest percentage of recoveries for the drift cards released in the western approaches of Cook Strait were made along beaches in the northeastern Taranaki Bight.

A current velocity of approximately 52 cm sec^{-1} was implied from these drift card studies (Garner, 1955).

The northerly and westerly winds with a resultant advective flow from west to east in Cook Strait will drive an Ekman flow toward the northern and eastern coast of the Taranaki Bight. A barotropic pressure gradient will be created that drives a slope current parallel to the bathymetry. The magnitude of the slope current velocity can be calculated by considering an alongshore balance between the wind stress ($\tau_s = \rho_a K_a W^2$) and the bottom stress ($\tau_b = \rho_w K_w V^2$) where τ_s is the wind stress, ρ_a is the density of air, K_a is the dimensionless drag coefficient of air, W is the wind velocity, τ_b is the bottom stress, ρ_w is the density of water, K_w is the dimensionless drag coefficient of water and V is the current velocity. The equation is solved for the current velocity (V):

$$\tau_s = \tau_b$$

$$V = (\rho_a K_a / \rho_w K_w)^{1/2} W$$

with $K_a = 1.4X10^{-3}$, $K_w = 2.5X10^{-3}$, $\rho_a = 1.5X10^{-3}$ g cm^{-3}, $\rho_w = 1.0$ g cm^{-3} (Pond and Pickard, 1978). The calculated current velocity for an average wind speed of 10 m sec^{-1} as experienced on January 30 and 31, 1980 is 29 cm sec^{-1}. The maximum wind speed of approximately

20 cm sec^{-1} during this same period suggests a slope current velocity of 58 cm sec^{-1} directed southward towards the narrows. Heath (1971) also deduced the presence of a southward flowing barotropic current through Cook Strait Narrows.

The slope of the sea surface in the northeast Taranaki Bight from a northerly wind calculated from a cross-shore balance between the pressure gradient due to a slope of the sea surface ($-1/\partial P/\Delta x = g\partial n/\Delta x$) and the coriolis force (fV):

$$fV = g\partial n/\Delta x$$

$$\partial n/\Delta x = fV/g$$

where P is pressure, Δx is the distance from the shore, ∂n is the vertical displacement of the sea surface, f is the coriolis parameter, g is the gravitational acceleration, and V is the velocity of the flow (Pond and Pickard, 1978). A sea surface slope of 5.9×10^{-6} is calculated using a current velocity (V) of 58 cm sec^{-1} at a wind speed of 20 m sec^{-1} with $f = -9.56 \times 10^{-5}$ sec^{-1} and $g = 980$ cm sec^{-2}.

The chemical and physical data for leg 1 of the 1981 cruise indicated that another period of advective flow from west to east was taking place in Cook Strait with intrusion of warm, nutrient depleted water in the narrows. This water advected into Cook Strait Narrows on leg 1 was subsequently mixed and transported toward the shelf off Clifford Bay where it upwelled. This upwelling is similar to the upwelling on leg 2 of the 1980 cruise and was the result of water flowing toward a decreasing depth. The temperature and salinity data from hydrostations on the shelf off Clifford Bay indicated the presence of a remnant of Southland Current water on the shelf with a salinity of approximately 34.6 $^{o}/oo$ and a temperature of approximately 11.2 ^{o}C. The nutrient distribution in the upwelling region off Clifford Bay for leg 1 of the 1981 cruise was similar to the distribution in the upwelling region off Clifford Bay on leg 2 of the 1980 cruise.

The water mass advected through Cook Strait Narrows appeared to branch and flow around Cape Terawhiti toward the east. The upwelling on the shelf off Wellington and Cape Palliser corresponded to two shallow embankments in the northeastern approaches to Cook Strait. This suggested that the segment of the advective flow that rounded Cape Terawhiti encroached upon the embankments and resulted in upwelling. The temperature, salinity, and nutrient data for the two upwelling regions indicated that the probable source of the upwelled water was bottom water from Cook Strait Narrows. Water with the proper nutrient values of 6.0 uM to 8.0 uM and a salinity of approximately 34.8°/oo with a temperature of 13.0° C was present at a depth of 100 m to 180 m in Cook Strait Narrows.

The surface chlorophyll 'a' distribution for leg 1 of the 1980 cruise indicated that the chlorophyll 'a' maximum at the eastern approaches to Cook Strait was located just beyond the coastal shelf. An adequate supply of nutrients for the region of high phytoplankton biomass was provided by the adjacent upwelling regions, while the increased stability of the more stratified waters offshore permitted accumulation and growth of phytoplankton. The surface silicate distribution illustrated in Figure 19 indicates a region of depleted silicate with a concentration of less than 1.0 uM in the area of the frontal boundary in the eastern approaches of Cook Strait near station 9. This area of depleted silicate suggests that diatoms may have contributed to the phytoplankton species composition of the high chlorophyll 'a' region in the eastern approaches of Cook Strait.

Chapter VI

Cape Farewell Upwelling Region

VI.1 Introduction

A region of nutrient rich, cold water was observed off Cape Farewell during both the 1980 and 1981 cruises. Stanton (1971) observed this region of cold temperatures off Cape Farewell in a 1970 survey of the region.

Cape Farewell forms a convex coastal bend in the southwestern approaches of Cook Strait. The circulation off the Cape Farewell coast is dominated by the Westland Current, which divides off Cape Farewell with one branch entering Cook Strait as the D'Urville Current.

VI.2 Leg 1 R/V Tangaroa 1980 Cruise

The region off Cape Farewell was sampled on leg 1 of the 1980 cruise from January 16- 19, 1980 during a period of northerly winds.

The region of elevated surface nitrate-nitrite levels, illustrated in Figure 7, extended from approximately 40 km south of the western approaches of Cook Strait at Kahurangi Point to approximately 10 km east of Farewell Spit within the western approaches. The maximum nitrate-nitrite concentration sampled in the nearshore mixed region was 5.9 uM. The highly stratified oligotrophic waters offshore from the mixed region had a nitrate-nitrite concentration of less than 0.5 uM. An area of slightly reduced nitrate-nitrite values of approximately 2.9 uM was situated within the nutrient rich region, just south of the western approaches to Cook Strait.

The ammonium values were slightly elevated for the mixed region off Cape Farewell with a value of approximately 0.4 uM. The offshore oligotrophic water had an ammonium concentration of approximately 0.2 uM.

The surface temperature distribution for leg 1 (Fig. 8) shows the region of cold water in the area of Cape Farewell that corresponded to the area of elevated nutrient values. The minimum temperature sampled in the mixed region was approximately 13.7 ^{o}C, while the temperature in the stratified offshore area was greater than 17 ^{o}C.

The surface distribution of chlorophyll 'a' for leg 1 is illustrated in Figure 9. The surface distribution for the Cape Farewell region indicated a maximum chlorophyll 'a' concentration of 1.2 mg m^{-3} associated with the front bounding the mixed region. In addition, elevated chlorophyll 'a' values greater than 0.9 mg m^{-3} corresponded to the area of reduced nitrate-nitrite values located just south of the western approaches to Cook Strait.

A series of hydrocast stations was sampled on January 20, 1980 forming a transect across the shelf just south of Cape Foulwind. The wind had shifted to a southerly direction with a velocity of approximately 8 m sec^{-1} on January 20, 1980 and subsequently returned to a northerly direction on January 21, 1980. Vertical sections of the physical and chemical properties derived from the hydrostation data for the transect are illustrated in Figures 28a to e. Vertical distributions of temperature and sigma-t indicated that there was no active upwelling taking place for locations along the west coast of South Island below Cape Farewell and Cape Foulwind during the sampling period. The isopleths of temperature and sigma-t did not intersect the surface along this transect. The nitrate-nitrite distribution correlated well with the temperature and sigma-t distributions, with nitrate-nitrite values remaining low in the surface layers over the entire section.

Chlorophyll 'a' concentrations for the January 20, 1980 transect are illustrated in Figure 28f. The vertical distribution of chlorophyll 'a' showed a subsurface maximum associated with the thermocline, which

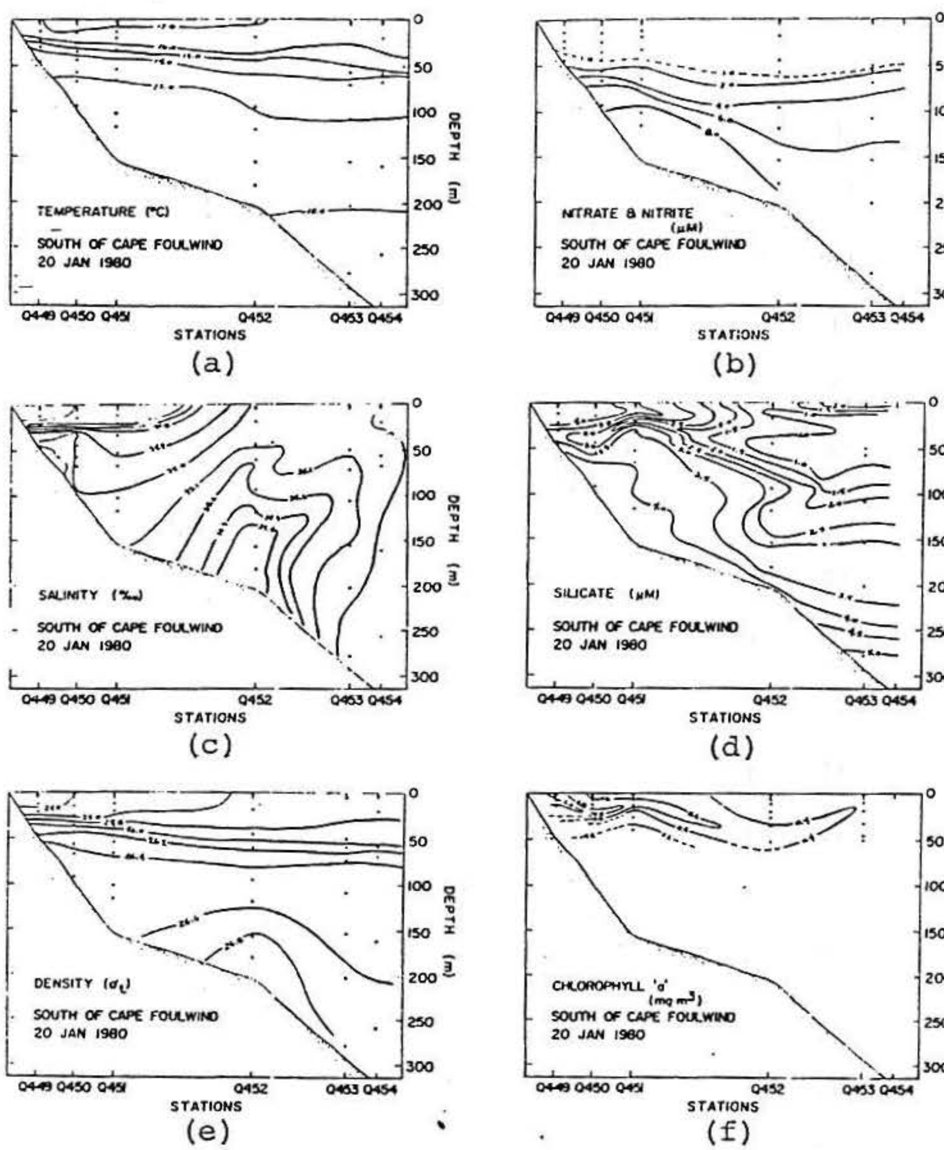

Fig. 28. Vertical distribution of physical, chemical and biological properties for the transect south of Cape Foulwind: a) temperature (^{o}C), b) nitrate-nitrite (uM), c) salinity (^{o}/00), d) silicate (uM), e) density (σ_t), f) chlorophyll 'a' (mg m^{-3}).

is typical of a well stratified water column.

Nutrient distributions were not measured off Cape Farewell on leg 2 of the 1980 cruise. However, the surface temperature distribution (Fig. 12) again indicated the presence of cold water off Cape Farewell.

VI.3 Leg 1 HMNZS Tui 1981 Cruise

The region of nutrient rich, cold temperature water off Cape Farewell was also observed during leg 1 of the 1981 cruise. The leg 1 surveys of the Cape Farewell region occurred during a period of prolonged northerly to westerly winds. The wind vectors for the January 28- 29 survey and the January 30- 31 survey are illustrated in Figure 17. The maximum wind velocity attained during the surveys was approximately 11.3 m sec^{-1} from the northwest on January 28 and the average wind velocity was less than 5 m sec^{-1} over the sampling period.

The surface distribution of nitrate-nitrite, illustrated in Figure 18, indicated the presence of elevated nitrate-nitrite values off Cape Farewell. Maximum surface nitrate-nitrite values were located in two nearshore areas off Cape Farewell. These areas were associated with the sharp convex coastal bends in the Cape Farewell region. The first area, located at the base of Farewell Spit, had a maximum surface nitrate-nitrite concentration of 6.6 uM. The second area had a surface maximum of 7.0 uM and was located just north of Kahurangi Point.

The surface silicate distribution for leg 1, illustrated in Figure 19, also indicated a region of elevated silicate values corresponding to the region of increased nitrate-nitrite concentrations. Maximum silicate concentrations corresponded to the two areas of maximum nitrate-nitrite values with a silicate value of 5.0 uM for the area at the base of Farewell Spit and approximately 6.0 uM for the area just north of Kahurangi Point.

The surface temperature distribution for leg 1, illustrated in Figure 21, showed good correlation with the nutrient values off Cape Farewell with an inverse relationship between temperature and nutrient values, i.e., minimum temperature values for leg 1 were located in the corresponding areas of maximum nutrient values.

The northerly to westerly winds during the sampling period would favor downwelling along the coast in the Cape Farewell region. However, the region of nutrient rich, cold temperature water again persisted throughout the sampling period.

A vertical section was constructed from Stations 74- 80 on January 30, 1981, which was positioned perpendicular to the coast leading from the base of Farewell Spit. The vertical distribution of physical and chemical properties for the transect are illustrated in Figures 29a to e. The nitrate-nitrite distribution indicated an upward bending in the isopleths toward the coast, intersecting the surface between Stations 74 and 75 to form a frontal zone. The concentration of nitrate-nitrite in the nearshore area was 6.6 uM and decreased to approximately 0.15 uM at a distance of 10 km offshore.

The silicate distribution showed good correlation with the nitrate-nitrite distribution and indicated an upward bending of the silicate isopleths toward the coast. The nearshore surface concentration of silicate approximately 4.9 uM and decreased to approximately 1.0 uM at the surface in the offshore stations.

The vertical distributions of temperature and sigma-t showed good correlation with the nutrient distributions with an inverse relationship between temperature values and nutrient and sigma-t values. The nearshore area had a temperature of approximately 13.4 ^{o}C with the temperature increasing to approximately 19.5 ^{o}C.

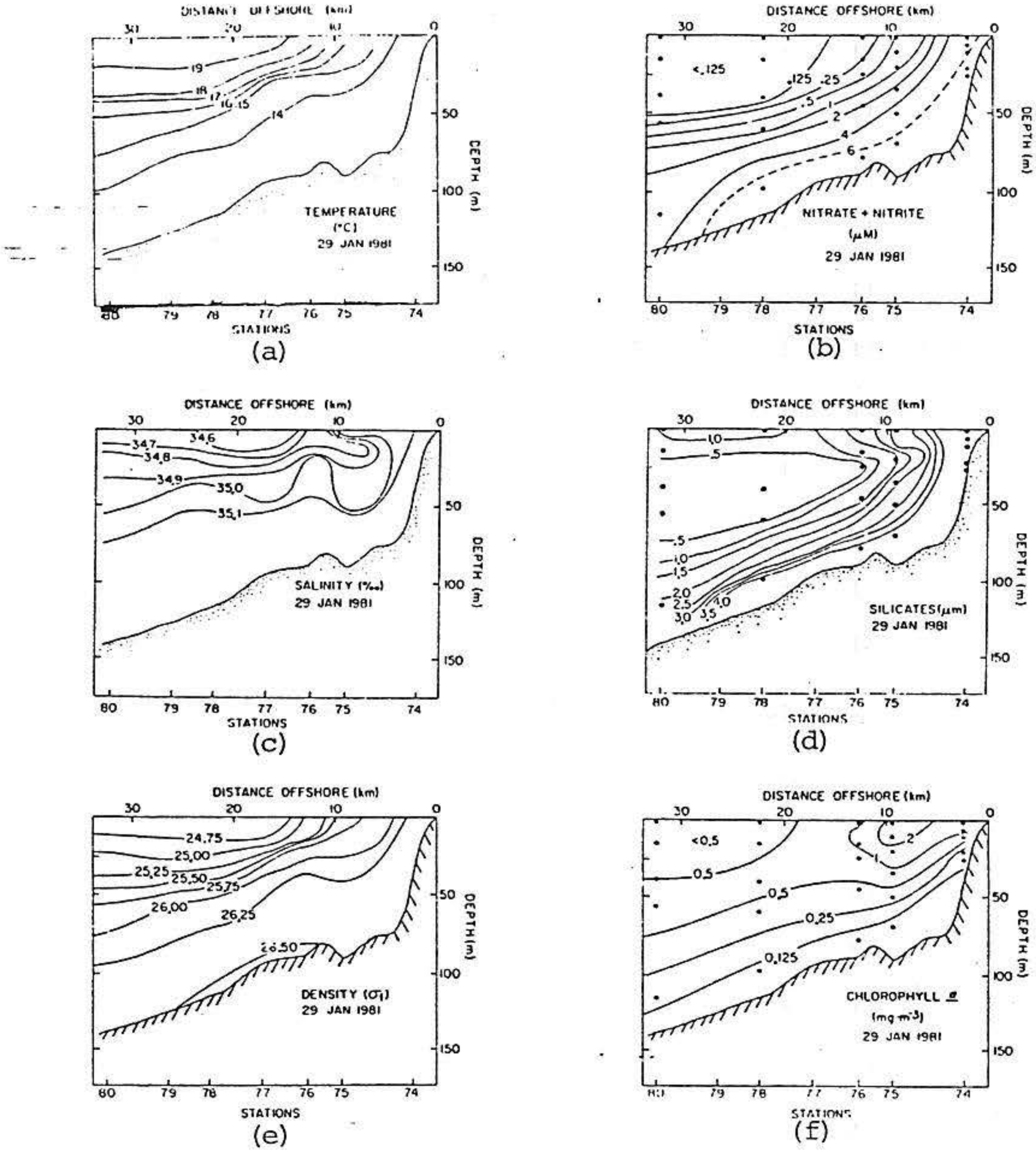

Fig. 29. Vertical distribution of physical, chemical and biological properties for Cape Farewell transect on leg 1 of 1981 cruise: a) temperature (°C), b) nitrate-nitrite (uM), c) salinity (°/11), d) silicate (uM), e) density (σ_t), f) chlorophyll 'a' (mg. m^{-3}).

at the offshore stations.

The vertical distribution of chlorophyll 'a' for the leg 1 transect is illustrated in Figure 29f. Maximum chlorophyll 'a' concentrations of approximately 2.2 mg m^{-3} were associated with the frontal zone in the vicinity of Station 75, which is probably the result of enhanced growth and accumulation due to increased water column stability and a sufficient supply of nutrients across the frontal boundary.

VI.4 Discussion

Stanton (1971) attributed the cold temperature regions off Cape Farewell and Cape Foulwind to local intensifications of wind induced upwelling off the west coast of South Island. This upwelling would be most favorable during southerly winds (Heath, 1971). In addition, the flow of the Westland Current past promontories and capes on the west coast of South Island will increase the relative vorticity, due to curvature in the streamlines, and combine with the planetary vorticity to intensify upwelling (Stanton, 1971). However, a period of northerly winds occurred for several days prior to and throughout the survey off Cape Farewell on leg 1 of the 1980 cruise. These winds would favor downwelling along the west coast. However, the region of cold, nutrient rich water persisted throughout the sampling period. In addition, vertical distributions of chemical, physical and biological properties for a transect south of Cape Foulwind (Fig. 28a to f) indicated that there was no general upwelling taking place along the west coast of South Island at this time. This suggests that the cold, nutrient rich region was not dependent upon southerly winds producing a wind induced upwelling on the west coast of South Island.

The surface nutrient and temperature distributions for leg 1 of the 1981 cruise indicated the presence of the cold, nutrient rich region off Cape Farewell during a period of northerly to westerly winds. The vertical distributions of the chemical and physical properties for leg 1 of the 1981 cruise (Fig. 29a to f) indicated that there was an onshore movement of bottom water along the transect that resulted in upwelling near the coast. In addition, the distribution of surface properties indicated that the highest nutrients and the coldest temperatures were associated with the sharp convex coastal bends and changes in bathymetry in the Cape Farewell region, although winds favored downwelling in the region during the sampling period.

This suggests that the upwelling was a consequence of a current flowing around a bend in the bathymetry. The extent of the possible influences of the tides on this upwelling off Cape Farewell cannot be determined at the present time.

The surface distribution of nitrate-nitrate on leg 1 of the 1980 cruise (Fig.7) suggested the presence of eddy shedding from the Cape Farewell region into the western approaches to Cook Strait. A circular patch of water with elevated nitrate-nitrite values of approximately 2.1 uM is evident in Figure 7. The surface temperature and chlorophyll 'a' distributions, illustrated in Figures 8 and 9 respectively, also indicated the possible presence of an eddy shed from the Cape Farewell upwelling region. Stanton (1971) observed the formation of mesoscale eddies in the Westland Current as it flowed past Cape Foulwind. However, the region just north of Cape Foulwind was not surveyed during the 1980 and 1981 cruises.

The Cape Farewell region was resurveyed in greater detail during January- February, 1981. The objectives of the 1981 surveys were to determine the processes responsible for the formation of mesoscale eddies in the Cape Farewell region. The results of the 1981 eddy surveys will be discussed in detail in Chapter VIII.

Chapter VII

Cook Strait Plume

VII.1 Introduction

The existence of a plume of cold temperature water emanating from the eastern approaches of Cook Strait was first suggested by photographic evidence obtained by Skylab astronauts in 1973 (Fig. 30). Surveys of the eastern approaches were undertaken on the 1980 and 1981 cruises to investigate the possible existence and oceanographic properties of the plume.

VII.2 Leg 2 R/V Tangaroa 1980 Cruise

The leg 2 survey of the surface properties in the eastern approaches of Cook Strait included 9 hydrostations to investigate the vertical properties of the region. The cruise track for the survey of the eastern approaches is illustrated in Figure 31. The sampling period of the survey extended from January 30 to February 5, 1980 and occurred during a period of strong northerly winds. The wind velocity reached a maximum of approximately 30 m sec^{-1} near the conclusion of the survey. The wind vectors for the period of the survey are illustrated in Figure 5.

The surface distribution of nitrate-nitrite for

Fig. 30. Visible band photograph of Cook Strait jet current, Dec. 1973, taken by American Skylab astronauts.

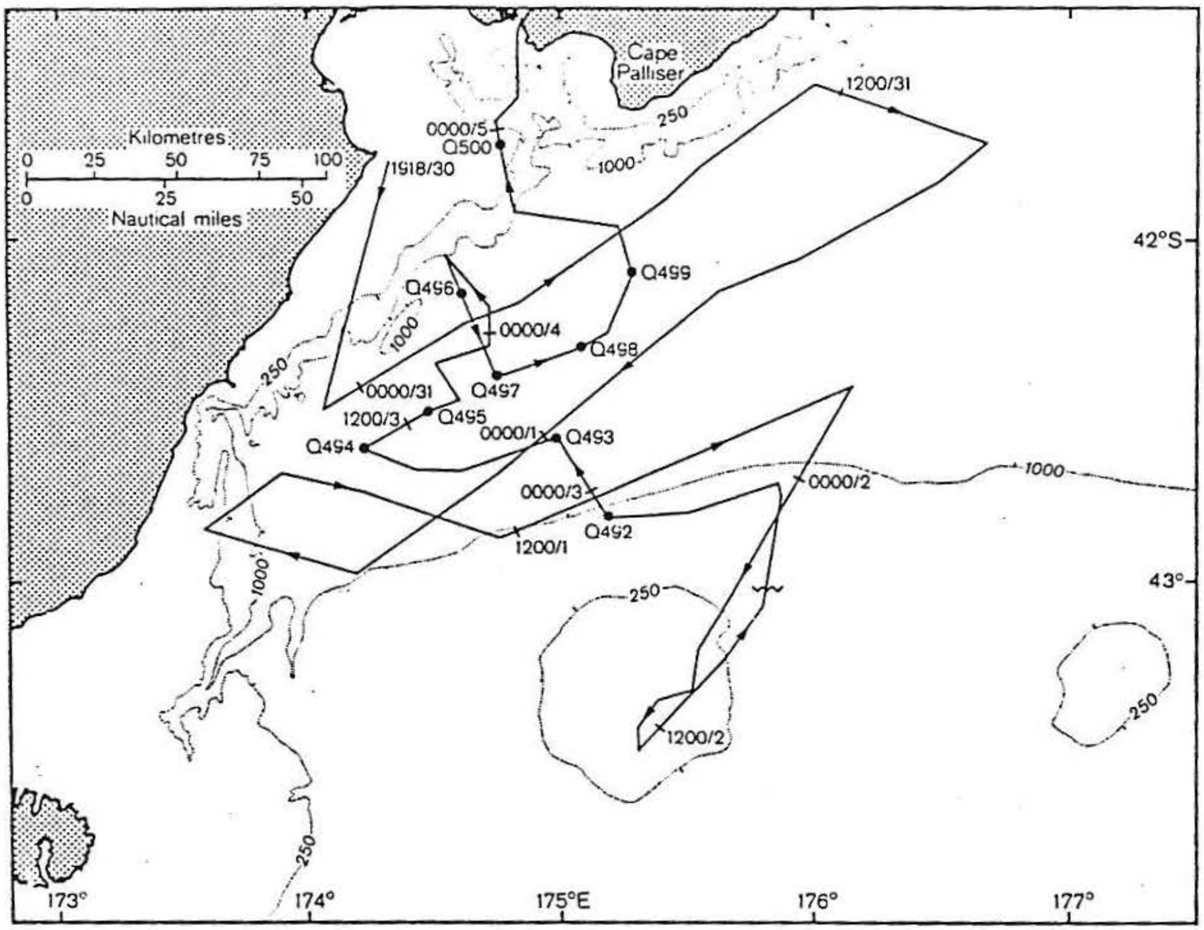

Fig. 31. Cruise track and station locations for January 30- February 5, 1980.

the eastern approaches of Cook Strait is illustrated in Figure 11. The elevated surface nitrate-nitrite values indicated the presence of a plume emanating from the eastern approaches during the sampling period. This plume extended outward approximately 120 km from Cook Strait into the southwestern Pacific Ocean. The source of the plume water appeared to originate from the area of Clifford Bay within southern Cook Strait. Water with a nitrate-nitrite concentration greater than 6.0 uM apparently issued from the Clifford Bay area and flowed south-eastward out of Cook Strait. The nitrate-nitrite concentration reached a maximum of approximately 8.0 uM in a small area off Clifford Bay on the last day of the survey. The oligotrophic waters at the outer boundaries of the plume had nitrate-nitrite concentrations of less than 0.5 uM.

The ammonium concentrations were slightly elevated in the central area of the plume water in comparison to the more stratified waters surrounding the outskirts of the plume. The ammonium values in the central area of the plume ranged between 0.5 to 0.6 uM. while the stratified waters outside the plume had an ammonium concentration of approximately 0.2 uM.

The surface temperature distribution for leg 2 of the 1980 cruise is illustrated in Figure 12. The temperature distribution indicated the presence of a plume of cold temperature water that emanated from the strait during the sampling period. The surface temperature distribution correlates well with the nutrient data with an inverse relationship between temperature and nutrient values. The cold temperature water again appeared to originate from the Clifford Bay region and extended southeastward from Cook Strait. The coldest waters with temperatures of less than 13.5 ^{o}C were situated in the nearshore area of Clifford Bay.

The more stratified water surrounding the outskirts of the plume had water temperatures greater than 16.5 ^{o}C. Therefore, the nutrient distributions and surface temperature distributions were both consistent with a common source within Cook Strait during the survey.

The surface distribution of sigma-t values for the eastern approaches of Cook Strait, which is illustrated in Figure 32, corresponded well with the surface distributions of nutrients and temperature. Figure 32 indicates that water with a sigma-t value greater than 26.0 emanated from the Clifford Bay region and extended southeastward from Cook Strait. The more stratified waters surrounding the plume water had a surface sigma-t

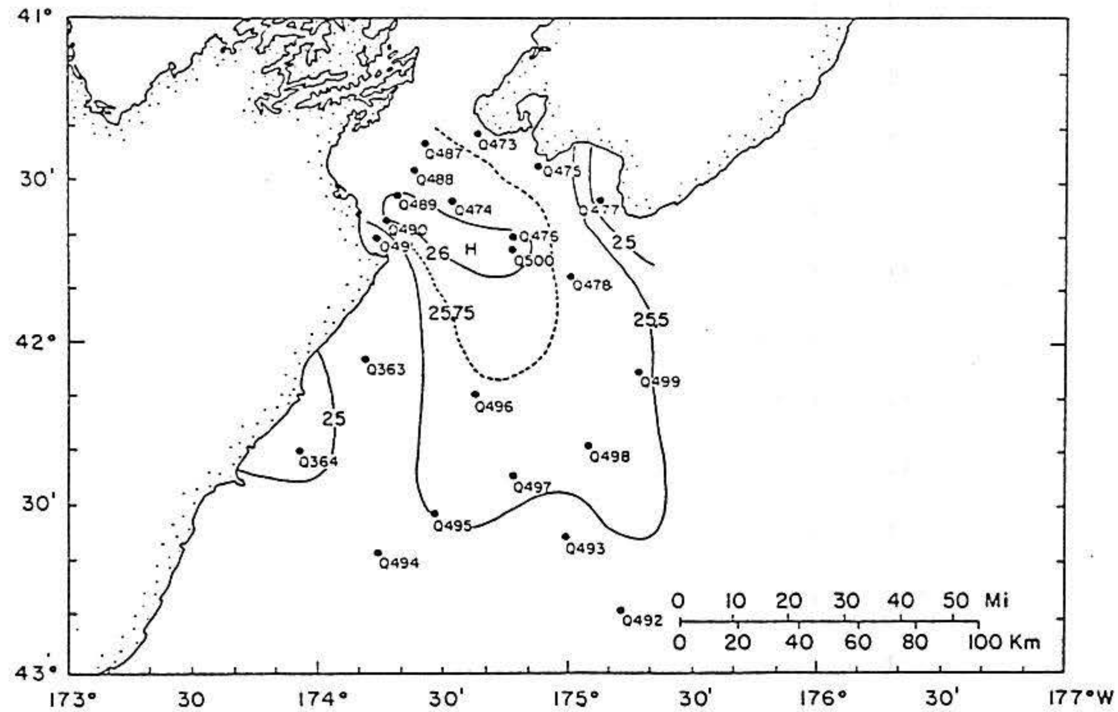

Fig. 32. Surface distribution of density (σ_t) for January 30- February 4, 1980, (Bowman et al., in press c).

value of approximately 25.0. The denser surface waters of the plume tend to subside as the plume water was transported southeastward into the less dense surface waters of the stratified region.

The surface chlorophyll 'a' distribution for leg 2 of the 1980 cruise is illustrated in Figure 13. The contours of chlorophyll 'a' in mg m^{-3} represented in Figure 13 indicated a region of elevated chlorophyll 'a' values that extended from Cook Strait southeastwards 200 km into the Pacific Ocean. The maximum chlorophyll 'a' concentration attained was approximately 1.8 mg. m^{-3} at a distance of 125 km seaward of the eastern approaches of Cook Strait. This maximum represented a fourfold increase in chlorophyll 'a' concentration from the origin of the water at Clifford Bay to the seaward extent of the plume of cold temperature water. The seaward extent of the elevated nitrate-nitrite values corresponded well with the position of the chlorophyll 'a' maximum. The nutrient and temperature data suggested that the downstream chlorophyll 'a' maximum was the result of enhanced production from nutrient enrichment and increased water column stability. This chlorophyll 'a' maximum of 1.8 mg m^{-3} was approximately 6 times greater than the chlorophyll 'a' concentrations in the oligotrophic waters adjacent to the plume.

Vertical sections generated from hydrographic stations sampled during the plume survey were utilized to study the source waters and the hydrological properties of the plume. Transverse and longitudinal vertical sections of the plume were produced from 9 hydrographic stations sampled during the survey. The transverse vertical section of the plume included Stations Q494, Q495, Q497, Q498, and Q499. The hydrographic station positions are depicted in Figures 31 and 32. The physical and chemical properties of the transverse section of the plume are illustrated in Figure 33 a to f. The nitrate-nitrite values for the transect is represented in Figure 33b. The nitrate-nitrite values indicated that Stations Q497 and Q498 were representative of the plume water. The surface nitrate-nitrite concentrations between Stations Q497 and Q498 were between 1.0 uM and 1.5 uM. The surface concentration of nitrate-nitrite at Stations Q494 and Q495, which was southwest of the plume, were approximately 0.3 uM. Station Q499, which was situated northeast of the plume, had a surface nitrate-nitrite concentration of approximately 0.4 uM. The nitrate-nitrite contours in Figure 33b indicated that the water mass southwest of the plume had a shallow

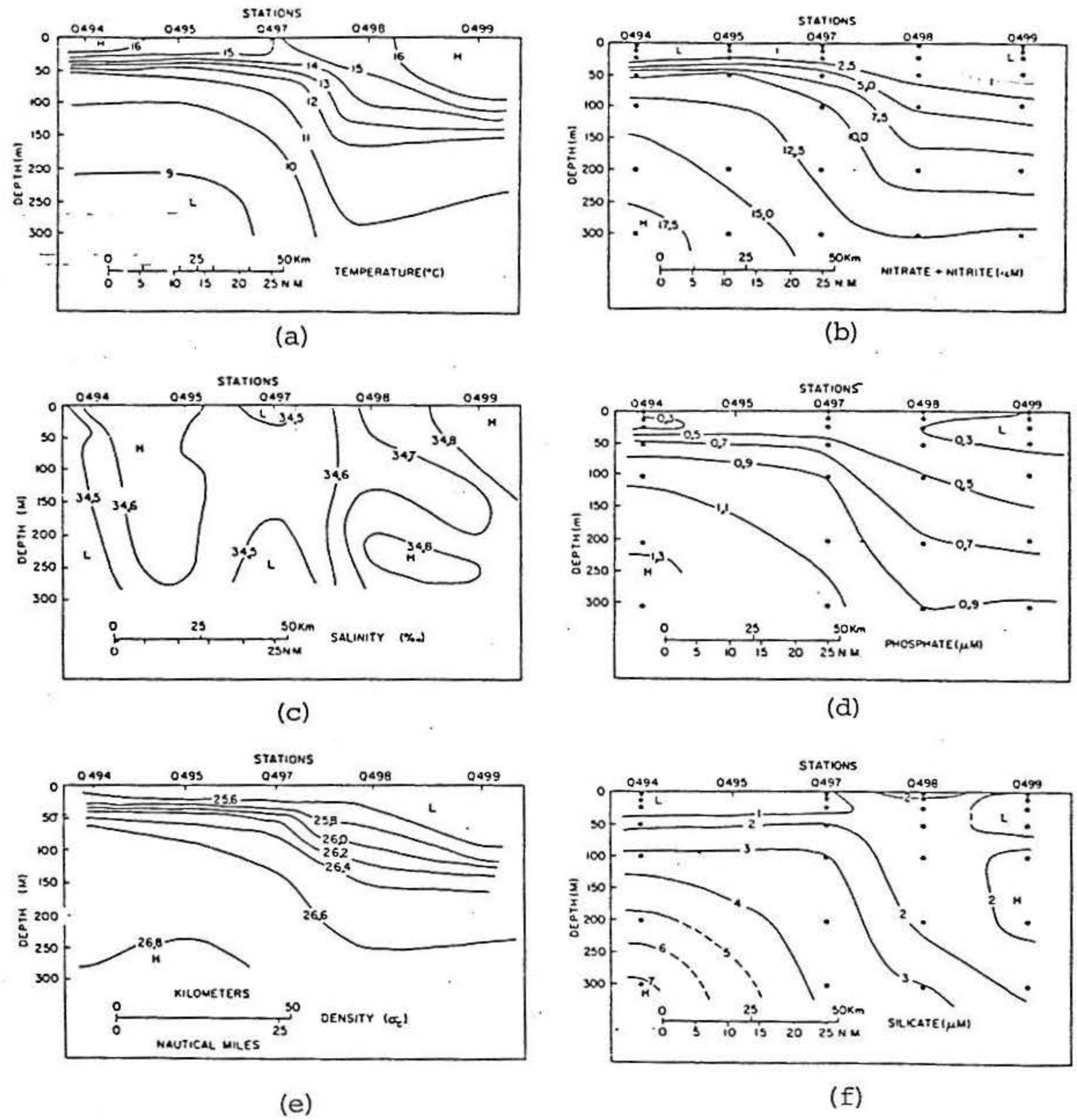

Fig. 33. Vertical distribution of physical and chemical properties for the transverse plume section: a) temperature (^{O}C), b) nitrate-nitrite (uM), c) salinity ($^{O}/oo$), d) phosphate (uM), e) density (σ_t), f) silicate (uM).

nutricline with a steep vertical gradient in nitrate-nitrite values. The shallow nutricline suggested that the water at Stations Q494 and Q495 was of Southland Current origin. Figure 33b indicated a deep downward bending in the isopleths of nitrate-nitrite between Stations Q497 and Q498, which represented plume water.

The vertical distribution of phosphate and silicate for the transverse section of the plume are illustrated in Figures 33d and 33f respectively. The phosphate and silicate distributions show good correlation with the distribution of nitrate-nitrite values. The highest surface values of phosphate and silicate for the transect were 0.45 uM and 3.1 uM respectively, which were sampled in the vicinity of Station Q498. Station Q494 and Q499 in the vertical section, which represented oligotrophic waters outside the plume, had a surface phosphate value of approximately 0.3 uM and a surface silicate value of less than 1.0 uM. In addition, a shallow nutricline at stations Q494 and Q495 was indicated in the vertical sections of phosphate and silicate.

The transverse vertical sections of temperature, salinity, and density are illustrated in Figures 33a, 33c, and 33e respectively. The vertical distribution of temperature and density indicated good correlation with the nutrient data. The temperature and salinity data in conjunction with the nutrient data were utilized to identify the various water masses in the transverse plume section. Temperature and salinity profiles constructed from historical data are illustrated in Figure 23 with D860 representing Southland Current water and D840 representing East Cape Current water (Heath, 1975). Station Q440 in Figure 23, which was sampled on leg 1 of the 1980 cruise, was representative of D'Urville Current water. Figure 23 indicated that Stations Q498 and Q499 were a mixture of Southland Current water and D'Urville Current water with evidence of a trace of East Cape Current water below 200 m. Station Q497 in Figure 23 appears to have been mainly composed of Southland Current water. Temperature and salinity profiles for Stations Q494 and Q495 in the transverse section are illustrated in Figure 34. Figure 34 indicated that Stations Q494 and Q495 were composed entirely of Southland Current water with an associated shallow nutricline. In addition, the Southland Current water that was present at Stations Q494 and Q495 appeared to have a high nitrate-nitrite to silicate ratio compared to D'Urville Current water,

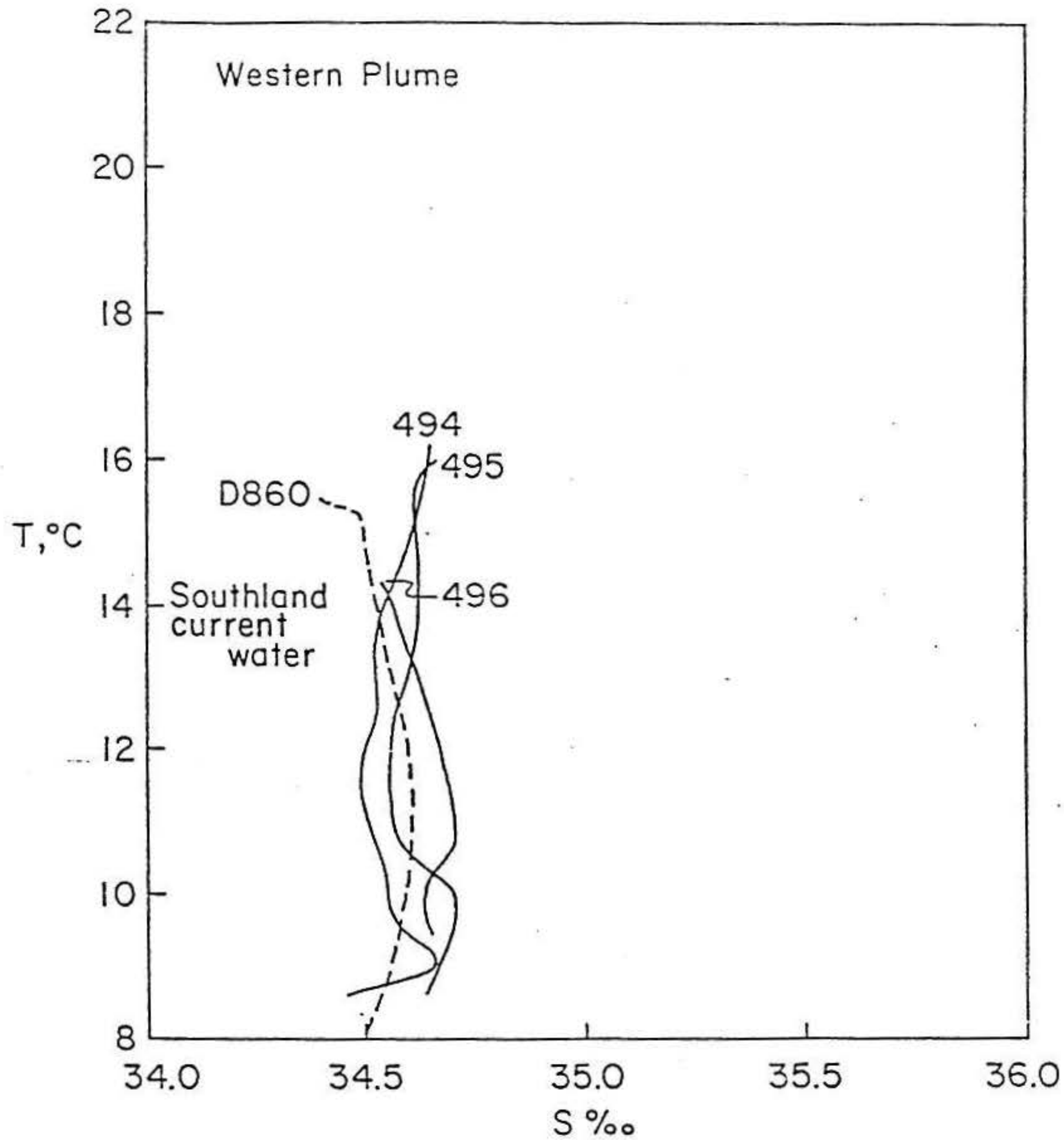

Fig. 34. Temperature-salinity diagram for the western section of the plume.

East Cape Current water, or the plume water.

The longitudinal section of the plume was constructed of hydrographic data from Stations Q492, Q493, Q497, Q496, and Q500 with the physical and chemical properties of the section illustrated in Figure 35a to f. The vertical section of nitrate-nitrite concentrations in Figure 35b indicated a downward bending of the isopleths leaving Cook Strait. The surface nitrate-nitrite values increased from less than 0.5 uM offshore at Station Q492 to greater than 7.5 uM within the strait at Station Q500.

The longitudinal sections of phosphate and silicate are illustrated in Figures 35d and 35e respectively. These distributions show good correlation with the nitrate-nitrite distribution. The phosphate and silicate distributions indicated a downward bending of the isopleths from the entrance of Cook Strait to the offshore areas. The surface values of phosphate reach a maximum of approximately 0.9 uM within the strait and decreased to less than 0.2 uM in the offshore waters. The surface silicate values reached a maximum of 3.6 uM within the strait and decreased to approximately 1.3 uM at the offshore station.

The vertical distributions of temperature and

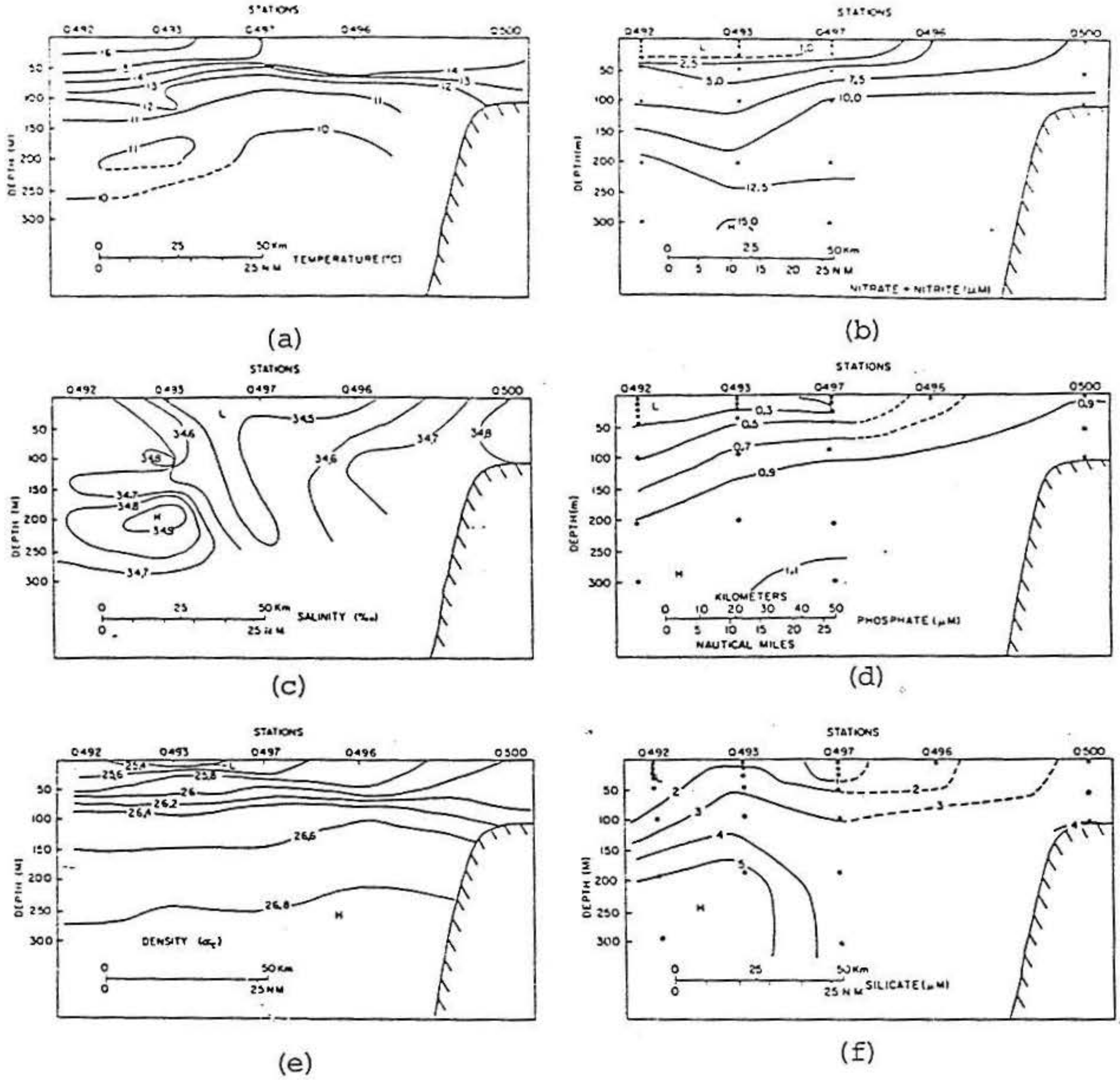

Fig. 35. Vertical distribution of physical and chemical properties for the longitudinal section of the plume: a) temperature (°C), b) nitrate-nitrite (uM), c) salinity (°/oo), d) phosphate (uM), e) density (σ_t), f) silicate (uM).

density for the longitudinal section of the plume are illustrated in Figures 35a and 35e respectively. The distributions of temperature and density show good correlation with the nutrient distributions. The downward bending in the isopleths of temperature and density indicated that the denser water mass that originated within the strait sank as it flowed outward from the eastern approaches.

The combined temperature, salinity, and nutrient data delineated the water masses that were present in the longitudinal section. A temperature-salinity diagram for the offshore stations of the section at Q492 and Q493 is illustrated in Figure 36. Figure 36 indicated that both Stations Q492 and Q493 were composed mainly of Southland Current water in the upper portion of the water column. Stations Q492 and Q493 appear to have East Cape Current water present below a depth of 180 m to 200 m, which is indicated in Figure 36. Stations Q497 and Q496 are illustrated in Figures 23 and 34 respectively and represented the southwestern edge of the plume. The figures indicate that both stations were composed entirely of Southland Current water. Station Q500 of the longitudinal section was representative of the source water within the eastern

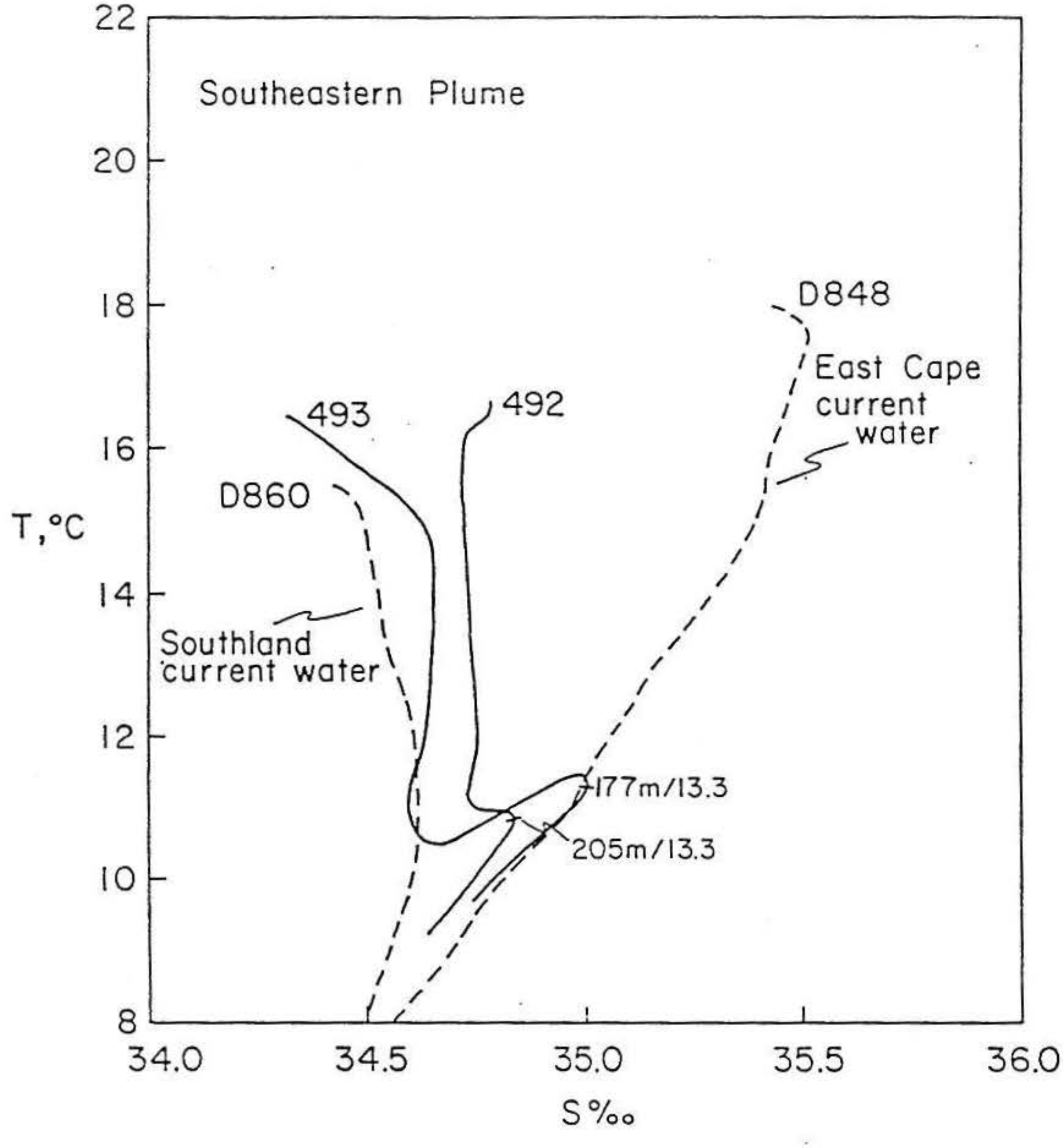

Fig. 36. Temperature-salinity diagram for the southeastern section of the plume, (Bowman et al., in press c).

approaches of Cook Strait. The temperature-salinity characteristics of Station Q500 is illustrated in Figure 23. Station Q500 appeared to be composed of a mixture of Southland Current water and D'Urville Current water.

The origin of the low temperature, high density, and high nutrient water in the area of Station Q500 can be identified from Figure 37. The depths and nitrate-nitrite concentrations are superimposed on the temperature-salinity profiles of stations that represent various water masses which are possible source waters for the plume. East Cape current water with a sigma-t of 26.0 had too high a salinity (35 $^{o}/oo$) and too high a temperature (16 ^{o}C) to be the source water. Station Q490, which represented inshore water of Clifford Bay, had too low a salinity (34.6$^{o}/oo$) to be the source water for the plume and appeared to be mainly composed of Southland Current water. Water with the appropriate combination of temperature, salinity, density, and nutrient values for the source water of the plume was limited to bottom water at Station Q482 off Pelorus Sound and Station Q489 off Clifford Bay.

The vertical distribution of chlorophyll 'a' and primary production for the longitudinal and transverse

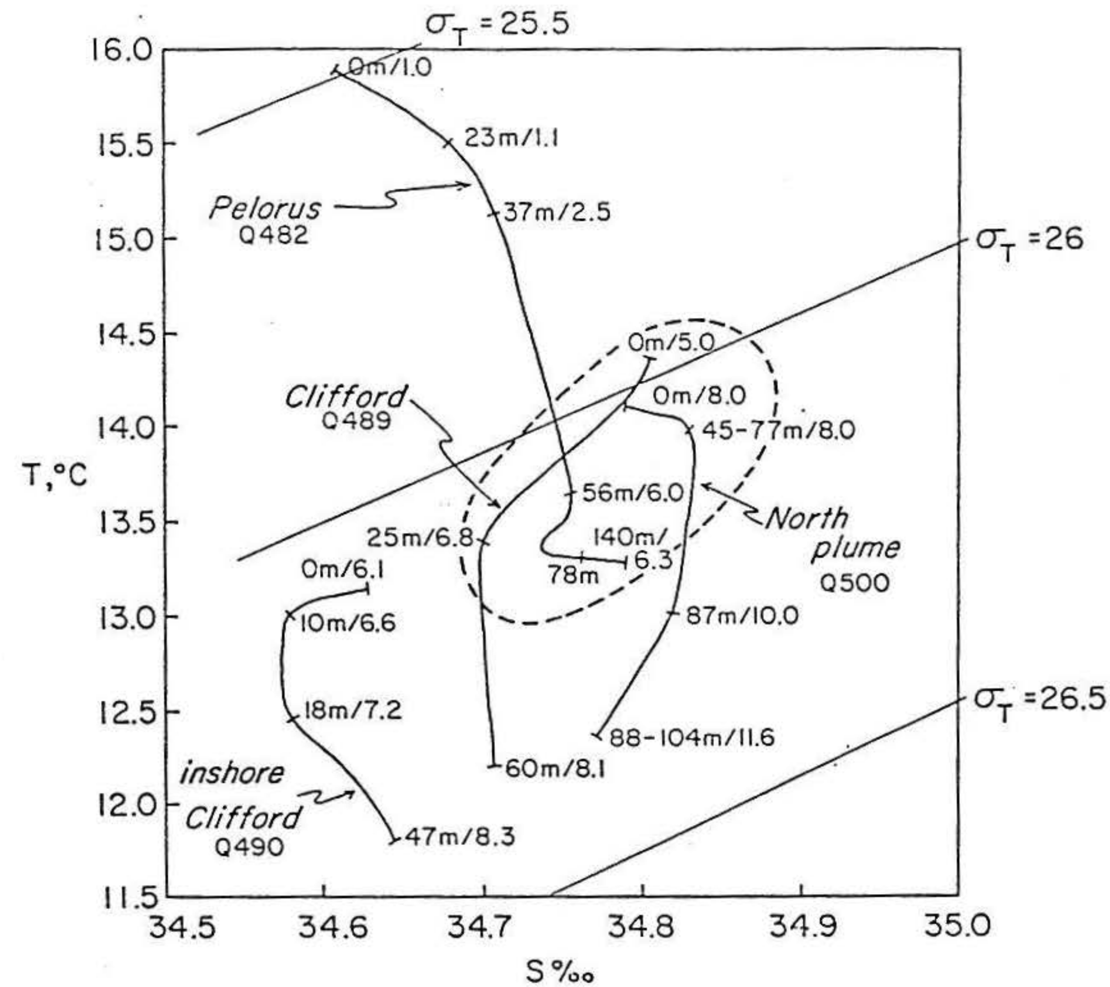

Fig. 37. Temperature-salinity diagram to identify origin of plume water, annotated values on porfiles are depth (m)/(NO_3+NO_2) (uM), (Bowman <u>et</u> <u>al</u>., in press c).

sections of the plume are illustrated in Figures 38a to d. The chlorophyll 'a' distribution for the transverse vertical section is shown in Figure 38c. Figure 38c indicates that the highest chlorophyll 'a' concentrations in the upper portion of the water column were located between Station Q497 and Station Q498. In addition, sinking and lateral spreading of the phytoplankton biomass was indicated in the transverse section by the increased subsurface chlorophyll 'a' concentrations in the direction of Station Q495. The longitudinal vertical section of chlorophyll 'a' is illustrated in Figure 38a. This section indicated an increase in chlorophyll 'a' concentration as the plume moved outward from the eastern approaches of Cook Strait. The chlorophyll 'a' concentrations in Figure 38a also indicated the sinking of the denser water as it moved outward from the strait, which was consistent with the chemical and physical data. The sinking process was indicated by the increase in subsurface chlorophyll 'a' concentrations between Station Q497 and Station Q492.

VII.3 Leg 1 HMNZS Tui 1981 Cruise

Leg 1 of the 1981 cruise occurred during a period of persistent residual flow from west to east in Cook Strait. The water masses that were mixed in Cook

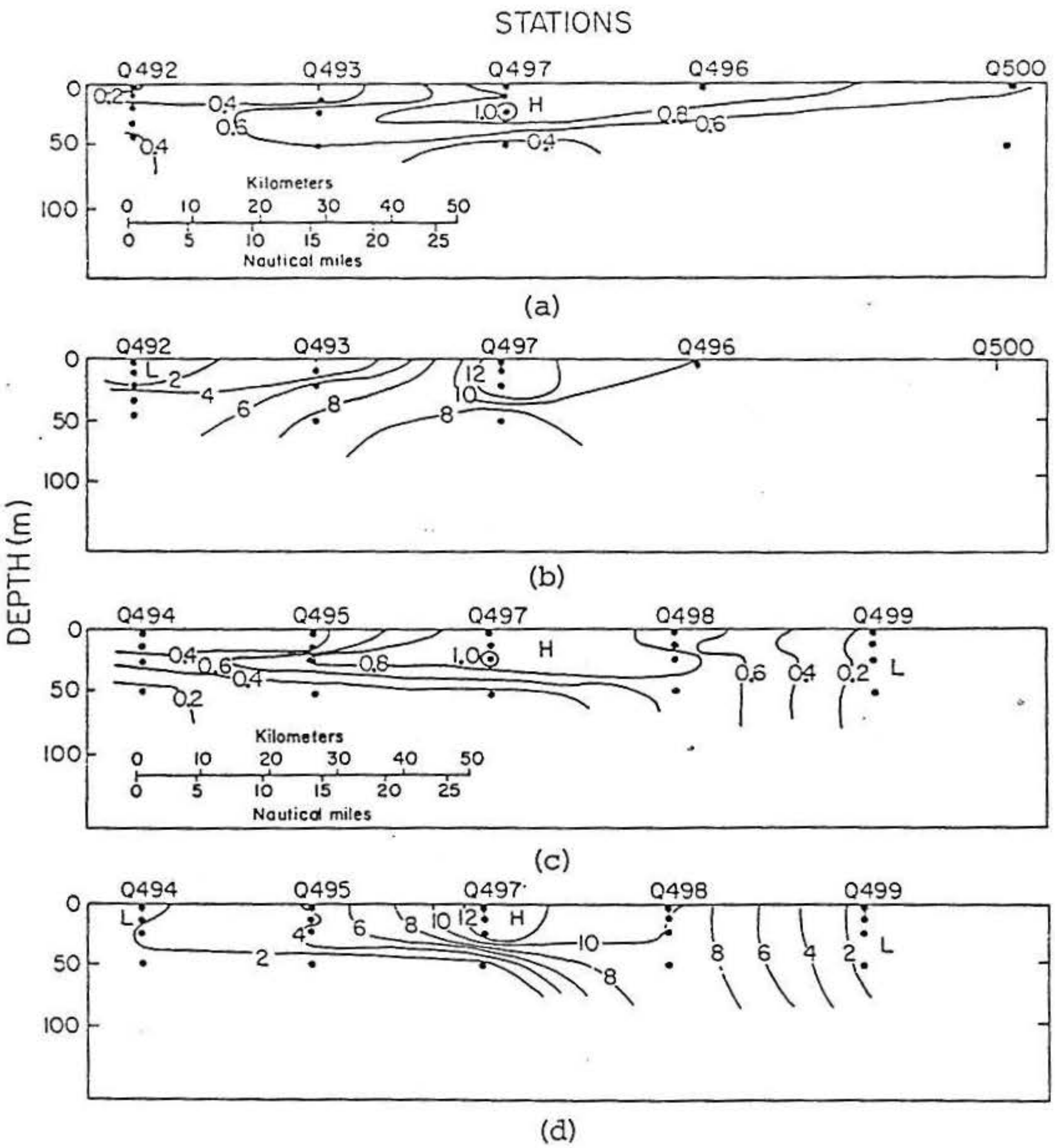

Fig. 38. Vertical distribution of biological properties for the plume: a) chlorophyll 'a' (mg m^{-3}) longitudinal section, b) primary production (mg C m^{-3} hr^{-1}) longitudinal section, c) chlorophyll 'a' mg m^{-3}) transverse section, d) primary production (mg C $m^{-3}hr^{-1}$) transverse section, (courtesy P. Lapennas).

Strait Narrows upwelled in a manner similar to leg 2 of the 1980 cruise. However, the upwelled water did not appear to be transported out of the eastern approaches of Cook Strait as a jet current, as illustrated in the surface nitrate-nitrite distribution of Figure 18. These nitrate-nitrite values suggested that the upwelled water off Clifford Bay was restricted to the coastal shelf around southeastern Cook Strait and did not extend outward into the Pacific Ocean.

A region with nitrate-nitrite values greater than 4.0 uM extended around Cape Cambell and down the east coast of South Island, to a distance of 40 km below Cape Cambell. In addition, the surface silicate and phosphate distributions, which are illustrated in Figures 19 and 20 respectively, agreed with the nitrate-nitrite values and indicated a region of elevated nutrient values that extended around Cape Cambell. This region had silicate concentrations greater than 3.5 uM and phosphate concentrations greater than 0.8 uM.

The surface chlorophyll 'a' distribution is illustrated in Figure 22. Maximum chlorophyll 'a' concentrations of 6.8 mg m^{-3} were located beyond the coastal shelf in the vicinity of Station 4. The increased stability of the water column in combination with a sufficient supply of nutrients from the adjacent water masses around Cape Cambell and Cape Palliser probably permitted a net accumulation of phytoplankton biomass.

VII.4 Discussion

The nutrient and temperature data from leg 1 of the 1980 cruise, which was sampled subsequent to a period of strong southerly winds in Cook Strait, indicated that there was no plume of cold, nutrient rich water emanating from the eastern approaches to Cook Strait at this time. The circulation in the vicinity of the eastern approaches appeared to be dominated by the presence of the Southland Current.

The nutrient, temperature and salinity data from leg 2 of the 1980 cruise indicated that there was a plume of cold, nutrient rich water emanating from the strait during the sampling period. This data, in conjunction with drogue trajectories indicated that water from the Taranaki Bight was advected into Cook Strait Narrows. The water advected into the narrows was subsequently mixed with the deep water residing in Cook Strait Canyon. The ensuing water mass was conveyed toward the shelf off Clifford Bay and upwelling resulted. The upwelled water mixed to some degree with water of Southland Current origin, which overlaid the shelf off Clifford Bay. The resultant water mass was then transported eastward during a period of persistent northerly winds.

A persistent period of northerly winds will reduce the barotropic component in the advective transport of the northwards flowing Southland Current (Heath, 1972). The eastward displacement and reduced transport of the Southland Current results in a decrease in its influence over the eastern approaches of Cook Strait. It is thought that this reduced influence permitted the upwelled water off Clifford Bay, that was transported eastward, to emerge as a plume. This plume water, which appeared to be mainly comprised of a mixture of Southland Current water and D'Urville Current water ("Cook Strait water"), flowed in a southeastward direction upon emerging from the strait. This denser, cold temperature water began to sink as it flowed from the strait and mixed with Southland Current water along its southwestern boundary. The plume water flowed above the denser East Cape Current water, which was located in the northeastern area of the plume. This East Cape Current water appeared to reside at depth in the northeastern section of the Cook Strait Canyon and offshore eastward beyond the coastal shelf. The velocity of the current which formed the plume was estimated from geostrophic calculations based on the hydrostation data that formed the transverse vertical of sigma-t illustrated in Figure 33e. The depth of no motion was assumed to be at 1000 m. As the maximum depth of the CTD was 300 m, sigma-t values between 300 m and 1000 m was extrapolated from historical measurements (Heath, 1975). A vertical section of the relative velocities is illustrated in Figure 39. The maximum surface velocity of the jet current, predicted by the geostrophic calculation was 48 cm sec^{-1} and was centered around Station Q497.

A jet current that emanated from Cook Strait was also indicated by the drogue trajectories illustrated in Figure 24. Drogue No. 28, which was released on January 31, 1980 and retrieved on February 1, 1980, indicated a minimum drogue velocity of 68 cm sec^{-1} to the southeast.

Velocities computed from drogue trajectories and the geostrophic calculations suggested that the chlorophyll 'a' maximum of 1.8 mg m^{-3} located 125 km offshore was about 2 to 3 days travel time from Cook Strait. Therefore, the phytoplankton population that

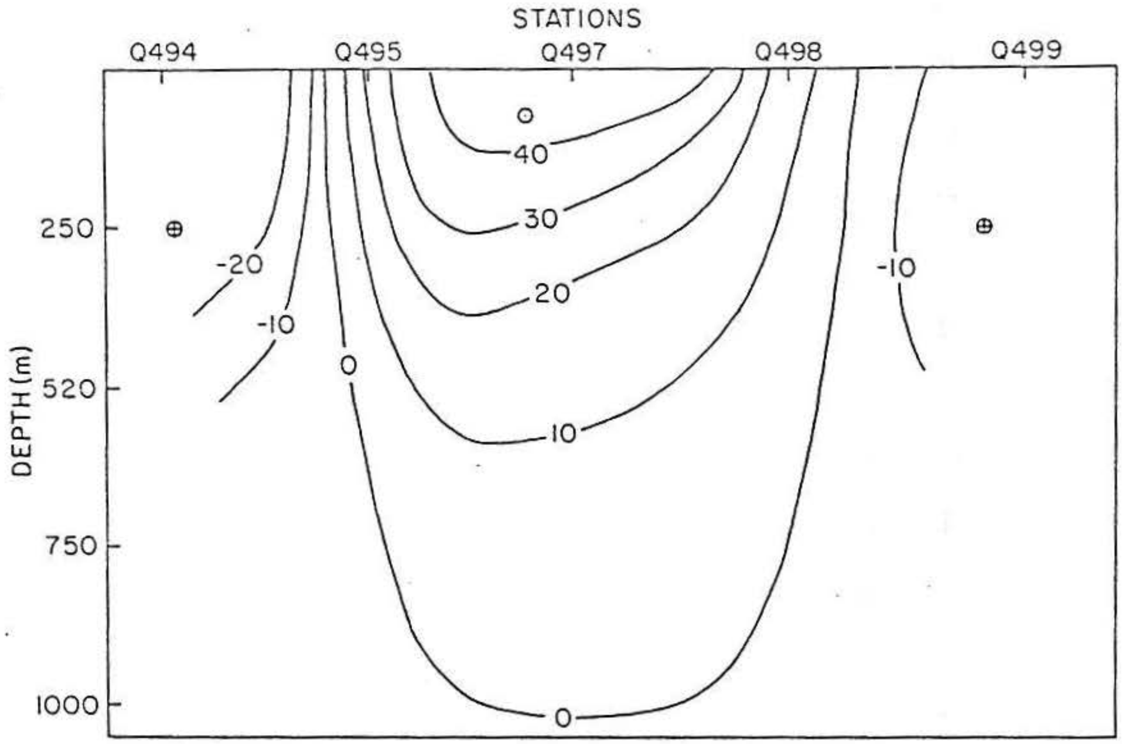

Fig. 39. Geostrophic estimates of plume velocities (cm sec^{-1}) relative to 1000 dbar, (Bowman <u>et al</u>., in press c).

was advected out of the strait, neglecting the effects of grazing, would have a minimum doubling time of approximately 1 day^{-1}.

The nutrient and temperature data from leg 1 of the 1981 cruise suggests that the influence and presence of the Southland Current in the eastern approaches of Cook Strait was not reduced sufficiently to permit the water that was upwelled off Clifford Bay to emerge as a plume from Cook Strait. It is thought that the light to moderate northerly and predominantly westerly winds during leg 1 of the 1981 cruise did not adequately reduce the transport of the Southland Current and divert it offshore. As a result, the upwelled water off Clifford Bay was restricted to the coastal shelf and spread around Cape Cambell.

The surface temperature and salinity data substantiated the conclusions deduced from the nutrient data and indicated that the source of the water mass with elevated nutrient values around Cape Cambell was off Clifford Bay. In addition, the temperature and salinity data from hydrostations in the eastern approaches of Cook Strait indicated that deep water in the northeastern section of Cook Strait was East Cape Current water.

Chapter VIII

Cape Farewell Eddy Structure

VIII.1 Introduction

The surface circulation on the western coastal shelf of New Zealand is closely related to the surface circulation off the east coast of Australia (Heath, 1971). Water masses that are cast off the East Australia Current as it turns eastward at the latitude of Sydney forms the eastward flowing Tasman Current (Stanton, 1971). This flow, upon meeting the New Zealand coast, divides near Jacksons Head with the northward flowing component becoming the Westland Current (Heath, 1971).

The Westland Current has been described as mainly barotrophic in nature by Bye *et al*. (1979) and as a result is not strongly dependent upon the internal density distribution. Therefore, the variability in the intensity of the Westland Current probably reflects changes in the local weather conditions (Brodie, 1960). The Westland Current divides in the vicinity of Cape Farewell with one component rounding Cape Farewell and entering Cook Strait as the D'Urville Current and the other component continuing northward toward the west coast of North Island. Strong southerly winds will minimize the indraught into Cook Strait and extend the Westland Current to the north, which may influence the entire west coast of North Island (Brodie, 1960). Northerly winds tend to increase the transport of the D'Urville Current.

The bathymetry and shape of the coastal shelf off Cape Farewell are important to the hydrology of the region. The bathymetry of the shelf off Cape Farewell is illustrated in Figure 40, which shows that the shelf is relatively steep from the coast out to a depth of 55 m, but with two shallow areas, the Kahurangi Shoals and Paturau Bank. Stanton (1971) observed intensive areas of cold water associated with the equatorward side of sharp coastal bends at Kahurangi Point and the base of Farewell Spit in a 1969 survey of the Cape Farewell region.

The sediments in the Cape Farewell region are derived from two major sources, one source is the erosion products from the Southern Alps which are supplied by steep mountain streams and rivers and the other source is the Kahurangi Shoals (Van Der Linden, 1969). The western shelf is mainly composed of fine and medium grain sands that are erosion products of the

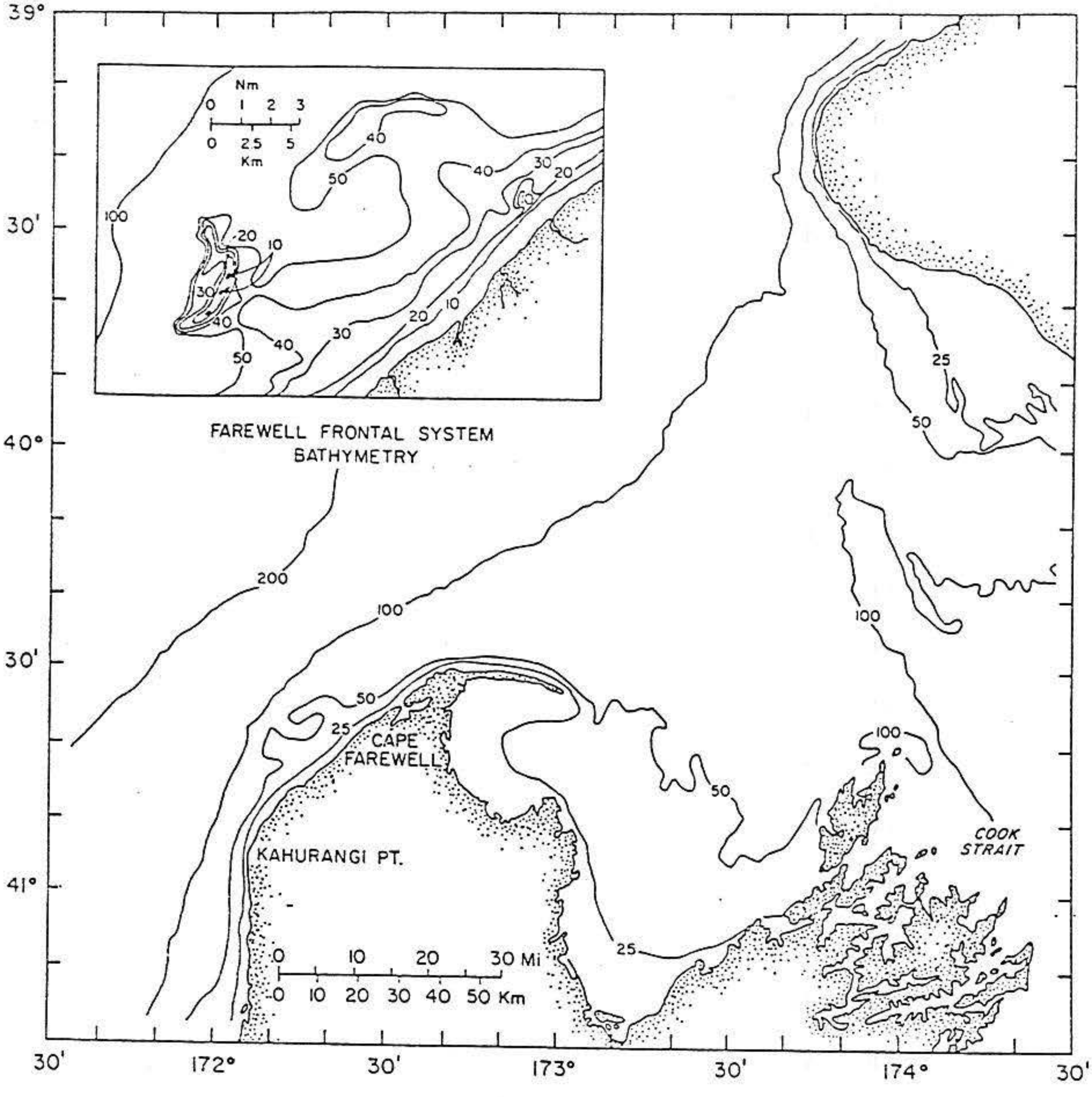

Fig. 40. Location and Bathymetry map of Cape Farewell region with depth in meters.

Southern Alps carried north by the Westland Current. Mineralogically these sands are a quartz-mica-feldspar composition indicating an origin from granites, gneisses, and schists. A belt of coarse clastics, comprised mainly of quartzites, is associated with the Kahurangi Shoals. These coarse sediments are moderately to well sorted in the central area of the shoals indicating maximum current energy. The position of the bifurcating Kahurangi Shoals belt of coarse clastics marks the path of the Westland and D'Urville Currents and is illustrated in Figure 41 (Van Der Linden, 1969).

The presence of cold, nutrient rich water in the region off Cape Farewell was observed during both the 1980 and 1981 cruises. A transect perpendicular to the coast of Cape Farewell on leg 1 of the 1981 cruise indicated that there was an offshore-onshore movement that resulted in upwelling. However, the northerly to westerly winds during leg 1 of the 1980 cruise and leg 1 of the 1981 cruise favored downwelling along the Cape Farewell coast. This suggested that the upwelling off Cape Farewell was not wind induced but was the result of bottom Ekman transport from a current flowing around a promontory or a change in the bathymetry.

Evidence of eddy formation and shedding from Cape

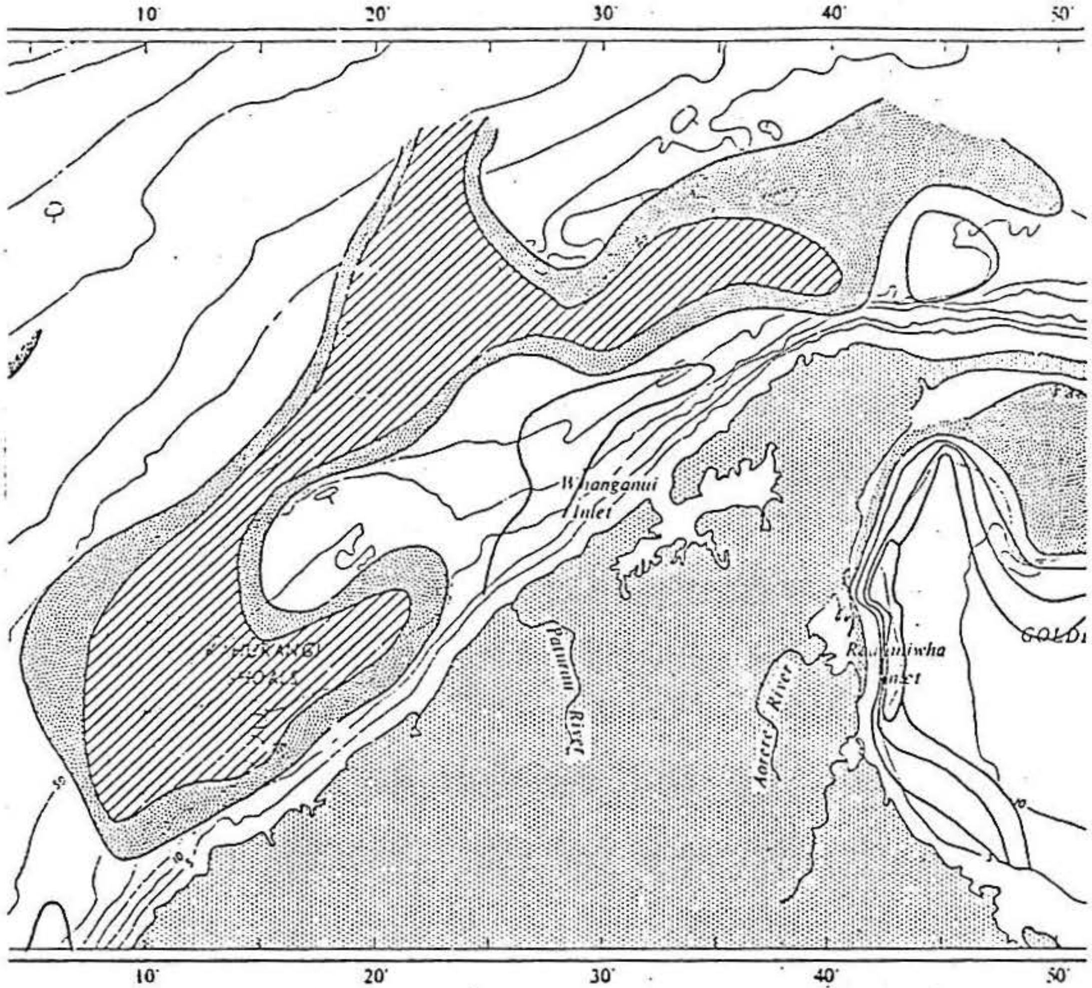

Fig. 41. Map of sediment classes off Cape Farewell with cross hatched area indicating the position of the bifurcated Kahurangi Shoals belt of coarse clastics (Van Der Linden, 1969).

Farewell's cold nutrient rich region was obtained on leg 1 of the 1980 cruise. The surface nitrate-nitrite, temperature and chlorophyll 'a' distributions all indicated a patch of elevated nitrate-nitrite and chlorophyll 'a' values and low temperature values in the western approaches to Cook Strait that appeared to originate from the cold, nutrient rich region off Cape Farewell.

VIII.2 Leg 1 HMNZS Tui 1981 Cruise

The surveys of the Cape Farewell region on leg 1 of the 1981 cruise occurred during a period of moderate northerly to westerly winds and neap tides. Wind vectors for the Cape Farewell surveys from January 28-January 31, 1981 are illustrated in Figure 17. The wind direction for the two leg 1 surveys of the Cape Farewell region favored downwelling along this section of the coast. However, the nutrient rich, cold temperature region persisted thoughout the surveys with the highest nutrients and coldest temperatures associated with the sharp convex coastal bends and changes in bathymetry in the Cape Farewell region.

The surface nitrate-nitrite distribution for the first survey on leg 1 is illustrated in Figure 18. Figure 18 indicated that the maximum nitrate-nitrite concentrations of approximately 7.0 uM were near the coast in the vicinity of Kahurangi Point and the base of Farewell Spit, which are the two sharpest convex coastal bends. Water with a nitrate-nitrite concentration of 7.0 uM appeared to upwell from a depth of 150 to 200 m along the continental slope. The offshore oligotrophic waters beyond the frontal boundary off Cape Farewell had a nitrate-nitrite concentration of approximately 0.15 uM. The range in nitrate-nitrite concentration off Cape Farewell is similar to the range in nitrate concentrations observed in upwelling regions off the east coast of Australia (Rochford, 1972, 1975). These values ranged from 0.5 uM or less in the oligotrophic waters to 5.0 to 10.0 uM in water that recently upwelled from a depth of 150 to 200 m.

In addition to the maxima in nitrate-nitrite values, there appeared to be several areas of higher nitrate-nitrite concentrations imbedded in the region of elevated nitrate-nitrite values off Cape Farewell, which formed eddies associated with unstable meanders in the upwelling front. Figure 18 indicates the presence of cyclonic eddies within the upwelling region with nitrate-nitrite concentrations of approximately 2.4 uM. In addition, the surface nitrate-nitrite distribution in Figure 18 indicates the presence of a detached eddy from the Cape Farewell region with a nitrate-nitrite value of approximately 1.0 uM.

The surface silicate distribution off Cape Farewell for the first survey (Fig. 19) shows good correlation with the surface nitrate-nitrite distribution in the vicinity of the source of the upwelled water. However, downstream of the source region the surface silicate distribution becomes more complex. Surface silicate concentrations were generally low in the entire Cook Strait region, including Cape Farewell, with maximum surface values between 4.0 uM and 5.0 uM. The two areas near the coast with surface nitrate-nitrite maxima had corresponding surface silicate values greater than 4.0 uM, while the offshore oligotrophic surface waters had a concentration of less than 1.0 uM. The cyclonic eddies, that were present within the region of elevated nutrient values had surface silicate concentrations of 2.0 uM to 3.0 uM.

The surface temperature distribution for the Cape Farewell region illustrated in Figure 21 indicates good correlation with the surface nitrate-nitrite distribution with an inverse relationship between temperature and nitrate-nitrite values. The region off Cape Farewell with water temperatures of less than 19 °C off Cape

Farewell was more extensive than the region of elevated nitrate-nitrite values. This suggested that active uptake of nitrate-nitrite by phytoplankton was taking place. As a result, there were sharp gradients in the concentration of nitrate-nitrite between the mixed regions and the adjacent waters that provided some degree of stability for phytoplankton growth. Surface temperature behaves as a more conservative seawater property than nitrate-nitrite, except for increases in surface temperature due to surface layer heating from solar insolation. Therefore, the gradients in the surface temperature distribution were much weaker than nitrate-nitrite. Nitrate-nitrite concentrations were generally reduced to levels equivalent to the adjacent oligotrophic waters, with a value of approximately 0.15 uM, when the surface water temperature reached a value of between 16.5 to 17.0 ^{o}C. The coldest surface water temperatures appeared to be located adjacent to the coast corresponding to the two areas of nitrate-nitrite maxima. The presence of the detached cyclonic eddy is also indicated in Figure 21 with a surface temperature low of approximately 16.6 ^{o}C and a corresponding nitrate-nitrite concentration of approximately 1.0 uM.

The surface chlorophyll 'a' distribution for the first survey on leg 1 off Cape Farewell region is illustrated in Figure 22. The highest chlorophyll 'a' concentrations were located in the western approaches to Cook Strait near the downstream extent of the region of elevated nitrate-nitrite values and in the nearshore area between the two colder nutrient rich areas. The maximum chlorophyll 'a' values attained on the first survey were approximately 2.6 mg m^{-3}.

The second survey of the Cape Farewell region on leg 1 took place from January 30 to January 31, 1981. The surface nitrate-nitrite distribution for the second survey, which is illustrated in Figure 42, indicates that there was significant movement of the frontal boundary since the prior survey. The highest nitrate-nitrite concentrations still appeared to be in close proximity to the coast with a maximum surface concentration of 6.6 uM at the sharp convex coastal bend at the base of Farewell Spit. The other sharp convex coastal bend at Kahurangi Point was not sampled on the second survey. Figure 42 shows a circular patch of elevated nitrate-nitrite with a value of approximately 0.7 uM that was detached from the frontal region near the coast. This circular patch was designated

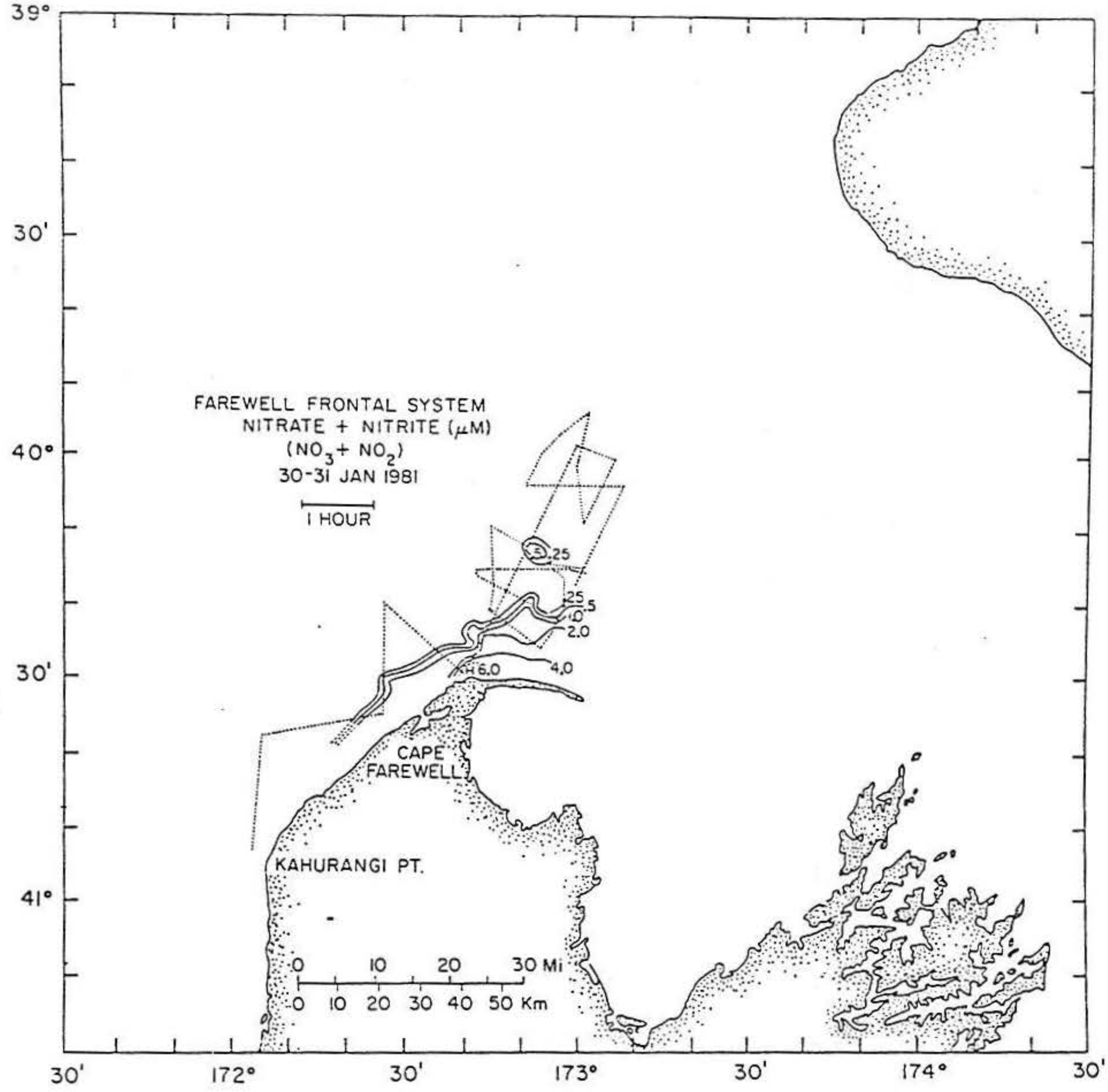

Fig. 42. Surface distribution of nitrate-nitrite (uM) off Cape Farewell on second survey of leg 1, January 30- 31, 1981.

Eddy Gail.

The surface silicate distribution for the second survey, illustrated in Figure 43, was more complex than the nitrate-nitrite distribution downstream of the source region in the western approaches of Cook Strait. Close to the Cape Farewell coast the surface silicate distribution corresponded well to the surface nitrate-nitrite distribution with the meanders in the frontal boundary of nitrate-nitrite correlating with the meanders in the frontal boundary of silicate. In addition, there was a surface maximum in silicate, with a value of 4.9 uM at the base of Farewell Spit that corresponded to the surface maximum in nitrate-nitrite. The silicate distribution differed from the nitrate-nitrite distribution in that a band of elevated silicate values slightly higher than 1.0 uM was located offshore from the frontal boundary and appeared to extend south of Kahurangi Point. This band of water with elevated silicate values probably originated from within the Karamea Bight and flowed northward around Kahurangi Point. Additional areas of elevated silicate values that ranged between 2.0 to 3.0 uM, which had no corresponding elevated nitrate-nitrite values, were located downstream in the western approaches. This suggested

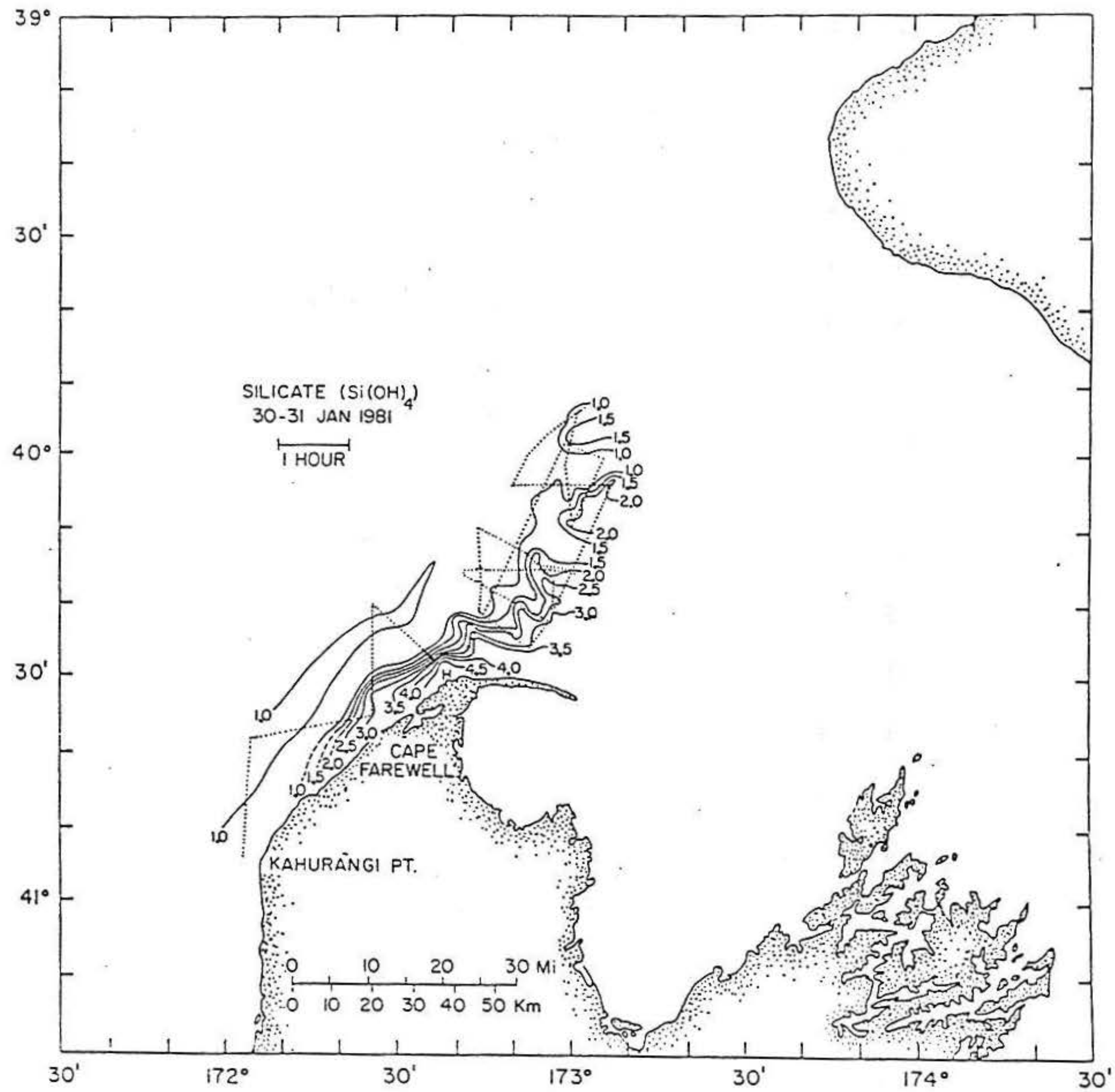

Fig. 43. Surface distribution of silicate (uM) off Cape Farewell on second survey of leg 1, January 30-31, 1981.

that water column regeneration of silicate may be significant in the Cape Farewell region.

The surface temperature distribution for the second survey of leg 1, (Fig. 44), shows generally good correlation with the surface nitrate-nitrite distribution in an inverse relationship. However, the region of low temperature values was more extensive than the region of elevated nitrate-nitrite values suggesting significant uptake of nitrate-nitrite by phytoplankton. Figure 44 indicates that the area of coldest water temperatures at the base of Farewell Spit, with a temperature of approximately 13.6 $^{\circ}$C, corresponding to the area of highest nitrate-nitrite values. The surface temperature distribution also indicated the presence of Eddy Gail, with temperatures of less than 17.0 $^{\circ}$C, in the western approaches. In addition, an area of low temperatures (17.5 to 18.0 $^{\circ}$C) was located just north of Eddy Gail in the western approaches and was designated Eddy Phillipa. This eddy was not evident in the surface nitrate-nitrite distribution of Figure 42, which suggests that phytoplankton uptake had reduced the nitrate-nitrite concentration to background levels. The surface temperature data indicated that Eddy Phillipa had detached from the Cape Farewell

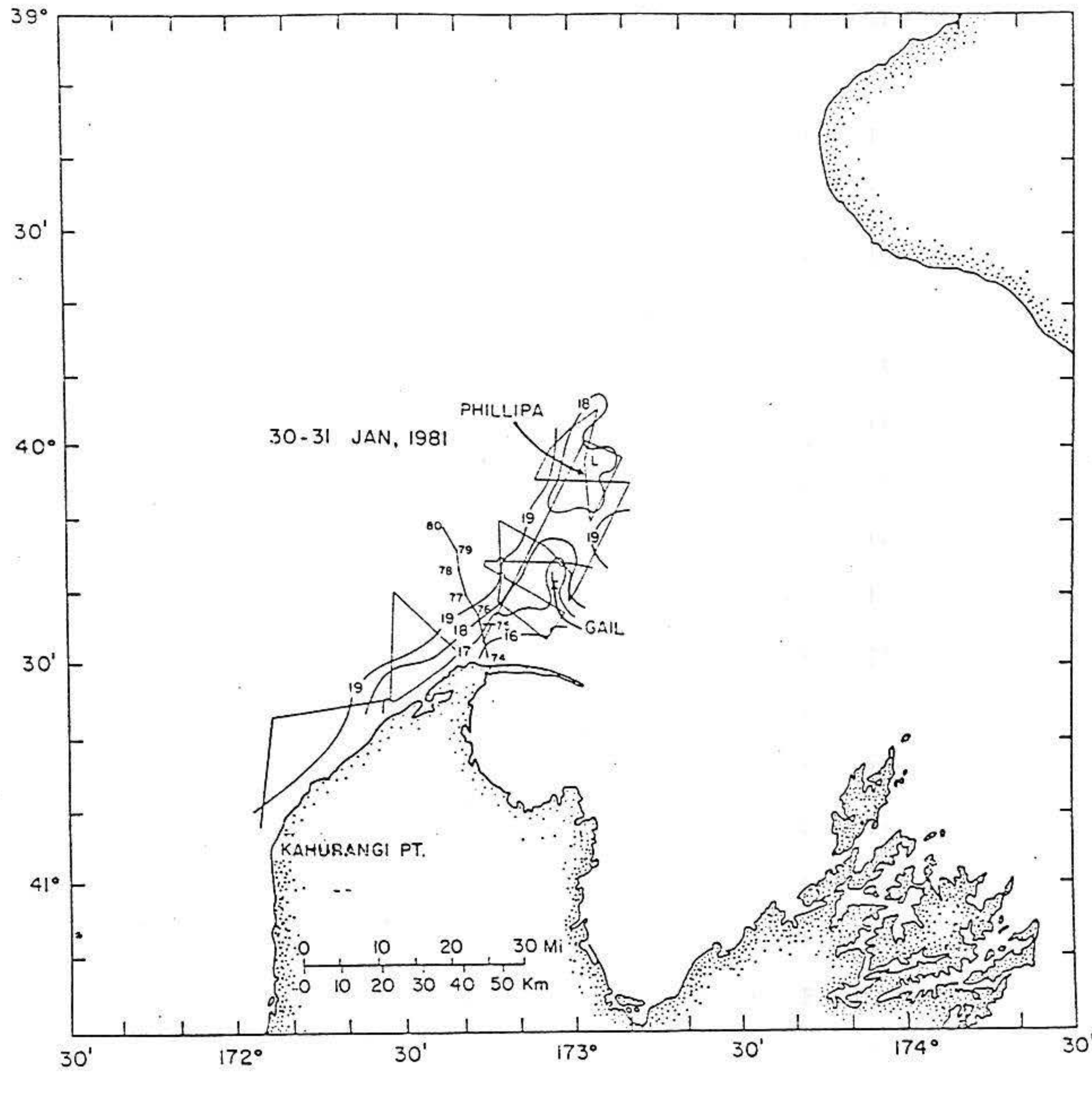

Fig. 44. Surface distribution of temperature (°C) off Cape Farewell on second survey of leg 1, January 30-31, 1981, (Bowman et al., in press a).

frontal region with a mean speed of about 18 cm sec^{-1} and was replaced by Eddy Gail approximately 48 hours later.

The surface chlorophyll 'a' distribution for the second survey is illustrated in Figure 45. Maximum concentrations were located at the frontal zone in the vicinity of Eddy Gail. This maximum of greater than 3.0 mg m^{-3} was approximately 9 times greater than concentrations in offshore oligotrophic waters. A favorable environment for phytoplankton growth was presumably provided by the marginal stratified frontal zone with an adequate supply of nutrients from the upwelling areas and eddies.

VIII.3 Leg 2 HMNZS Tui 1981 Cruise

The upwelling region off Cape Farewell was sampled in detail from February 8-12, 1981, during a period of spring tides. The sampling program included four surface surveys and hydrostation data, which produced three vertical transects through the region. The winds prior to and during the surveys were light to moderate with an average speed of approximately 5 m sec^{-1}. Wind direction was mainly southerly for a few days just prior to the first survey of leg 2, which would be upwelling favorable at Cape Farewell. The wind subsequently shifted to a northerly and easterly direction

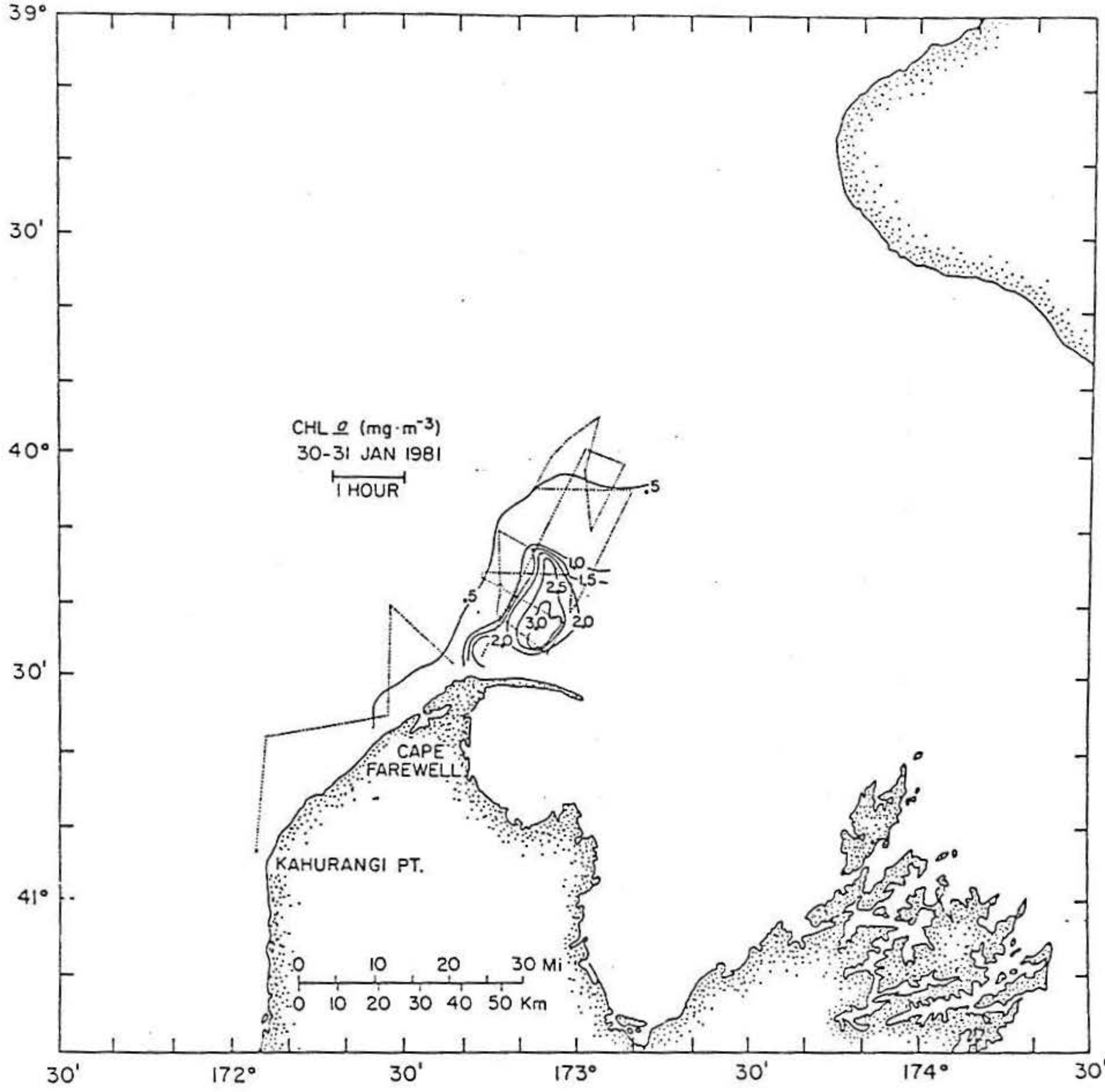

Fig. 45. Surface distribution of chlorophyll 'a' (mg m^{-3}) off Cape Farewell on second survey of leg 1, January 30- 31, 1981, (courtesy P. Lapennas).

at the beginning of first survey, which was downwelling favorable at Cape Farewell. The wind vectors for leg 2 of the 1981 cruise are illustrated in Figure 17.

The surface nitrate-nitrite distribution for the first survey (February 8-9) is illustrated in Figure 46. Figure 46 indicates that the region of elevated nitrate-nitrite values had greatly expanded in comparison to the leg 1 surveys and had extended well into the western approaches of Cook Strait. In addition, the region of elevated nitrate-nitrite values appears to have separated from the coast of Cape Farewell north of Kahurangi Point. Figure 46 indicates that a band of water with nitrate-nitrite values of less than 0.25 uM was situated in the nearshore area and extended well down the coast of Cape Farewell toward Kahurangi Point. In contrast to the leg 1 surveys, the area of intensified upwelling with maximum nitrate-nitrite values at the base of Farewell Spit was not present. The surface nitrate-nitrite distribution indicated that the area of intensified upwelling, with a maximum nitrate-nitrite concentration of approximately 8.0 uM, was located at just one position at the sharp convex coastal bend at Kahurangi Point. In addition, the surface nitrate-nitrite distribution showed the

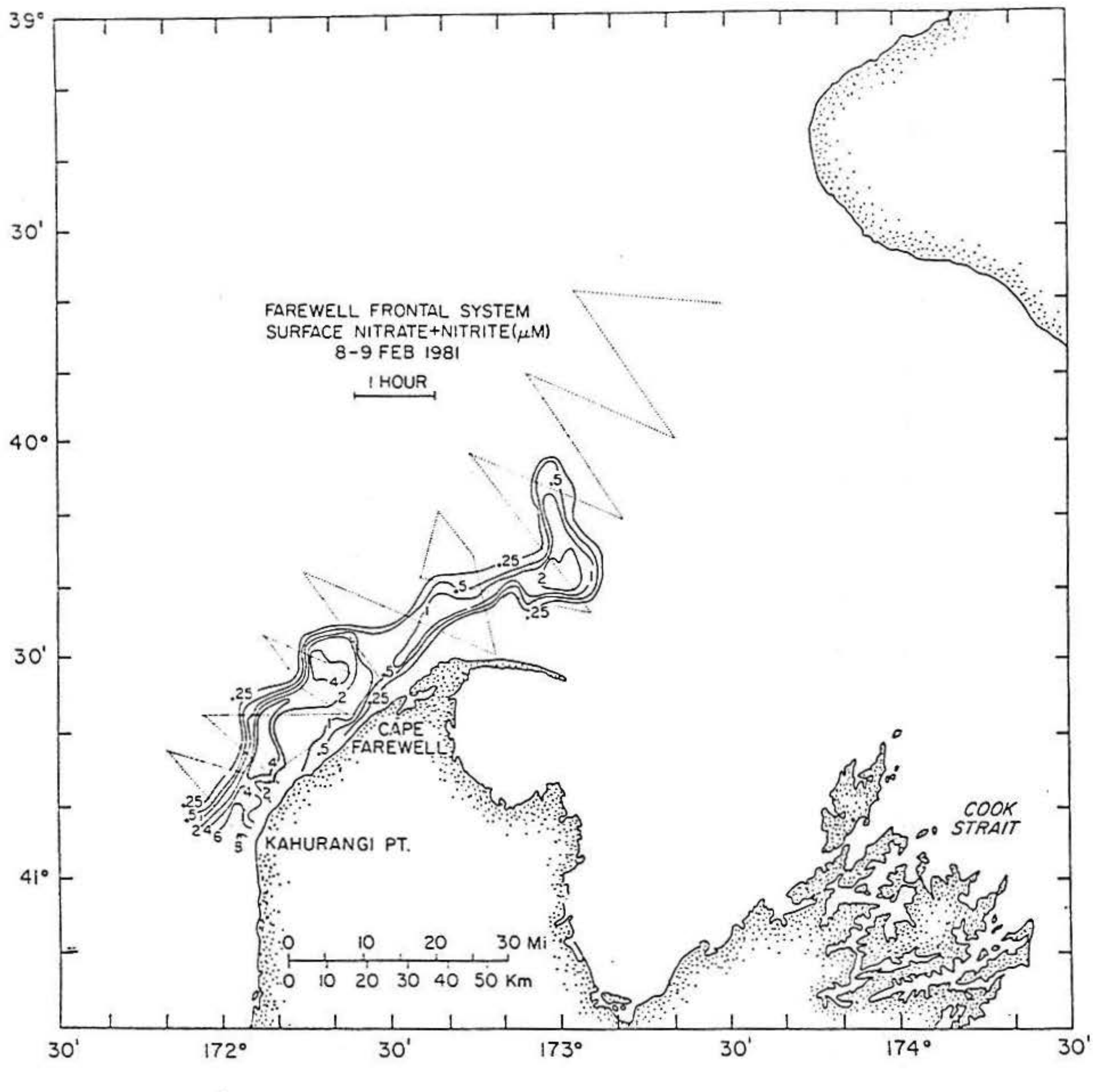

Fig. 46. Surface distribution of nitrate-nitrite (uM) off Cape Farewell on first survey of leg 2, February 8- 9, 1981.

presence of three cyclonic eddies with higher nitrate-nitrite concentrations imbedded in the plume. The nitrate-nitrite data also suggested the development of a fourth eddy near Kahurangi Point. The northern most cyclonic eddy, designated Eddy Leilani, contained a maximum nitrate-nitrite concentration of approximately 2.8 uM. The next cyclonic eddy, located in a southwesterly direction along the plume, contained a maximum nitrate-nitrite concentration of approximately 5.3 uM and was designated Eddy Rhoanna. The third cyclonic eddy, located southwest of Eddy Rhoanna, was designated Eddy Karol and contained a maximum nitrate-nitrite concentration of approximately 6.3 uM. The oligotrophic waters surrounding the plume had a nitrate-nitrite concentration of approximately 0.15 uM.

The surface silicate distribution for the first survey of leg 2 (Fig. 47) indicates that the surface silicate distribution corresponded well to the surface nitrate-nitrite distribution in the vicinity of the source area at Kahurangi Point. However, the distribution became more complex and did not correspond well to the nitrate-nitrite distribution further downstream. The maximum silicate concentration in the source area at Kahurangi Point was approximately 4.9 uM. The

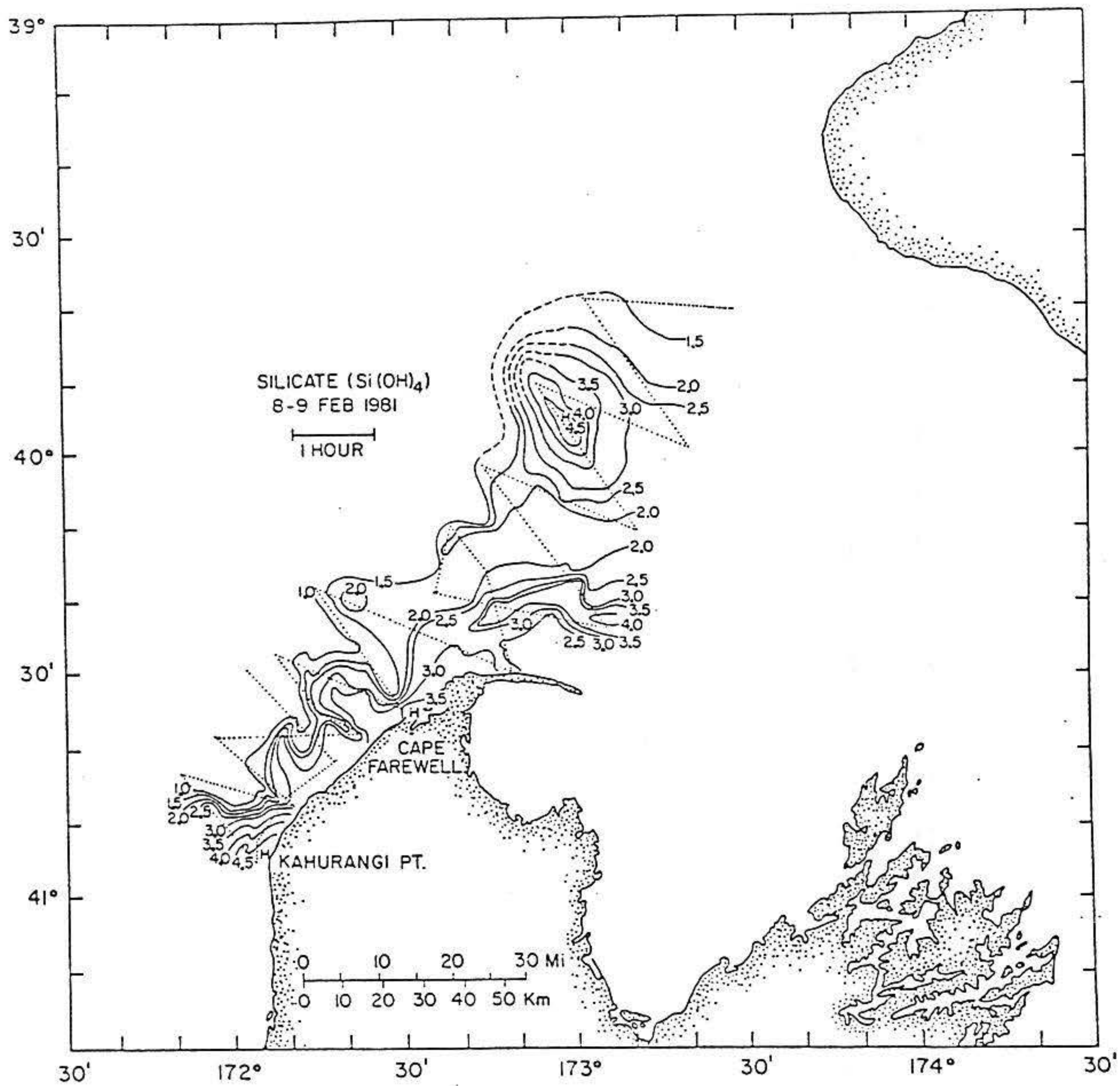

Fig. 47. Surface distribution of silicate (uM) off Cape Farewell on first survey of leg 2, February 8- 9, 1981.

meanders in the frontal boundary of the surface silicate distribution corresponded well with the meanders in the nitrate-nitrite distribution just north of Kahurangi point. However, the nitrate-nitrite distribution in Figure 46 indicated the presence of a band of depleted water close inshore that was not evident in the surface silicate distribution. The nearshore surface silicate values for the first survey generally ranged between 2.5 uM to 3.5 uM. The oligotrophic water offshore from the Cape Farewell frontal zone had a silicate concentration of less than 1.0 uM. A nearshore maximum of 3.7 uM was located approximately 15 km south of the base of Farewell Spit near the mouth of the Paturau River suggesting that this maximum was due to freshwater input. Silicate concentrations of approximately 30 uM were sampled in waters with a salinity of 4 $^{o}/oo$ on the west coast of South Island during the 1980 cruise. Stanton (1971) states that coastal dilution by rivers is considerable on the west coast of the South Island. As a result freshwater silicate inputs can be significant. Figure 47 indicates that there were several areas with elevated silicate values of 3.0 to 4.0 uM in the downstream sections of the plume within the western approaches to Cook Strait. The downstream and nearshore areas of elevated silicate values, which corresponded to areas of nitrate-nitrite depletion, suggest the importance of water column regeneration of silicate off Cape Farewell.

The surface temperature distribution for the first survey of leg 2 (fig. 48) indicated that the region of reduced temperature had greatly expanded compared to the leg 1 surveys and extended over most of the western approaches. The surface temperature distribution corresponded well with the surface nitrate-nitrite distribution in an inverse relationship. However, the region of reduced temperatures was much more extensive than the region of elevated nitrate-nitrite values suggesting significant uptake of nitrate-nitrite by phytoplankton. Figure 48 also indicates that the plume of upwelled water was detached from the Cape Farewell coast north of Kahurangi Point with a band of warm temperature water in the nearshore area. Figure 48 also indicates that the source region of the upwelled water was localized to the area around Kahurangi Point similar to the nutrient distributions. Eddies Karol, Rhoanna and Leilani with the associated meanders in the frontal boundary were evident in the surface temperature distribution, which correlated with the

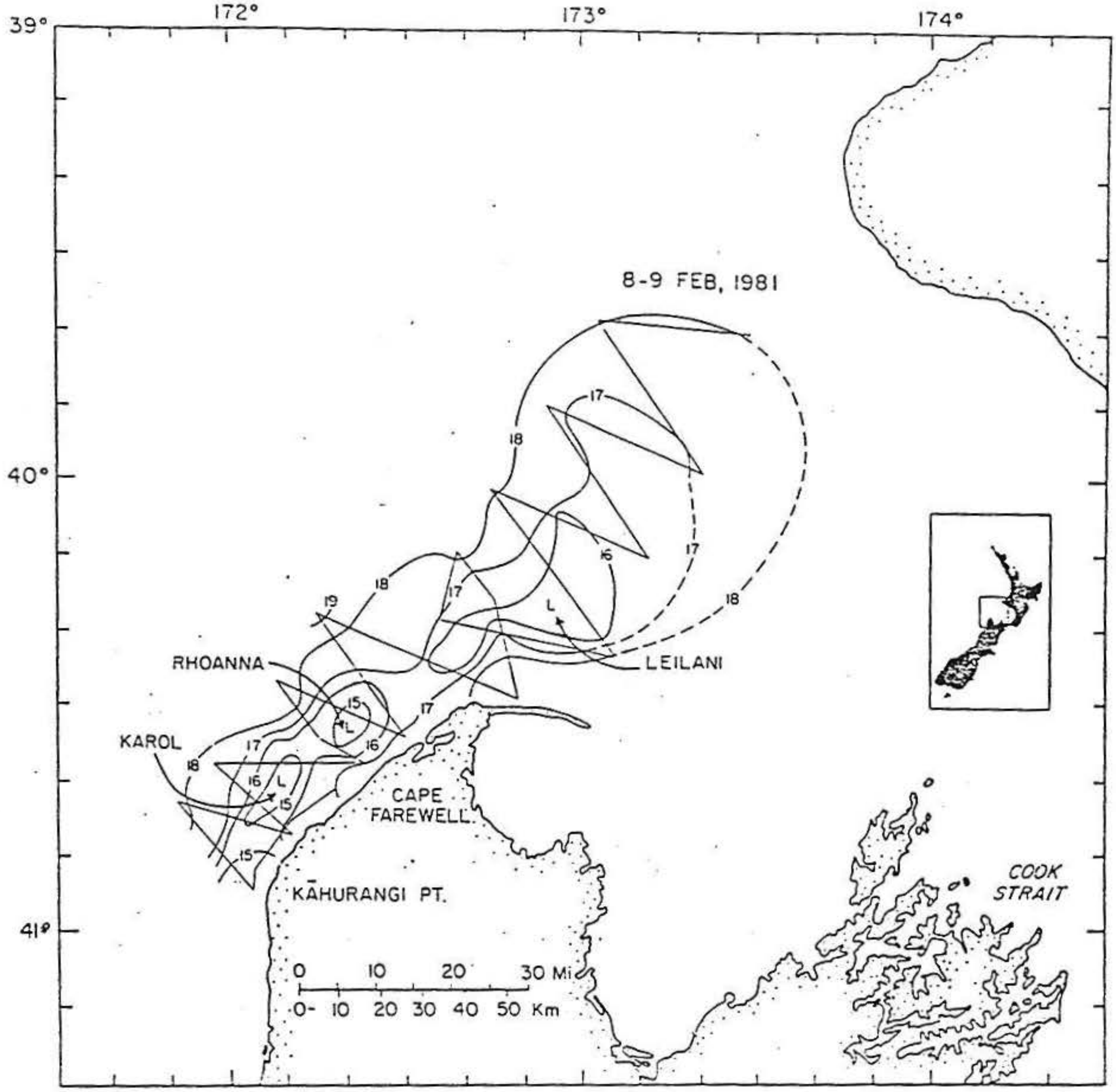

Fig. 48. Surface distribution of temperature (^{o}C) off Cape Farewell on first survey of leg 2, February 8- 9, 1981, (Bowman et al., in press a).

surface nitrate-nitrite distribution. Eddies Karol and Rhoanna had surface temperature minimums of less than 15 ^{o}C and Eddy Leilani had a surface temperature of less than 16 ^{o}C. The surface temperature in the offshore oligotrophic water was approximately 19 ^{o}C.

The surface chlorophyll 'a' distribution is illustrated in Figure 49. The maximum surface chlorophyll 'a' concentration was greater than 2.5 mg m^{-3}. This maximum, which was located in the western approaches, was associated with the southern edge of Eddy Leilani. In addition, a second chlorophyll 'a' maximum of approximately 2.5 mg m^{-3} was located in the nearshore area 10 km north of Kahurangi Point just below the southern limit in extent of the nearshore band of warm nutrient depleted water. A small patch of water with a surface concentration of 2.5 mg m^{-3} was located at the base of Farewell Spit near the area of intensified upwelling observed on leg 1. This suggests that subsequent stability in this area during leg 2 with adequate nutrients supplied by the previous upwelling permitted a net accumulation of phytoplankton.

A transect of 7 hydrostations (Stations 86- 87), across the upwelling zone and through Eddy Karol, was sampled at the conclusion of the first survey. Vertical

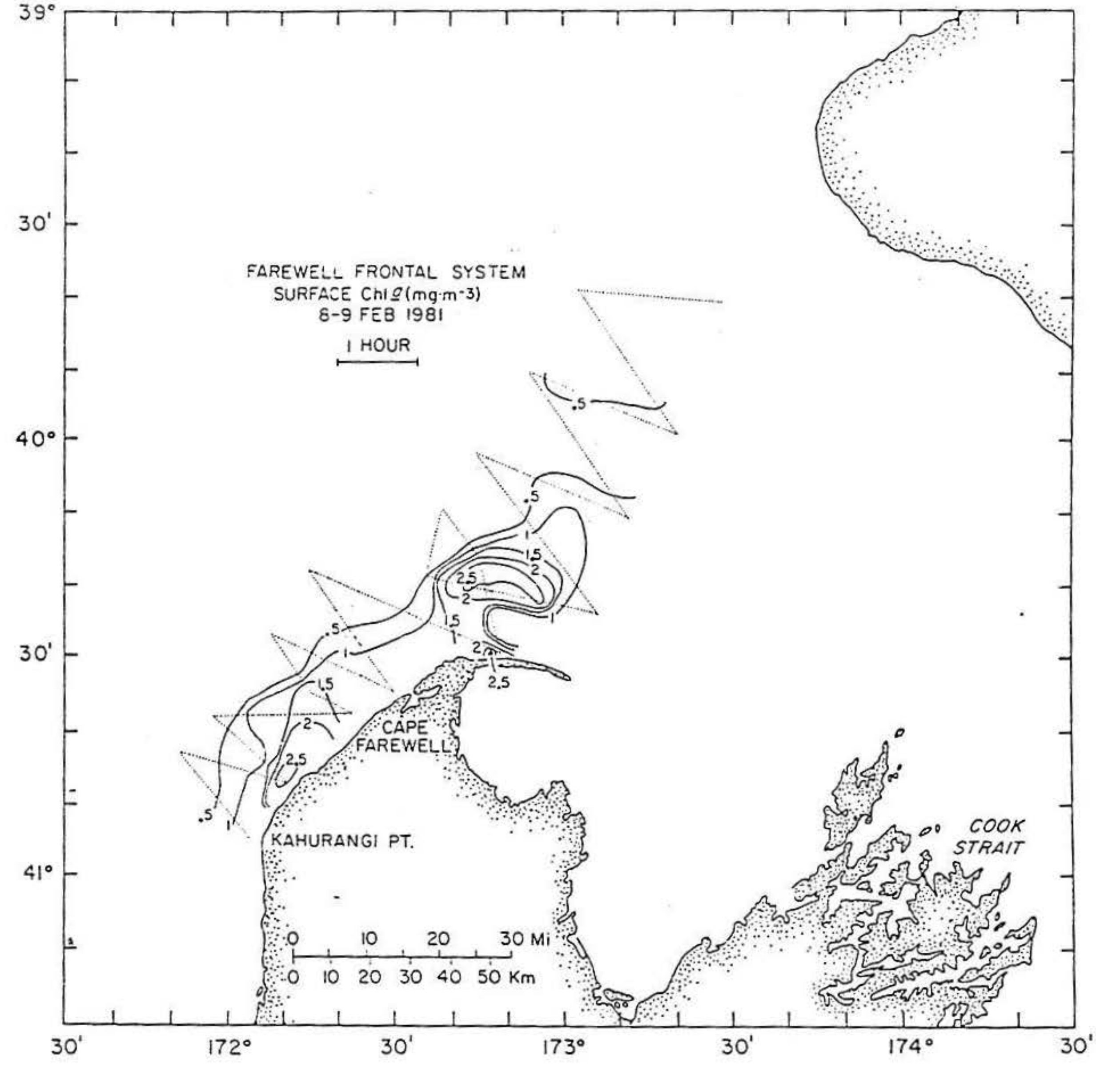

Fig. 49. Surface distribution of chlorophyll 'a' (mg m^{-3}) on first survey of leg 2, February 8- 9, 1981, courtesy P. Lapennas).

sections of the physical, chemical and biological properties are illustrated in Figures 50a to f.

The vertical distribution of nitrate-nitrite (Fig. 50b) indicated that there was an upward bending in the isopleths of nitrate-nitrite moving towards Eddy Karol from both onshore and offshore. The maximum surface nitrate-nitrite concentration, which was greater than 3.5 uM, was situated near Station 88 at a distance of 13 km offshore. The nearshore nitrate-nitrite concentration offshore at Station 86 was approximately 0.9 uM, while the nitrate-nitrite concentration offshore at Station 89 decreased to less than 0.2 uM.

The vertical distribution of silicate (Fig. 50d) indicates that there was a nearshore silicate maximum of approximately 4.0 uM at Station 86. The silicate isopleths all bend upward in the direction of Eddy Karol similar to the nitrate-nitrite distribution with the exception of the nearshore area. In addition, Figure 50d indicates that there was a subsurface minimum with a value of approximately 1.1 uM in the vicinity of Station 90 at a depth of 40 m. This suggests possible silicate utilization by a subsurface diatom population at the frontal zone of Eddy Karol.

The vertical distributions of temperature (Fig.

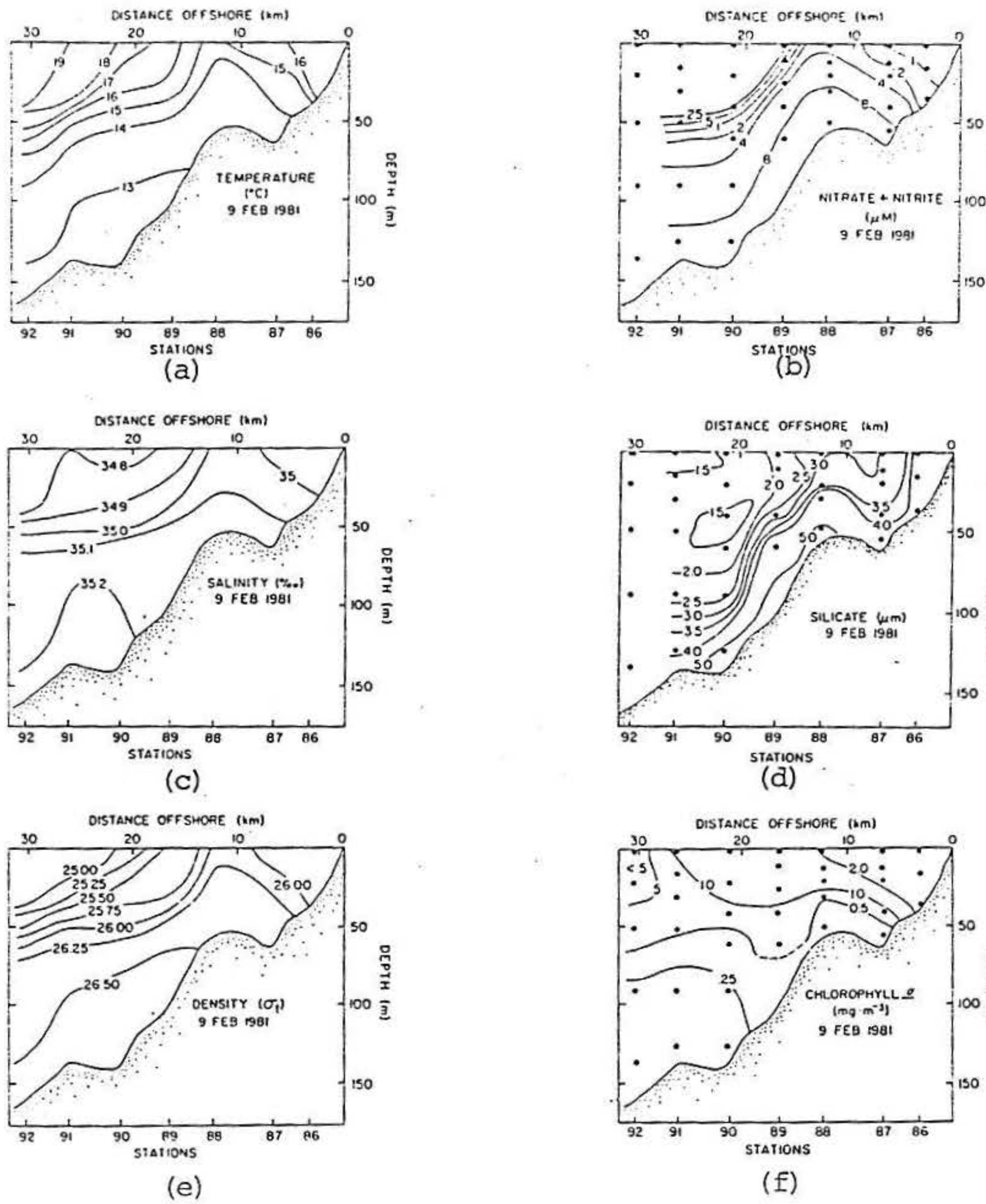

Fig. 50. Vertical distribution of physical, chemical and biological properties through Eddy Karol off Cape Farewell, February 8- 9, 1981: a) temperature (^{o}C), b) nitriate-nitrite (uM), c) salinity (^{o}/oo), d) silicate (uM), e) density ( ), f) chlorophyll 'a' (mg m^{-3}).

50a) and sigma-t (Fig. 50e) corresponded well with the nitrate-nitrite distribution. All the isopleths of temperature and sigma-t bend upward toward the surface in the direction of Eddy Karol, from both the onshore and offshore directions.

The vertical distribution of chlorophyll 'a' (Fig. 50f) indicates that the maximum chlorophyll 'a' concentrations of approximately 2.5 mg m^{-3} were located in the nearshore area at Stations 86 and 87. The inshore side of Eddy Karol had a chlorophyll 'a' concentration of approximately 2.0 mg m^{-3}. The offshore waters of Eddy Karol had a chlorophyll 'a' concentration of approximately 1.1 mg m^{-3} at the surface and a subsurface maximum of approximately 1.4 mg m^{-3} at 12 m. The seaward edge of the frontal zone at Eddy Karol in the vicinity of Station 90 had a large subsurface chlorophyll 'a' maximum of approximately 2.0 mg m^{-3}.

The second survey on leg 2 of the Cape Farewell region took place on February 9- 10, 1981 with light winds that blew persistently from a northerly direction.

The surface nitrate-nitrite distribution for the second survey (Fig. 51) indicated that during the second survey Eddy Leilani had detached from the upwelling plume. In addition, Figure 51 indicated that

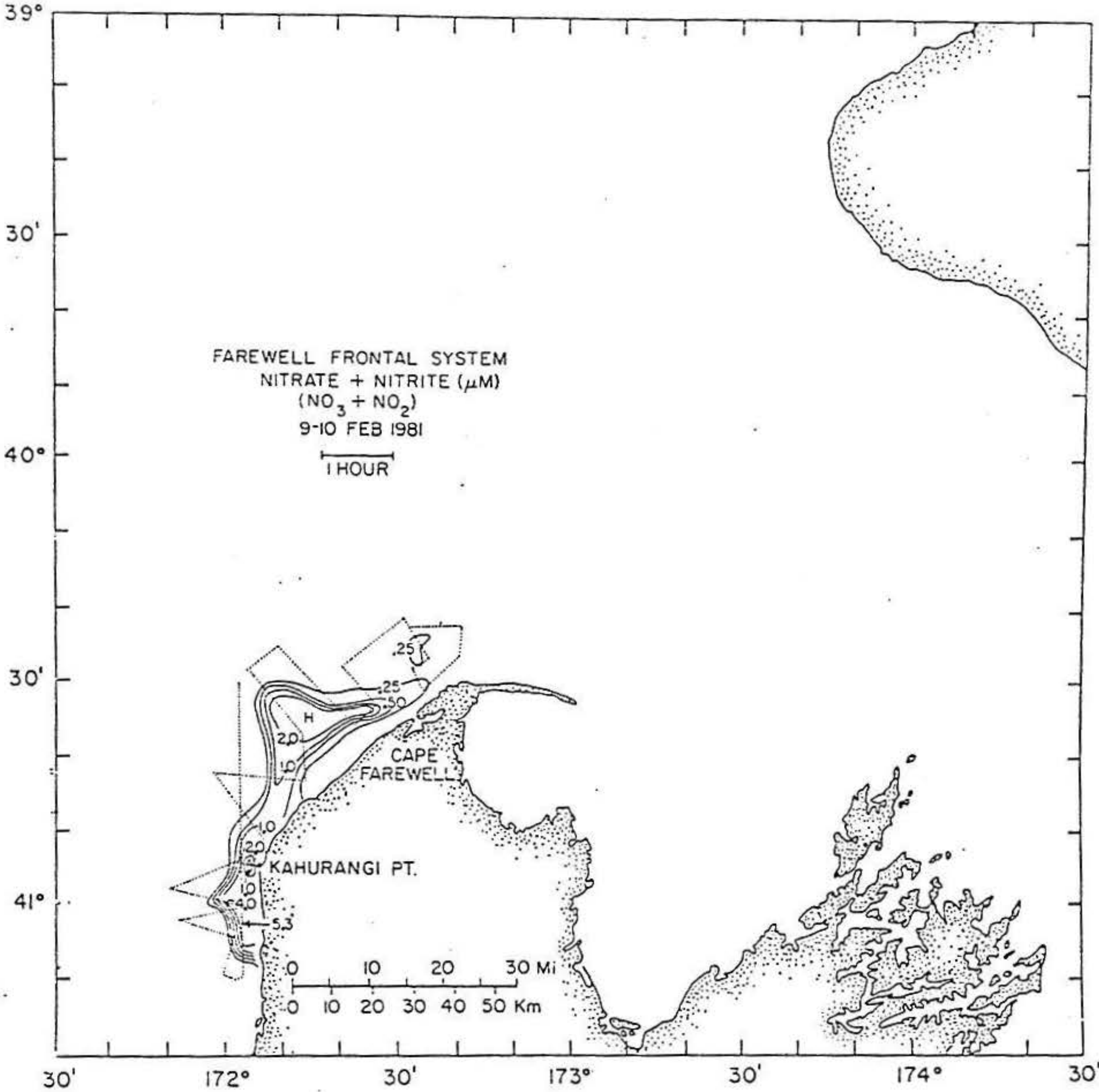

Fig. 51. Surface distribution of nitrāte-nitrite (uM) off Cape Farewell on second survey of leg 2, February 9- 10, 1981.

Eddy Rhoanna had stalled and reversed its northeastward movement coalesing with Eddy Karol to form Eddy Karolanna. Eddy Karolanna was imbedded in a plume of elevated nitrate-nitrite values with a maximum concentration of 4.0 uM within the eddy. The oligotrophic water surrounding Eddy Karolanna had a nitrate-nitrite concentration of approximately 0.15 uM.

The surface nitrate-nitrite distribution on the second survey also indicated the presence of a nearshore band of nitrate-nitrite depleted water with a concentration of less than 0.2 uM, which extended well down the coast of Cape Farewell toward Kahurangi Point. The area of intensified upwelling had apparently moved to the south of Kahurangi Point and the maximum nitrate-nitrite concentration decreased to 5.3 uM as compared to 8.0 uM on the previous survey.

The surface silicate distribution for the second survey (Fig. 52) corresponds well to the surface nitrate-nitrite distribution with the exception that the surface gradients in nitrate-nitrite were sharper than the surface gradients in silicate. In addition, there were areas of elevated silicate values that extended to the northeast with no corresponding elevated nitrate-nitrite values. A band of silicate depleted

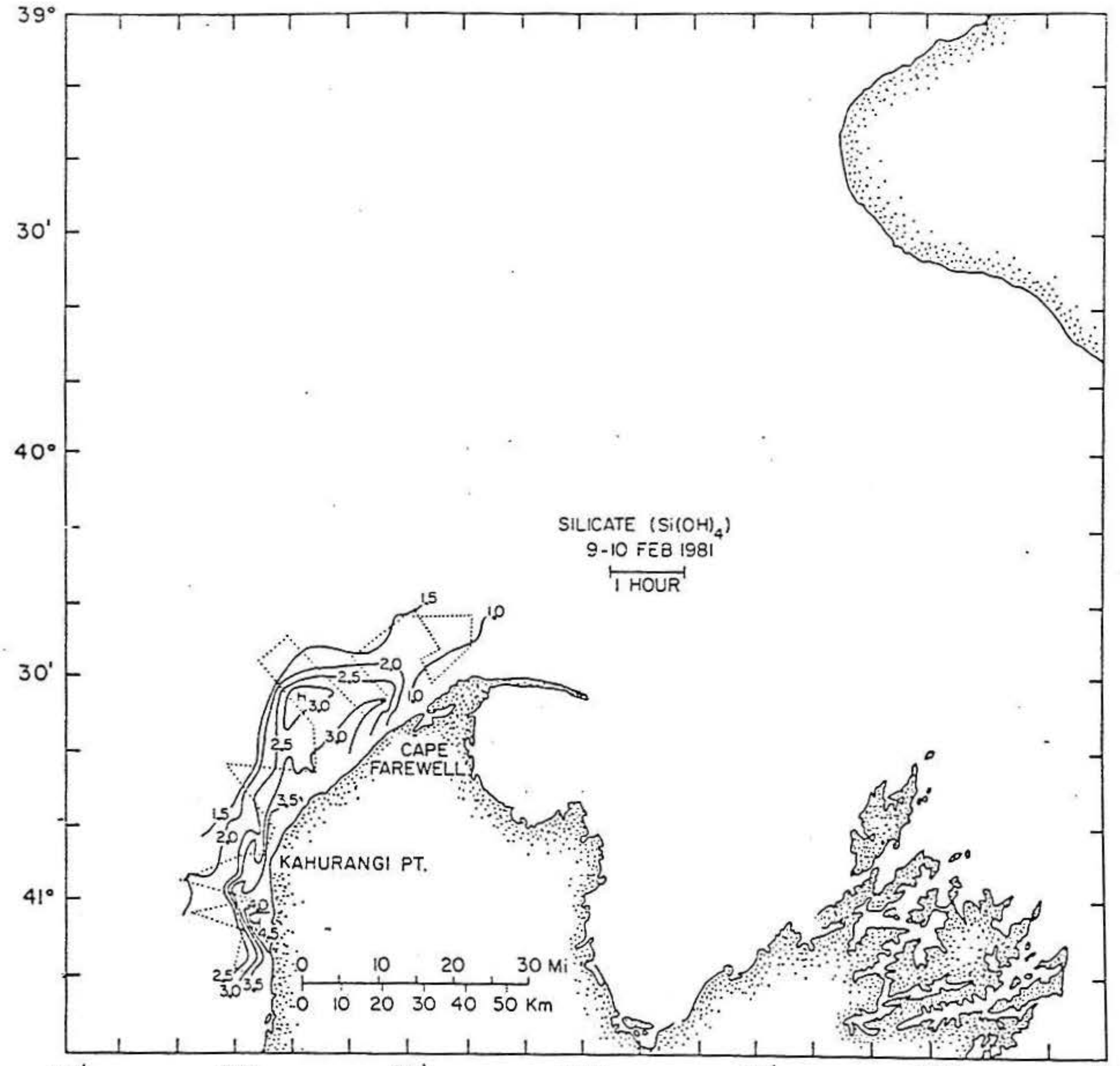

Fig. 52. Surface distribution of silicate (uM) off Cape Farewell on second survey of leg 2, February 9- 10, 1981.

nearshore water was indicated in the surface silicate distribution corresponding to the band of nitrate-nitrite depleted water. However, the band of reduced silicate values did not extend down the coast of Cape Farewell to the extent of the reduced nitrate-nitrite values suggesting water column regeneration of silicate in the nearshore area. The presence of Eddy Karolanna was indicated in the surface silicate distribution with a maximum silicate value of 3.1 uM within the eddy. The maximum silicate value in the source water just south of Kahurangi Point was approximately 4.7 uM.

The surface temperature distribution for the second survey (Fig. 53) corresponds well to the surface nutrient distributions in an inverse relationship. The presence of Eddy Karolanna is indicated in the surface temperature distribution with values of approximately 15 ^{o}C. A band of nearshore water with surface temperatures greater than 17 ^{o}C corresponded to the band of water with depleted nutrients. The nearshore area of source water south of Kahurangi Point is also indicated in Figure 53 with temperatures of less than 16 ^{o}C.

The surface chlorophyll 'a' distribution of the second survey is illustrated in Figure 54. The maximum

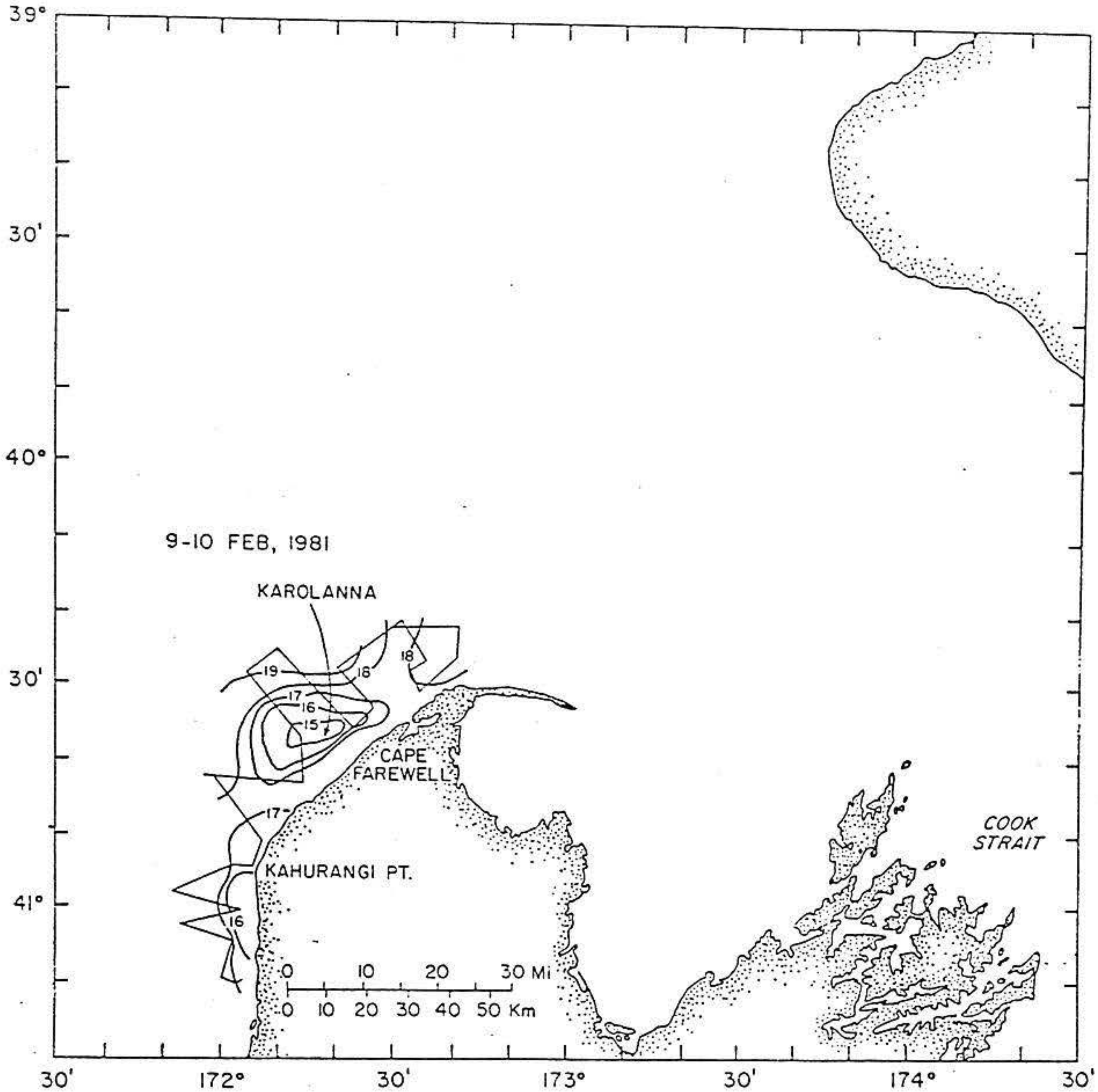

Fig. 53. Surface distribution of temperature (°C) off Cape Farewell on second survey of leg 2, February 9- 10, 1981, (Bowman <u>et</u> <u>al</u>., in press a).

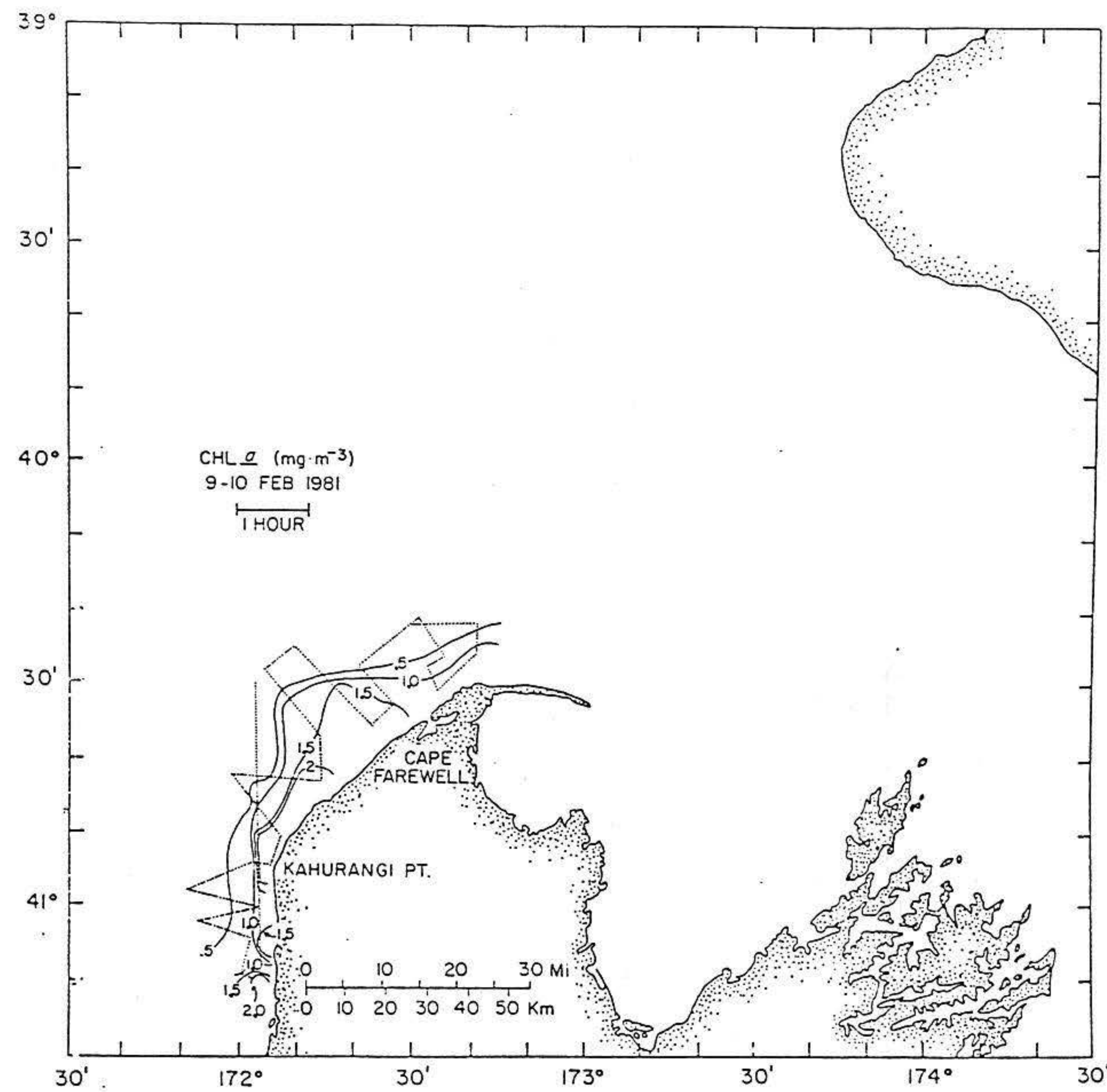

Fig. 54. Surface distribution of chlorophyll 'a' (mg m^{-3}) off Cape Farewell on second survey of leg 2, February 9- 10, 1981, (courtesy P. Lapennas).

chlorophyll 'a' concentrations of approximately 2.0 mg m^{-3} were located in the nearshore area around Kahurangi Point. The offshore oligotrophic waters possessed concentrations of less than 0.5 mg m^{-3}.

The third survey of the Cape Farewell region on February 11, 1981 took place during a period of light winds that blew persistently from a northerly direction. Eddy Karolanna and Eddy Leilani were relocated and mapped during this survey.

The surface nitrate-nitrite distribution for the third survey (Fig. 55) indicated the same general pattern for Eddy Karolanna as observed on the previous survey. The band of nearshore water, which was depleted in nutrients, is indicated in Figure 55 with a concentration of approximately 0.15 uM. However, the maximum nitrate-nitrite concentration within Eddy Karolanna had decreased from 4.0 uM on the previous survey to 3.2 uM for this survey. The area of elevated surface nitrate-nitrite values that represented Eddy Leilani, which had moved into the western approaches of Cook Strait, was no longer distinguishable from the background levels of nitrate-nitrite (0.15 uM) in the oligotrophic waters on the third survey.

The surface silicate distribution for the third

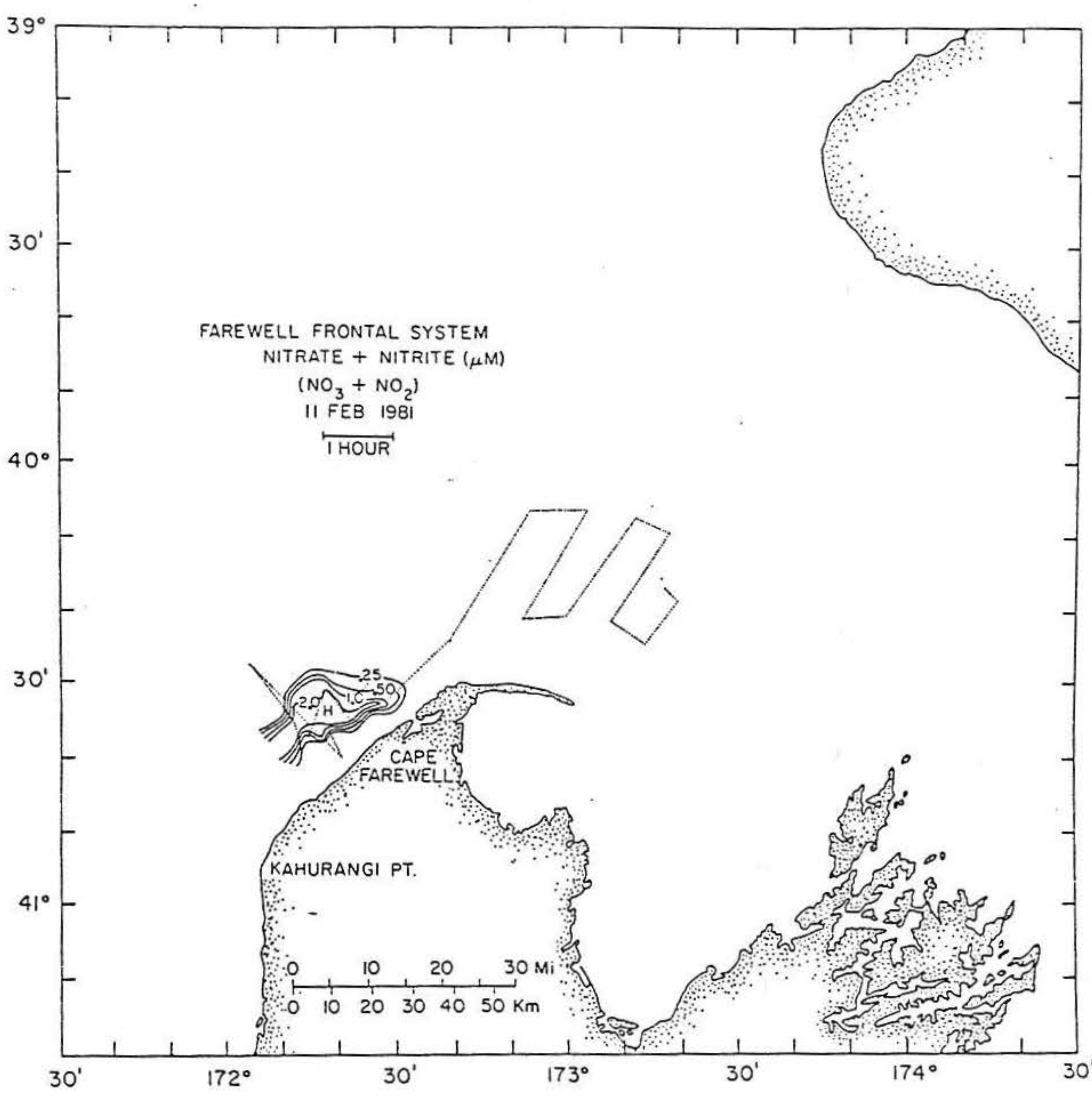

Fig. 55. Surface distribution of nitrate-nitrite (uM) off Cape Farewell on third survey of leg 2, February 11, 1981.

survey (Fig. 56) indicates the presence of Eddy Karolanna with a maximum surface silicate value of 2.8 uM. The region of elevated silicate values extended further northward than the region of elevated nitrate-nitrite values. Eddy Leilani, located in the western approaches of Cook Strait, was still evident in the surface silicate distribution with a maximum value of 2.9 uM, but with no corresponding elevated nitrate-nitrite values.

The surface temperature distribution for the third survey (Fig. 57) indicated the presence of Eddy Karolanna with a minimum temperature of approximately 16 °C within the eddy. The band of nutrient depleted water in the nearshore area adjacent to Eddy Karolanna had a surface temperature of approximately 18 °C, while the offshore oligotrophic waters had a surface temperature that ranged between 18 °C to 19 °C. Figure 57 also indicates the presence of Eddy Leilani in the western approaches of Cook Strait with a surface temperature minimum within the eddy of approximately 17 °C. This minimum had no corresponding elevated nitrate-nitrite value. Apparently utilization of nitrate-nitrite by phytoplankton had reduced the concentration to background levels.

The surface chlorophyll 'a' distribution for the

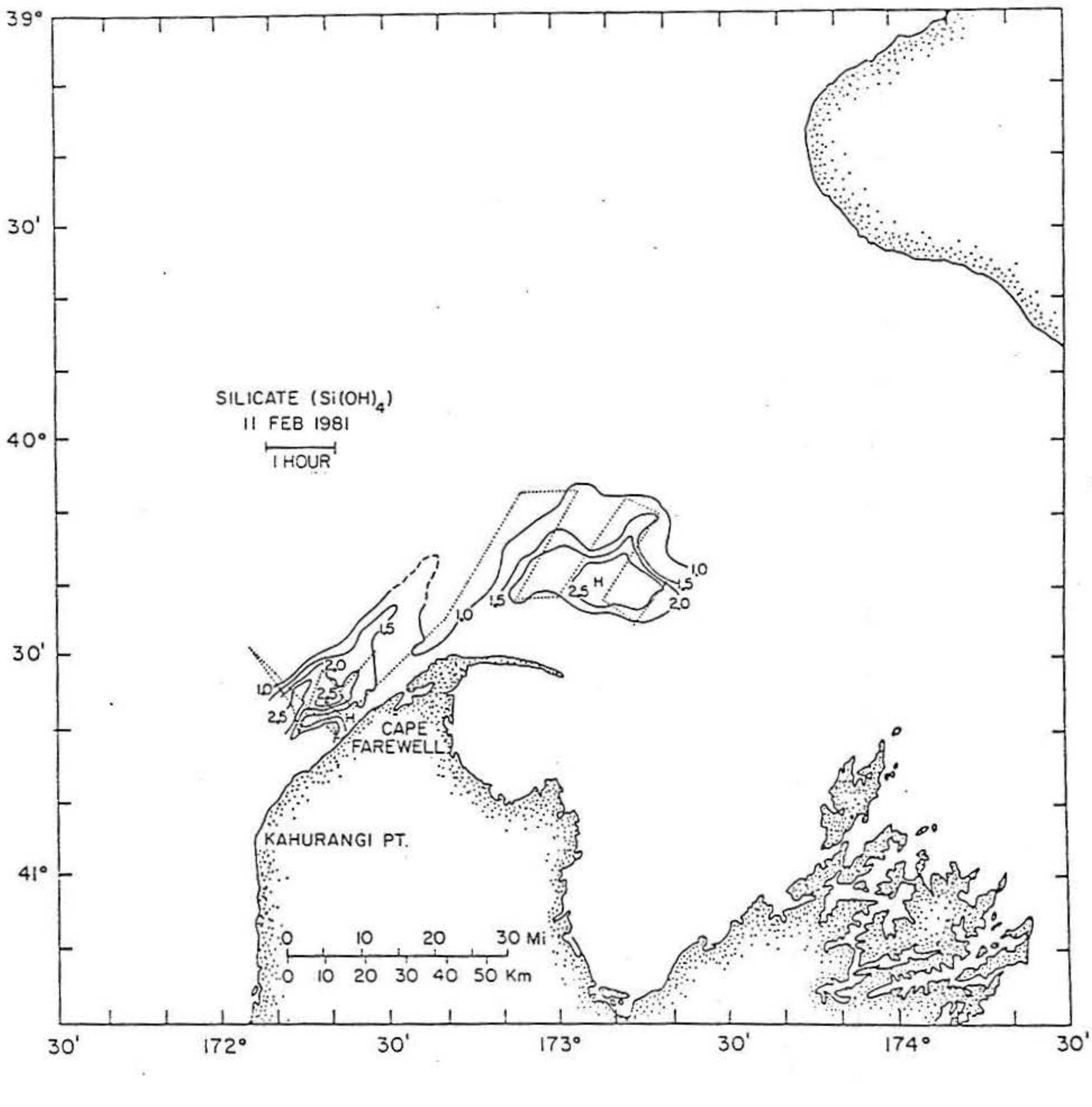

Fig. 56. Surface distribution of silicate (uM) off Cape Farewell on third survey of leg 2, February 11, 1981.

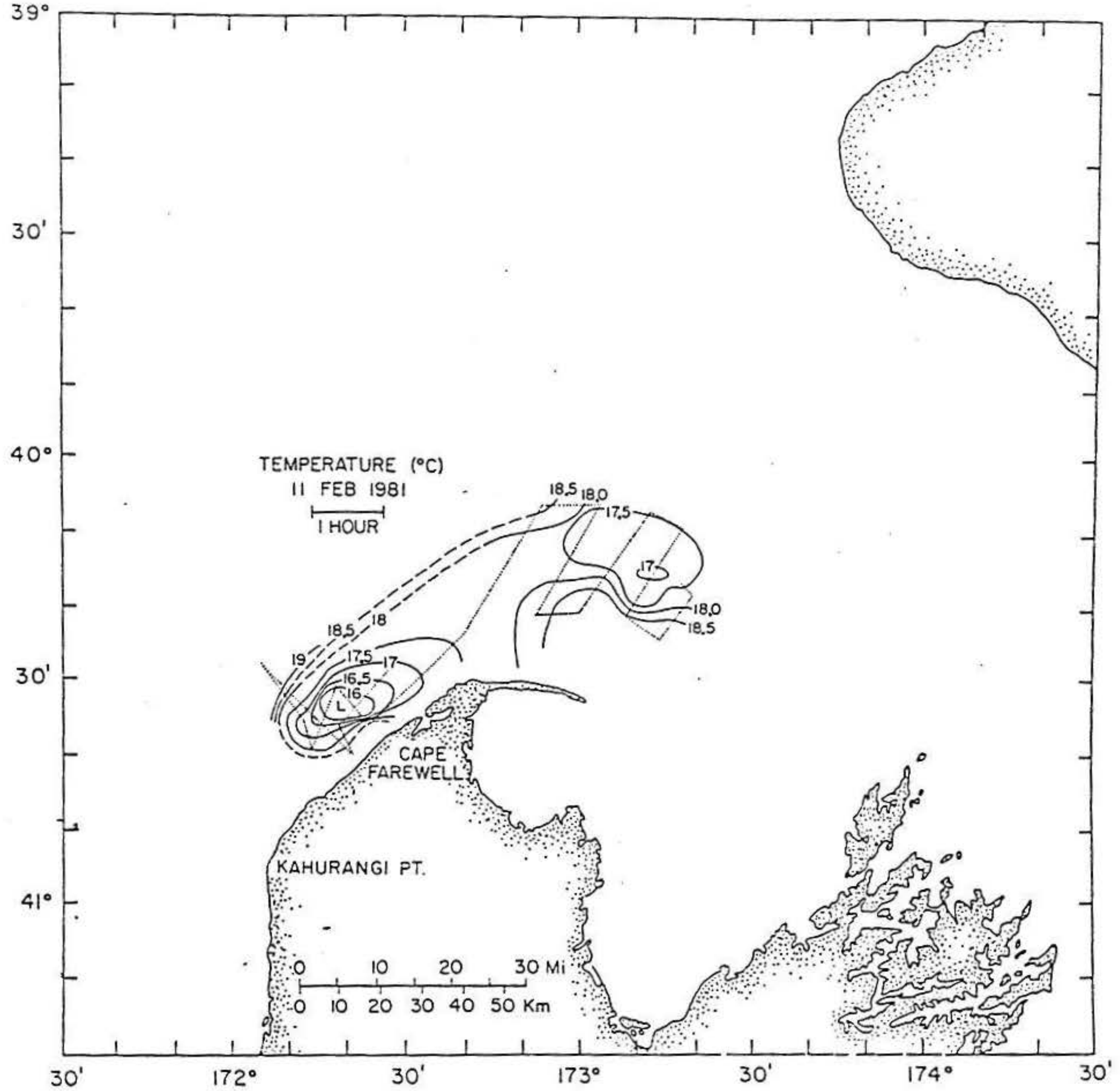

Fig. 57. Surface distribution of temperature (°C) off Cape Farewell on third survey of leg 2, February 11, 1981, (Bowman et al., in press a).

third survey is illustrated in Figure 58. The maximum chlorophyll 'a' concentration of approximately 2.0 mg m^{-3} appeared to be associated with the nearshore side of Eddy Karolanna. Figure 58 indicated an area of slightly elevated chlorophyll 'a' concentration of approximately 1.0 mg m^{-3} associated with Eddy Leilani. The oligotrophic waters offshore of the Cape Farewell region had a chlorophyll 'a' concentration of less than 0.5 mg m^{-3}.

Vertical sections of physical, chemical and biological properties (Figures 59a to f) through Eddy Karolanna were produced from Stations 93- 99 on February 10, 1981.

The vertical distribution of nitrate-nitrite (Fig. 59b) indicated a nearshore area depleted in nitrate-nitrite with a concentration of approximately 0.15 uM at Station 93. Eddy Karolanna is indicated in the vertical distribution as having been situated in the area of Stations 94, 95 and 96. This area had a maximum surface nitrate-nitrite concentration of approximately 2.6 uM at Stations 95 and 96. The offshore frontal zone for Eddy Karolanna appears to have been situated between Stations 96 and 97. The nitrate-nitrite values decreased to approximately 0.15 uM from

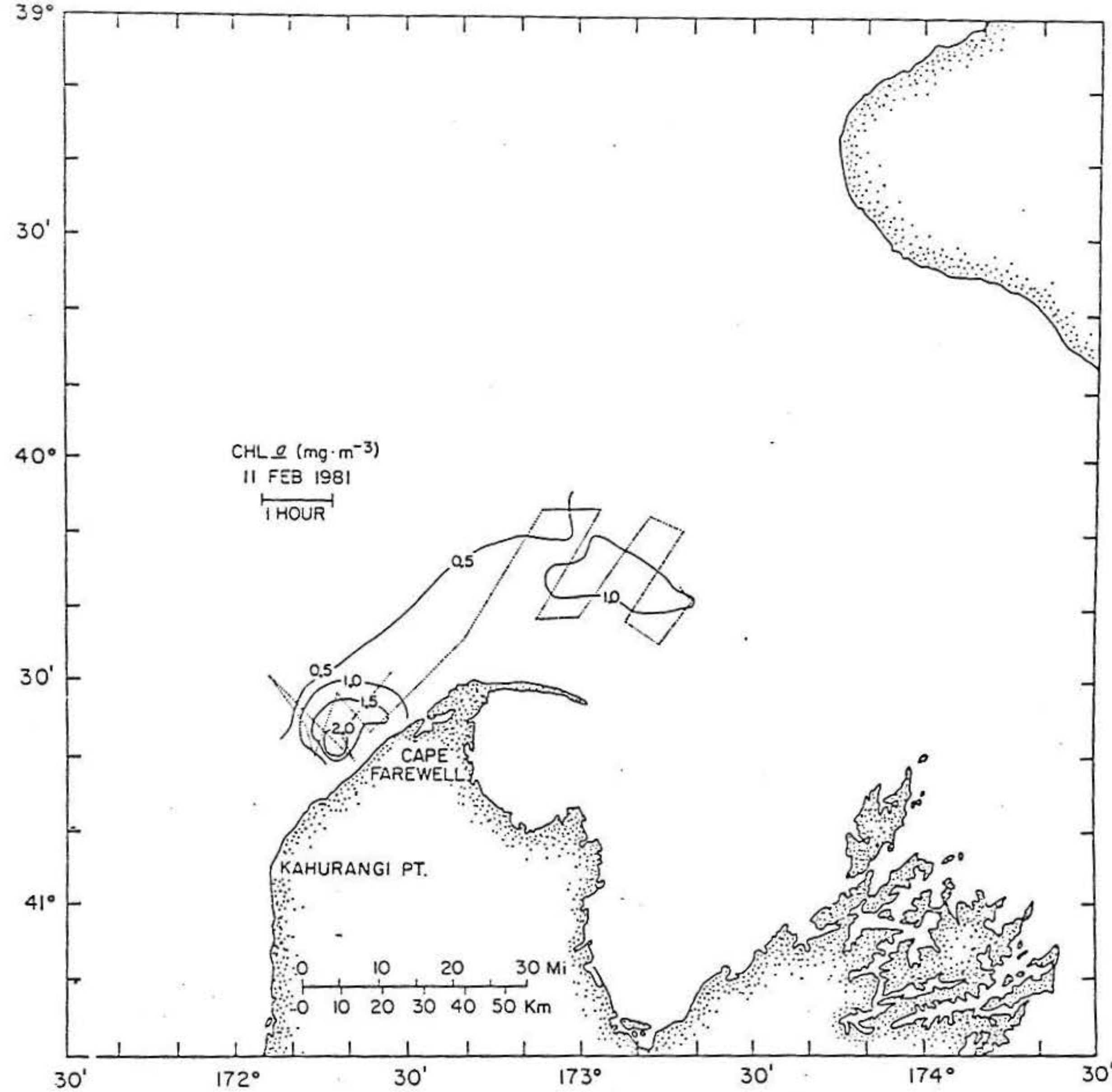

Fig. 58. Surface distribution of chlorophyll 'a' (mg m^{-3}) off Cape Farewell on third survey of leg 2, February 11, 1981, (courtesy P. Lapennas).

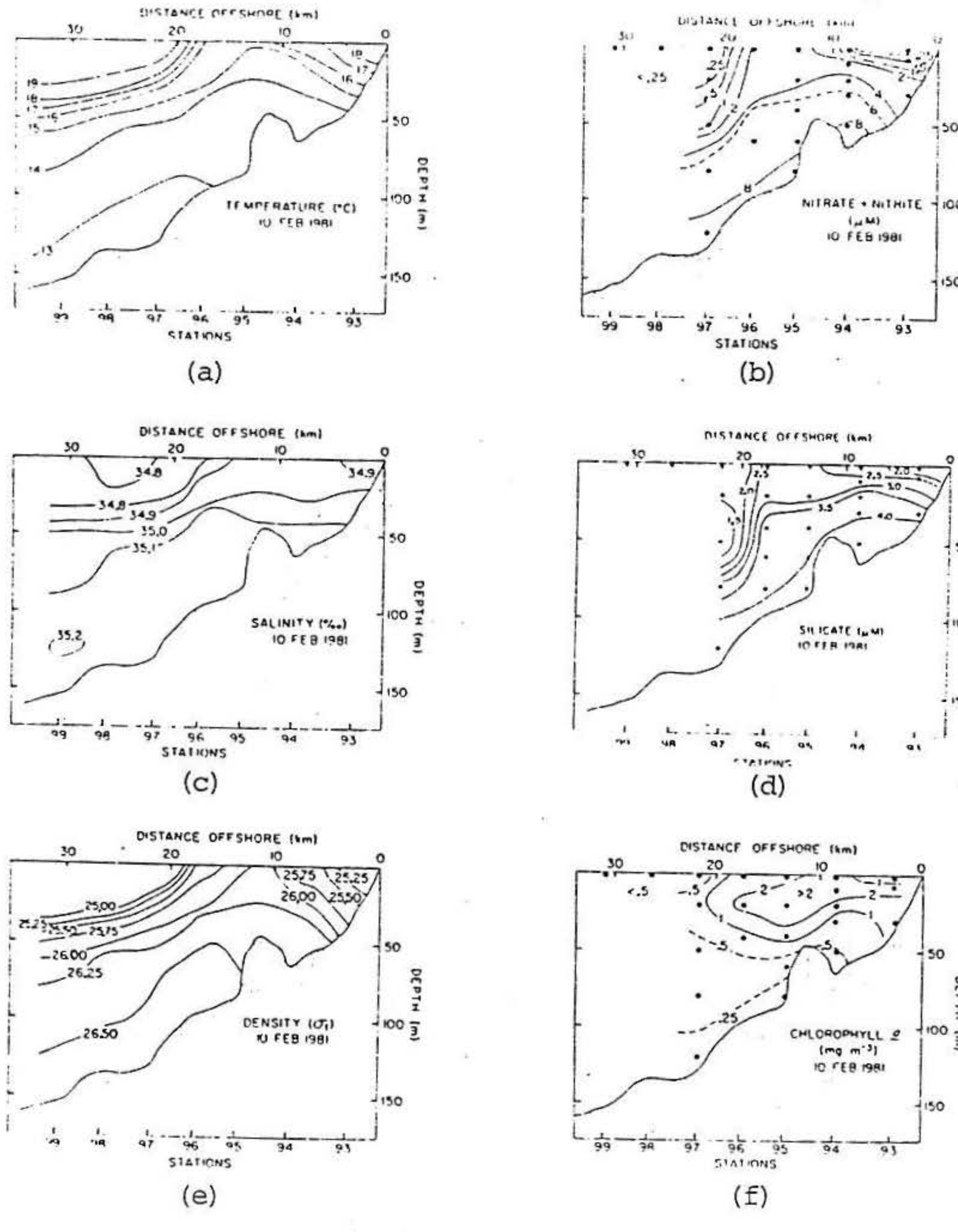

Fig. 59. Vertical distribution of physical, chemical, and biological properties through Eddy Karolanna off Cape Farewell, Feb. 10, 1981: a) temperature (^{O}C), b) nitrate-nitrite (uM), c) salinity ($^{O}/oo$), d) silicate (uM), e) density (σ_t), f) chlorophyll 'a' (mg m^{-3}).

Station 97 seaward. Most of the isopleths of nitrate-nitrite tended to bend upward toward Eddy Karolanna from both onshore and offshore.

The vertical distribution of silicate (Fig. 59d) indicated that the nearshore area was comparatively low in silicate off Cape Farewell with a concentration of approximately 1.6 uM at Station 93. The area of maximum surface silicate corresponded to the area of maximum nitrate-nitrite values with a silicate concentration of 2.7 uM at Station 96. The surface silicate concentration in the offshore oligotrophic water seaward of Station 97 was less than 1.0 uM. Isopleths of silicate tended to bend upward toward Eddy Karolanna corresponding to the nitrate-nitrite distribution. In addition a subsurface silicate minimum of approximately 1.0 uM on the seaward side of the frontal zone at a depth of 50m suggests silicate utilization by a subsurface diatom population.

The vertical temperature distribution (Fig. 59a) shows a clear inverse correlation with the nutrient distributions. The isopleths of temperature bent upwards toward Eddy Karolanna with a minimum temperature within the eddy of 15.4 ^{o}C. The presence of the warm, nutrient depleted, nearshore band of water with a temperature greater than 18 ^{o}C is indicated in Figure 59a.

The vertical distribution of chlorophyll 'a' (Fig. 59f) indicated that maximum chlorophyll 'a' concentrations of greater than 2.0 mg m^{-3} were located at the surface within the nearshore section of Eddy Karolanna in the vicinity of Station 94. This maximum extended as a subsurface maximum across Eddy Karolanna toward the seaward frontal zone of the eddy. The offshore oligotrophic water from Station 97 seaward had a surface chlorophyll 'a' concentration of approximately 0.3 mg m^{-3}.

The fourth survey of the Cape Farewell region took place from February 11- 12, 1981. The winds continued to be light and blew from a northerly to northwesterly direction. The fourth survey relocated and mapped Eddy Leilani in the western approaches of Cook Strait.

The surface nitrate-nitrite distribution indicated that nitrate-nitrite values (0.15 uM) for Eddy Leilani were now indistinuishable from background concentrations in surrounding oligotrophic waters. However, the other chemical, physical and biological properties still indicated the presence of Eddy Leilani in the survey area.

The surface silicate distribution for the fourth survey (Fig. 60) indicated a small area with a minimum silicate value of less than 1.0 uM. This minimum was surrounded by water with elevated silicate values of approximately 2.5 uM suggesting significant water column regeneration of silicate in the vicinity of Eddy Leilani. Oligotrophic waters to the north had a silicate concentration of less than 1.0 uM.

The surface temperature distribution (Fig. 61) indicated the presence of Eddy Leilani in the western approaches with temperatures of approximately 17 ^{o}C. These reduced water temperatures had no corresponding elevated nitrate-nitrite values suggesting that phytoplankton utilization had depleted the available nitrate-nitrite. Oligotrophic waters surrounding Eddy Leilani possessed temperatures greater than 18 ^{o}C.

The surface chlorophyll 'a' distribution (Fig. 62) indicated that maximum chlorophyll 'a' concentrations within Eddy Leilani were approximately 1.5 mg m^{-3}, while oligotrophic waters surrounding Eddy Leilani in Figure 62 had a chlorophyll 'a' concentration of less than 0.5 mg m^{-3}.

Vertical sections of physical, chemical and

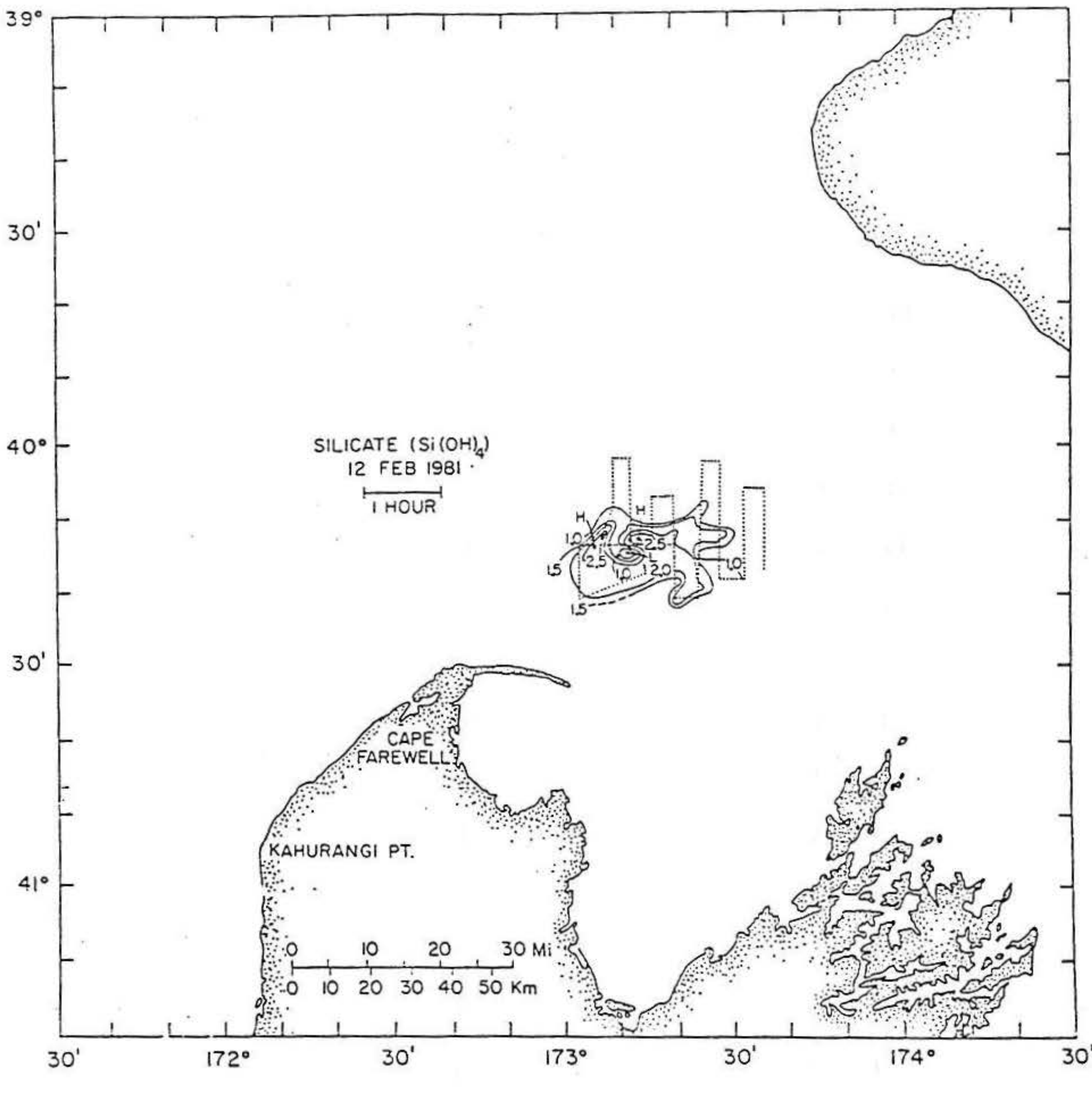

Fig. 60. Surface distribution of silicate (uM) off Cape Farewell on fourth survey of leg 2, February 12, 1981.

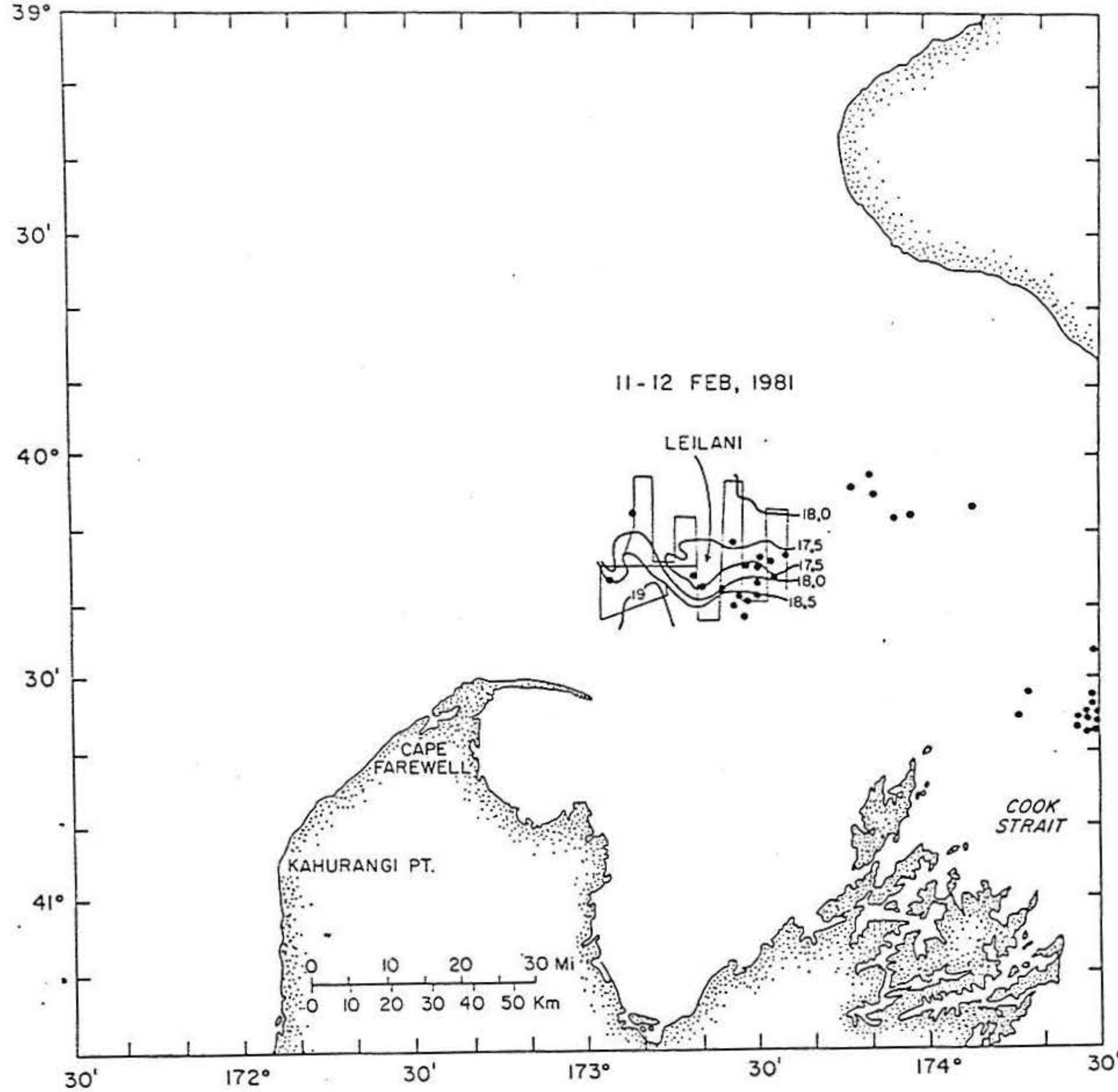

Fig. 61. Surface distribution of temperature (^{O}C) off Cape Farewell on fourth survey of leg 2, February 12, 1981, dots indicate the positions of squid fishing vessels in the western approaches of Cook Strait during the sampling period, (Bowman _et al_., in press a).

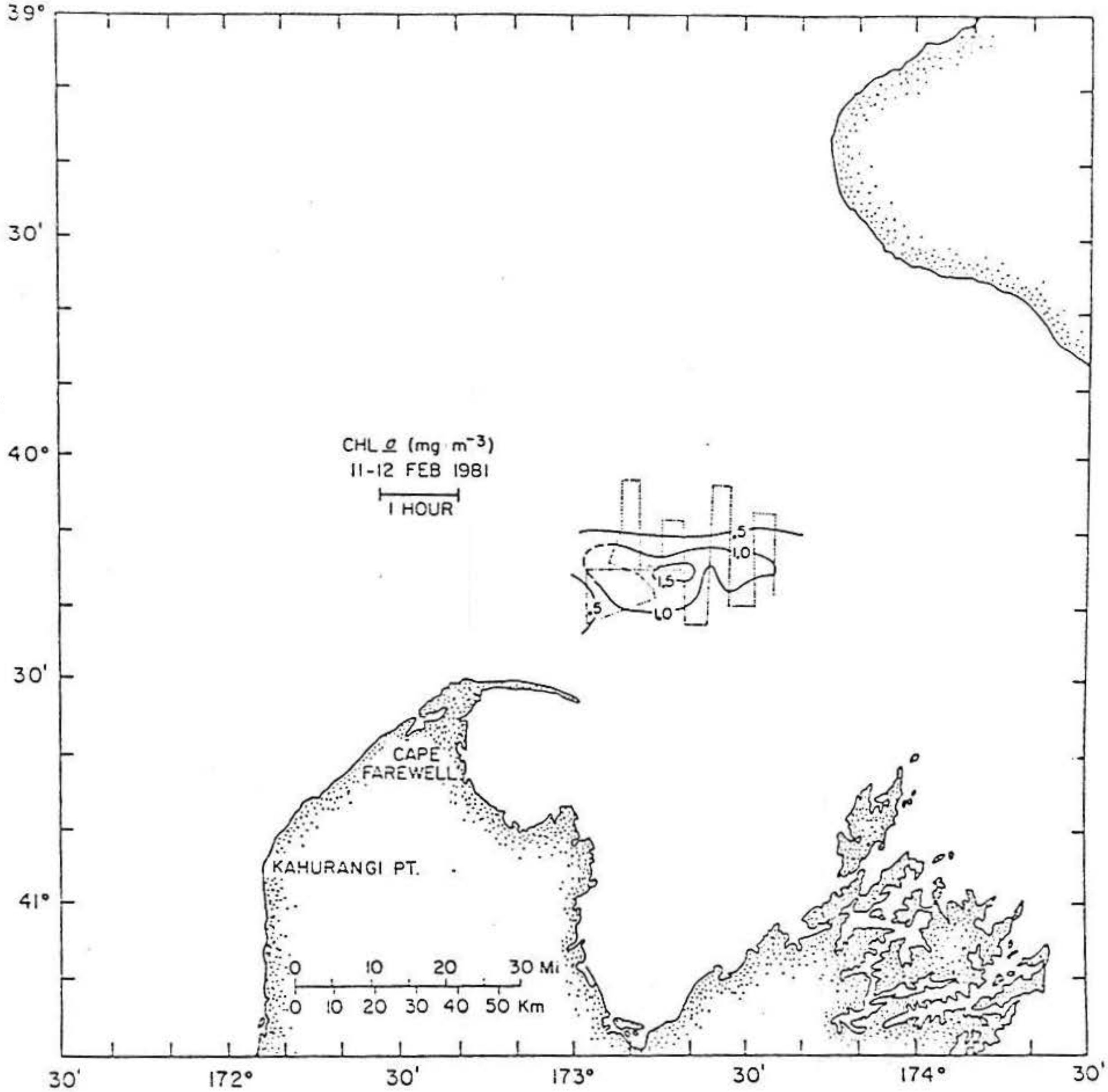

Fig. 62. Surface distribution of chlorophyll 'a' (mg m^{-3}) off Cape Farewell on fourth survey of leg 2, Feb. 11- 12, 1981, (courtesy P. Lapennas).

biological properties (Figures 63a to f) were produced from Stations 100- 107 sampled across Eddy Leilani, which was now in a senescent state, on February 12, 1981.

The vertical distribution of nitrate-nitrite (Fig. 63b) indicated that the upper layers of the water column were depleted in nitrate-nitrite with concentrations of approximately 0.15 uM. However, the presence of Eddy Leilani can still be perceived by an upward bending in the subsurface isopleths of nitrate-nitrite in the vicinity of Station 103.

The vertical distribution of silicate (Fig. 63d) indicated a subsurface structure in the lower portion of the water column similar to the nitrate-nitrite distribution. However, several subsurface areas with low silicate values of less than 1.0 uM were located in the upper portion of the water column suggesting utilization by subsurface diatom populations.

The vertical distributions of temperature (Fig. 63a) and sigma-t (Fig. 63e) both indicated an upward bending of the isopleths at Station 103. In addition, an area of reduced water temperature was indicated at the surface between Stations 103 and 104.

The temperature, density and nutrient data suggest that Eddy Leilani had become senescent, as

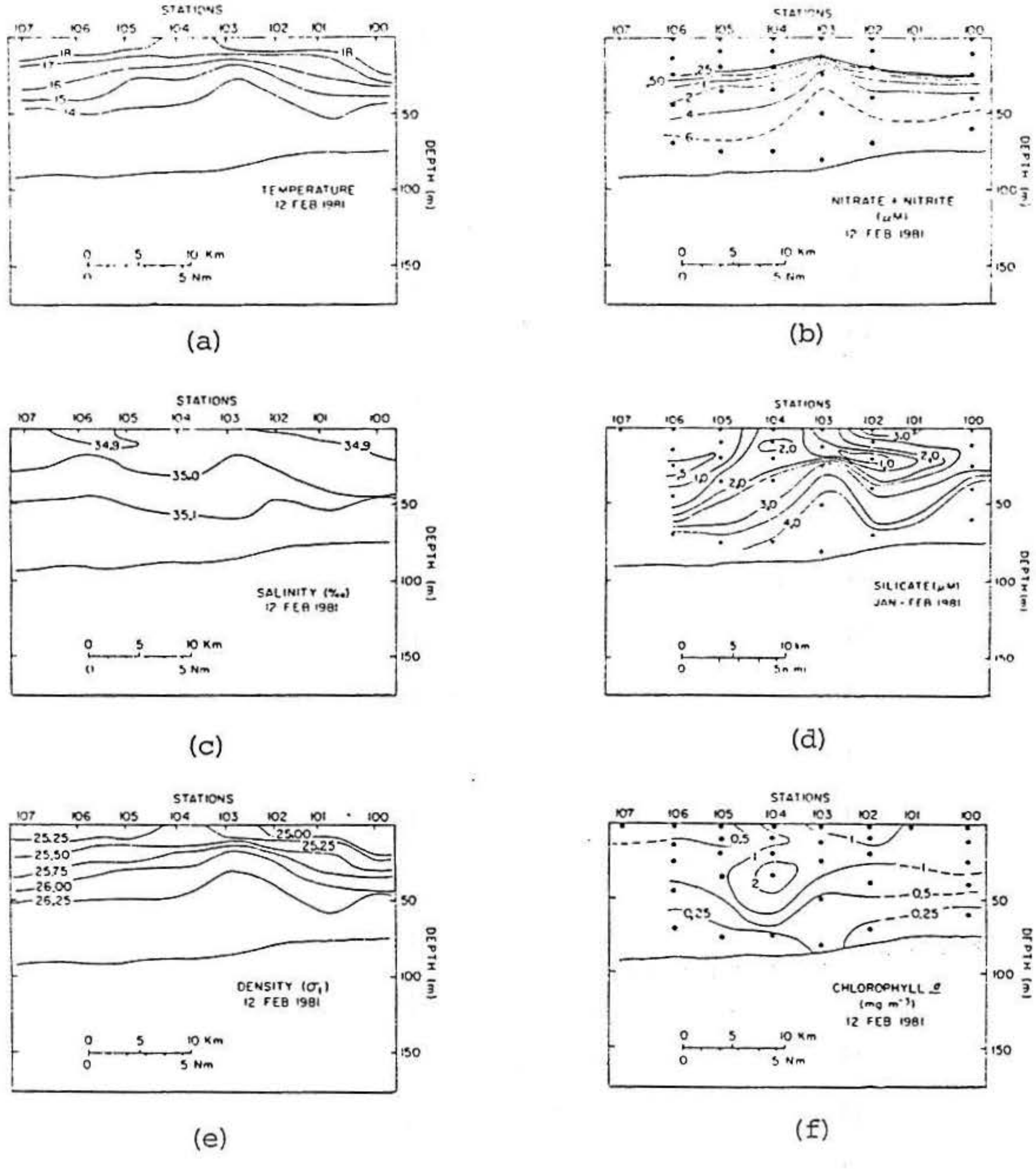

Fig. 63. Vertical distribution of physical, chemical and biological properties through Eddy Leilani, Feb. 12, 1981: a) temperature (^{o}C), b) nitrate-nitrite (uM), c) salinity (^{o}/oo), d) silicate (uM), e) density (σ_t), f) chlorophyll 'a' (mg m^{-3}).

indicated by slumping of the isopleths. The extremities of Eddy Leilani were fragmented due to lateral mixing.

The vertical distribution of chlorophyll 'a' (Fig. 63f) indicated that the maximum chlorophyll 'a' concentrations of approximately 2.8 mg m^{-3} were subsurface, located at a depth of 35 m, in the vicinity of Station 104. In addition, there was an area of elevated chlorophyll 'a' values at the surface between Stations 103 and 104. This suggests that there was a sinking phytoplankton population located in the vicinity of the thermocline.

VIII.4 Discussion

The nutrient rich, cold temperature region off Cape Farewell persisted throughout the leg 1 surveys despite the moderate northerly to westerly winds, which favored downwelling along the coast during the sampling period. This suggested that the upwelling was mainly the result of a current rounding a bend in the bathymetry.

The nutrient and temperature data from the leg 1, 1981 surveys, of the Cape Farewell region indicated that the cold, nutrient rich water was in close proximity to the coast during the sampling period. The data also indicated the two areas of intensive upwelling associated with the sharp convex coastal bends in the Cape Farewell region at Kahurangi Point and the base of Farewell Spit. In addition, the nutrient and temperature data indicated the presence of cyclonic eddies associated with unstable baroclinic meanders in the upwelling front, which appeared to become detached from the upwelling zone.

The areas of elevated silicate values downstream of the source region in the western approaches of Cook Strait, with no corresponding elevated nitrate-nitrite values, suggested that water column regeneration of silicate might be significant in the Cape Farewell region.

The vertical sections produced from hydrostation data sampled on the second survey of leg 1 (Figures 29a to f) indicated that there was an onshore movement of bottom water in this area of Cape Farewell. The vertical distributions of nitrate-nitrite and silicate (Fig. 29b and 29d respectively) can be used to indicate the presence of silicate regeneration in the waters overlying the shelf (Friederich and Codispoti, 1981). Nitrate-nitrite and silicate values, sampled by Friederich and Codispoti (1981), for deep water on the northwest African shelf were similar to the values for deep water on the west coast of New Zealand. A graph of silicate to nitrate-nitrite ratio versus distance offshore for water with a sigma-t value of 26.49, illustrated in Figure 64, is similar to the change in the ratio observed by Friederich and Codispoti (1981) on the northwest African shelf. The data indicated that silicate was regenerated at a faster rate than both nitrate-nitrite and ammonium, with a silicate input of approximately 0.47 uM day $^{-1}$ of which 0.44 uM day^{-1} was contributed by a flux from the bottom (Friederich and Codispoti, 1981). The similarity of the New

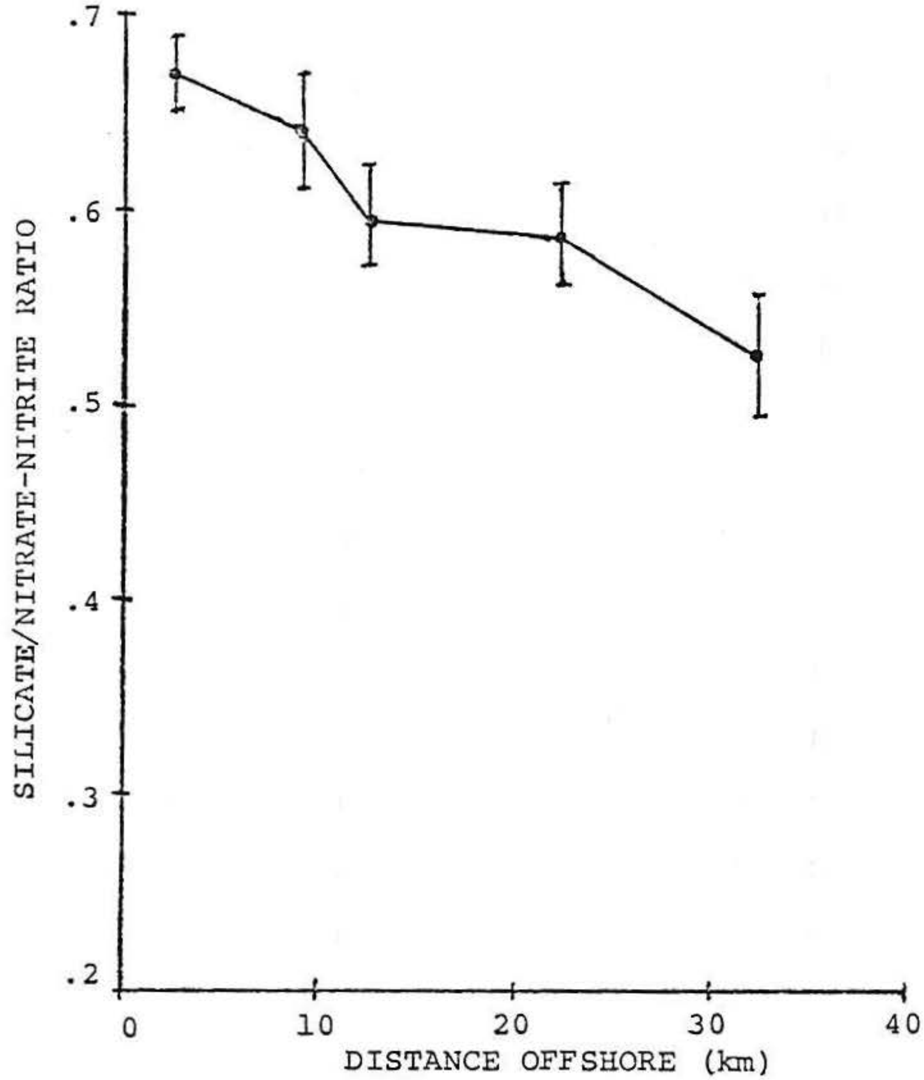

Fig. 64. Graph of silicate to nitrate-nitrite ratio versus distance offshore for water with a sigma-t value of 26.49.

Zealand data to the data on the northwest African shelf suggests that silicate flux from the fine to medium grain sands, which comprise the bottom sediments off Cape Farewell, is a significant source of silicate to the bottom and nearshore waters off Cape Farewell.

The nutrient and temperature data indicate that the extent of the upwelling region of cold, nutrient rich water off Cape Farewell had increased considerably between the leg 1 surveys and the first survey of leg 2. The plume of elevated nutrient values and reduced water temperatures on the first survey of leg 2 had extended well across the western Taranaki Bight towards Cape Egmont. This leg 2 plume was detached from the coast of Cape Farewell north of Kahurangi Point with an apparent return flow of warm, nutrient depleted, oligotrophic water in the nearshore area. In addition, the area of intensified upwelling associated with the sharp convex coastal bend at the base of Farewell Spit, that was evident on the leg 1 surveys, was not observed on the leg 2 surveys. However, upwelling at Kahurangi Point appeared to have increased in intensity with maximum surface nitrate-nitrite values increasing from 7.0 uM on leg 1 to 8.0 uM on leg 2.

The data suggests that the period of upwelling favorable southerly winds just prior to the first survey of leg 2 increased the magnitude of the transport of the Westland Current and extended it to the north, while minimizing the indraught into Cook Strait known as the D'Urville Current. The subsequent surveys on leg 2 indicated a contraction of the upwelling region with a displacement to the south of the area of nitrate-nitrite maxima at Kahurangi Point and a decrease in the maximum surface value from 8.0 uM to 5.3 uM. The reduction in intensity and contraction of the upwelling region is probably a result of the persistent light northerly winds that occurred during the sampling period. A projected course of events as a result of prolonged northerly winds would be increased transport into Cook Strait and the reestablishment of the area of intensified upwelling at the base of Farewell Spit.

The nutrient and temperature data also indicated the presence of cyclonic eddies that were both detached from and imbedded within the upwelling region. This data indicated that the eddies were associated with unstable baroclinic meanders in the frontal boundary and were approximately 20 km in extent with a strong cyclonic rotation.

The dynamics of the eddies in the Cape Farewell region have been studied by Bowman *et al.*, (in press). A strong jet current is sustained at the front with a speed of approximately 90 cm sec^{-1}. The Rossby radius of deformation, which gives an estimate of the width of this jet and therefore a scale for the eddies, was approximately 9 km. A first order approximation of the onshore bottom flow near Cape Farewell was U = 23 cm sec^{-1} and the upwelling velocity w = 10 m day^{-1}.

Cyclogensis is produced in the Cape Farewell region by three mechanisms that each generate negative relative vorticity:

i) the change in relative vorticity due to the conservation of potential vorticity when water flows over a changing depth.

ii) relative vorticity generated from a lateral shear in the flow as a result of the quadratic representation of bottom friction.

iii) relative vorticity generated due to a depth-distributed friction force when the depth varies normal to the local velocity field.

Maximum contributions ~~to~~ the generation of relative vorticity will take place at the sharp convex bends at Kahurangi Point and the base of Farewell Spit and in areas with sharp changes in depth such as Kahurangi

Shoals. Eddies generated near Kahurangi Point will be supplied with relative vorticity as the eddies move northward toward the western approaches of Cook Strait, simultaneously the eddies will tend to lose vorticity by dissipation due to processes such as friction. The frictional processes that tend to dissipate the eddy will predominate when the eddy moves into the broad flat expanse of the western Taranaki Bight. The physical, chemical, and biological data indicated that an eddy generated at Kahurangi Point and that moved into the western Taranaki Bight had a detectable lifetime of approximately 1 to 2 weeks.

In addition to the low frequency, large scale variations in the transport of the Westland Current that affect the extent of the upwelling region off Cape Farewell, there also appeared to be high frequency small scale variations in the intensity of upwelling, that are associated with the meanders in the upwelling front and the related eddies. The temperature and nutrient data indicated that the meanders had a wavelength of approximately 28 km, a phase velocity of approximately 40 cm sec^{-1}, and a period of approximately 19 hours (Bowman _et al._, in press). The extent of the effects of tidal variations on the intensity of the upwelling off Cape Farewell cannot be determined at the present time.

Nutrient uptake processes in the Cape Farewell region obviously have an important role in determining nutrient distributions in the euphotic zone. Uptake of a limiting nutrient can be described by Michaelis-Menton enzyme kinetics as expressed by the Monrod equation:

$$\nu = \nu_{max}\ C/k_s + C \qquad \text{(Parsons } \underline{et}\ \underline{al}.\text{, 1977)}$$

where ν = uptake rate of the limiting nutrient

ν_{max} = maximum uptake rate of the limiting nutrient

C = concentration of the limiting nutrient

k_s = concentration of the limiting nutrient at which the uptake rate equals 1/2 the maximum rate.

The equation is modified for silicate uptake to include a threshold concentration C_o. The equation becomes:

$$\nu = \nu_{max}\ (C-C_o)/k_s + (C-C_o) \qquad \text{(Parsons } \underline{et}\ \underline{al}.\text{, 1977)}$$

when the concentration of silicate equals C_o the uptake rate is equal to 0 and the phytoplankton population can no longer utilize silicate (Parsons et al., 1977).

A graph of nitrate-nitrite concentration versus temperature for the February 8-9 survey of the Cape

Farewell region was prepared by Dr. P. Lapennas and is illustrated in Figure 65. The uptake of surface nitrate-nitrite leads to an exponential decrease in nitrate-nitrite concentration in relation to temperature. The graph suggests that the loss of nitrate-nitrite by uptake was about four times the loss by physical processes. This graph represents a conservative estimate of nitrate-nitrite losses from phytoplankton uptake because of temperature increases from surface heating, which was neglected in the analysis.

The variability of the silicate distribution in relation to uptake and regenerative processes appeared to be more complicated than nitrate-nitrite in the Cape Farewell region. Diatoms require silicate to construct their frustules and as a result diatom growth could be limited by silicate depletion (Davis *et al.*, 1978). Many flagellated forms do not require silicate and are not affected by silicate depletion. Nelson *et al.*, (1981) claims that studies of silicate uptake by natural marine phytoplankton populations indicate that silicate behaves differently from other primary nutrients in coastal upwelling regions and that each region studied is unique in relation to silicate dynamics. Silicate limitation in regions where silicate values are low may

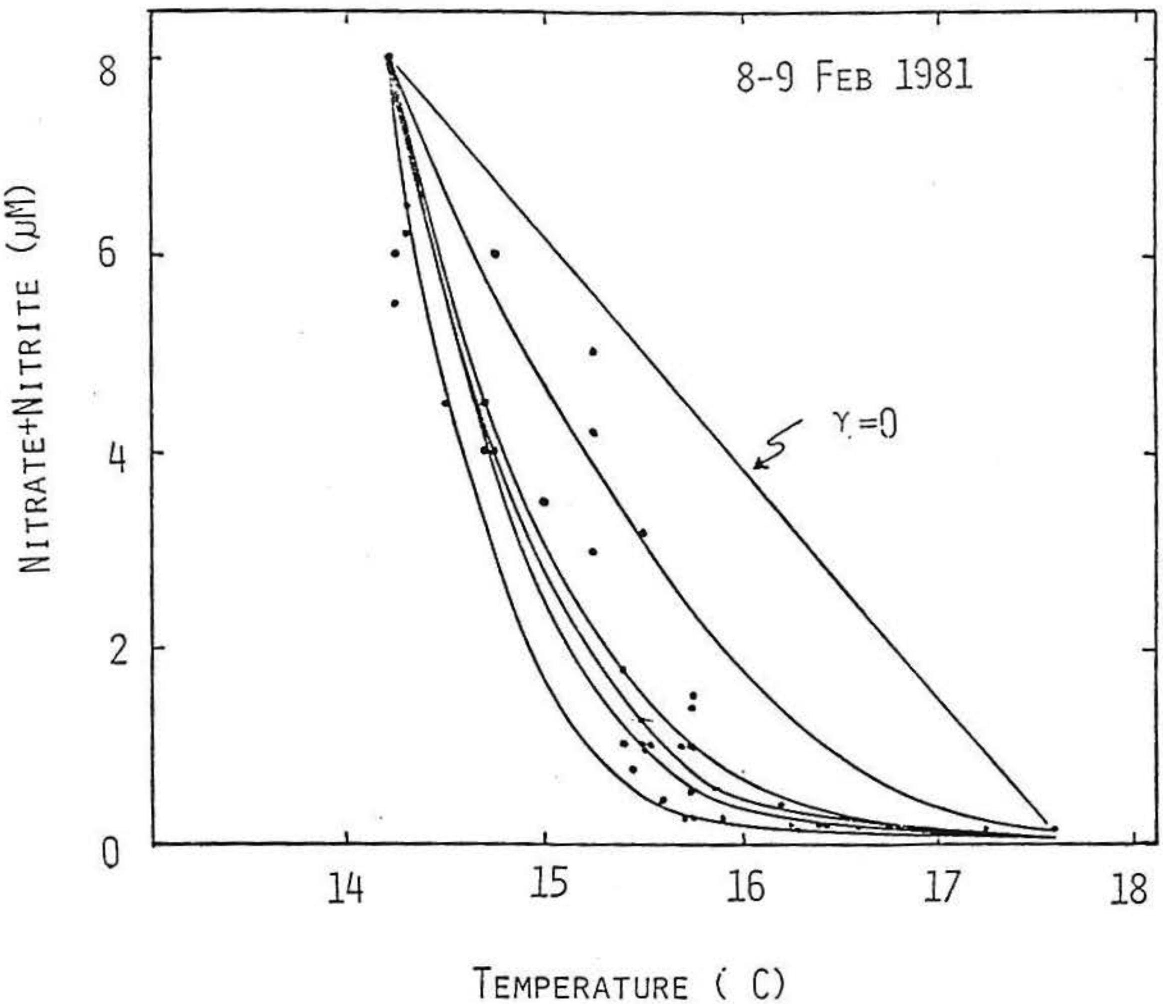

Fig. 65. Graph of surface nitrate-nitrite concentration versus temperature for the February 8- 9, 1981 survey of the Cape Farewell region, (courtesy P. Lapennas).

play an important role in controlling the production cycle and phytoplankton species succession in an upwelling region.

Silicate uptake studies of a natural marine phytoplankton population using a Si stable isotope technique by Goering (1974) indicated that the population in a culture became silicate limited at approximately 8 uM and that the k_s value was 2.93 uM. In addition, Davis et al., (1978) stated that the threshold silicate level (C_o) at which silicate is no longer available to the cell was approximately 0.2 uM for the diatom Skeletonema costatum and may be as high as 1.5 uM for some other diatom species. However, silicate isotope tracer studies of the northwest Africa upwelling region (Nelson and Goering, 1975; Nelson et al., 1981), which had a range in nitrate-nitrite and silicate values similar to the Cape Farewell region, indicated that there was significant silicate regeneration in relation to uptake in the upper portion of the water column. Nelson et al., (1981) stated that limitation of silicate uptake did not occur in the upwelling region off northwest Africa when the surface silicate concentration was greater than 2.5 uM.

Silicate values off Cape Farewell were generally low with concentrations of approximately 4.0 uM to 5.0 uM in recently upwelled waters and 1.0 uM or less in the oligotrophic waters. Therefore, these relatively low values of silicate in the upwelling regions and the additional areas of subsurface silicate depletion, with values of 0.3 to 0.6 uM, indicate that silicate may be an important nutrient in controlling phytoplankton succession and composition in the Cape Farewell region.

Primary production and species composition is controlled in the natural marine environment by a combination of several limiting factors, which include the physical mixing regime and interactions between the various limiting nutrients (Walsh, 1976). The effects of the interactions of two limiting nutrients on species composition and primary production were studied with a series of culture experiments carried out by Holm and Armstrong (1981) in which the concentration of phosphate and silicate were varied and observations were made on the relative dominance of diatom and a blue green algae.

Preliminary analysis of phytoplankton samples taken on leg 2 of the 1981 cruise on the Cape Farewell region by Dr. P. Lapennas have indicated that there were an increased number of diatoms within the upwelling region and the associated eddies. The diatoms appeared to be sinking and spreading as the water flowed northward toward the western approaches of Cook Strait. The sinking and spreading diatom populations appeared to be replaced by an increased number of flagellated forms, such as dinoflagellates, in the upper layers of the water column. In addition, the nearshore area with a return inshore southward flow on the leg 2 surveys appeared to have a phytoplankton population comprised predominantly of flagellated forms (P. Lapennas, pers. comm.).

The phytoplankton distributions and species composition were relatively consistent with the nutrient distributions and the physical mixing regime. Eddies that have been recently formed within the upwelling region have large nutrient inputs with high nitrate-nitrite values of 6 uM to 8uM and silicate values of 4 uM to 5 uM with strong vertical mixing that favors an increase in diatom populations. As the eddies move toward the western approaches of Cook Strait the nutrient values within the eddies decrease and the water column stability increases resulting in a sinking diatom population and an increased number of flagellated forms in the upper portion of the water column. Senescent eddies with high water column stability were depleted in nitrate-nitrite in the upper portion of the water column and had predominantly flagellated forms of phytoplankton in the surface layers. The subsurface layers above the thermocline in the senescent eddies were silicate depleted corresponding to the sinking diatom population.

Vertical distributions of sea water properties through a senescent eddy were represented by the vertical sections through Eddy Leilani on February 12 illustrated in Figures 63 a to f. The changes in species composition associated with the eddies off Cape Farewell appears to indicate a phytoplankton succession similar to a seasonal succession taking place within the lifetime of the eddies.

In the nearshore area off Cape Farewell, although the silicate concentration was apparently sufficient for diatom growth, the low values of nitrate-nitrite and the reduced mixing regime favored the flagellated forms of phytoplankton.

Chlorophyll 'a' concentrations for the Cape Farewell region showed a comparatively small increase in concentration of 1 mg m^{-3} to 2 mg m^{-3} relative to the amount of nutrients supplied to the region. This suggests that phytoplankton losses due to grazing and sinking were high in the Cape Farewell region. Walsh (1976) related the levels of phytoplankton production attained and zooplankton grazing stress to the habitat variability. An upwelling region with high frequency variability may lead to a higher phytoplankton standing crop due to separation of herbivore grazing stress, while a region of low variability will have low phytoplankton standing crops due to high grazing stresses. The region of upwelling off Cape Farewell appeared to be persistent with small periods of relaxation in upwelling. Therefore, the low variability of the Cape Farewell region implies that phytoplankton losses due to grazing stress may be high in the region. Preliminary analysis of zooplankton samples taken on the leg 2 surveys of Cape Farewell region by Dr. B. Foster indicated that the largest numbers of microzooplankton herbivores were associated with the cold temperature eddies, which also suggests high grazing stress.

A Japanese squid fishing fleet exploits populations of arrow squid (Notodarus solani) in the western approaches of Cook Strait. The fishing fleet appears to use daily hydrographic and weather data to search out concentrations of squid, which are especially abundant near the frontal boundaries of senescent eddies (Bowman *et al.*, in press). The positions of Japanese squid fishing vessels on February 12 are shown as dots in Figure 61 indicating their proximity to Eddy Leilani. The upwelling region off Cape Farewell and the associated eddies results in a shortening of the length of the food chain in the region and increases the amount of production available to the higher trophic levels. Therefore, the persistence of the upwelling region off Cape Farewell may result in a substantial contribution to the productivity of the western New Zealand coastal shelf.

Chapter XI

Summary

Nutrient distributions were studied in relation to mixing, upwelling and phytoplankton uptake in Cook Strait, New Zealand on two cruises in the austral summers of 1980 and 1981.

XI.1 Tidal Mixing

Three regions of tidal mixing are predicted by the stratification index, with critical values of 1.5 $m^{-2}sec^3$ derived from the non-linear M_2 tidal model of Bowman *et al*. (1980). The first region of critical values was located off Patea in the northwestern Taranaki Bight. The second region was located off the northern section of D'Urville Island. The third region surrounds the eastern portion of the Marlborough Sounds and extends across the narrows of Cook Strait to Cape Terawhiti. High values of the stratification index, which indicated strong stratification, are predicted in the sheltered embayments of Tasman and Golden Bays and in the northeastern and central areas of the Taranaki Bight.

Nutrient distributions were sampled during a period of neap tides and no apparent advective flow in Cook Strait on leg 1 of the 1980 cruise.

Surface nitrate-nitrite distributions showed excellent agreement with the predicted areas of mixing from the M_2 tidal model on the southern side of Cook Strait in the regions of the eastern Marlborough Sounds, the Narrows of Cook Strait and off D'Urville Island. Maximum surface concentrations of nitrate-nitrite were 2.7 uM off D'Urville Island and 3.9 uM off the south-eastern section of the Marlborough Sounds and Cook Strait Narrows. These concentrations are consistent with the fact that these are tidally mixed regions where properties are expected to be an average of the surface and bottom values in the stratified areas.

The nitrate-nitrite distribution indicated no elevated nitrate-nitrite values and corresponding low temperatures in the temperature distribution for the region predicted as tidally mixed off Patea. The vertical distribution of temperature and sigma-t from stations off Patea indicated a well mixed water column. However, the shallow water shelf off Patea intercepts the thermocline and there is no source of cold nutrient rich bottom water available on this shelf.

A region of marginal stability, due to the sheltering effect of D'Urville Island and the eastern Marlborough Sounds, appears to be located in the vicinity of Pelorus Sound indicated by the stratification index. This region corresponds with an area of relatively low nitrate-nitrite values and high chlorophyll 'a' values. This data indicated that the marginal water column stability provided in this area permitted net phytoplankton production and accumulation, while sufficient nutrients are supplied by adjacent tidally mixed regions.

Nutrient distributions were sampled on leg 2 of the 1980 cruise during a period of neap tides and advective flow from west to east in Cook Strait as a result of northerly winds.

Surface nitrate-nitrite distributions for leg 2 indicated the presence of the tidal mixing regions off D'Urville Island and the eastern Marlborough Sounds. However, the distributions indicated that the tidally mixed regions were much more extensive than the leg 1 survey, despite the fact that both surveys occurred during the same state of neap tides. The greater extent of the mixed region indicated that the advective flow and possible wind induced upwelling had a large influence on the extent of the region of elevated nitrate-nitrite values. The maximum nitrate-nitrite values in the mixed regions were 2-4 uM suggesting that the predominant mechanism supplying nutrients to the surface layers was tidal mixing modified by an advective flow, as opposed to wind induced upwelling with expected concentrations of 6-8 uM.

The surface chlorophyll 'a' distributions for leg 2 indicated that the maximum concentrations were located off Pelorus Sound. This corresponds to an area where the frontal boundary in the nitrate-nitrite distribution is diffused and the concentrations are relatively low.

Vertical sections of physical, chemical, and biological properties for the Pelorus Sound transect on leg 2 showed the classical structure of a tidally mixed system as described by Pingree _et al_. (1976) with the isopleths bending both upwards to the surface and downwards toward the bottom in the direction of the tidally mixed region. The vertical section of chlorophyll 'a' indicated that the chlorophyll 'a' maximum was located on the offshore side of the tidal mixing front. The existence of the phytoplankton maximum at the front must be considered in terms of achieving a balance between loses from dispersal plus grazing and enhanced growth from increased nutrients plus aggregation due to a convergence (Pingree _et al_., 1976).

The vertical section of sigma-t indicated that the tidal mixing front was a baroclinic zone, considered to be in approximately geostrophic balance (Simpson, 1976). A baroclinic jet derived from the geostrophic balance will flow parallel to the tidal mixing front, which in Cook Strait is directed toward the Narrows. However, frictional damping will produce an unbalanced pressure field and will set up a circulation perpendicular to the front. The result is an upwelling and divergence on the well mixed side in the area of the front and a downwelling and convergence on the stratified side in the area of the front (Simpson, 1976). The front in the Pelorus Sound region appears to be relatively diffused and the geostrophic velocity shear across the front is weak.

The surface distribution of nitrate-nitrite and silicate for leg 1 of the 1981 cruise indicated an advective flow from west to east in the Strait with the same general pattern and extent to the tidally mixed regions as leg 2 of the 1980 cruise.

The highest surface chlorophyll 'a' concentrations on leg 1 for the tidal mixing regions were located in the vicinity of Pelorus Sounds, similar to the other surveys.

The weak gradient in the stratification index off the Marlborough Sounds and the broad flat bathymetry indicate the potential for large fluctuations in the extent of the tidally mixed region with changes in the tidal shearing and advective flows. The diffused frontal boundary and the large onshore-offshore fluctuations in the frontal zone in the vicinity of Pelorus Sound indicates this as a region of intermittent stability. Simpson et al. (1978) state that areas of intermittent stability with large movements in the frontal zone could be important to biological processes. The periodic release of nutrients from mixing and subsequent stability is important in phytoplankton growth (Pingree et al., 1977).

Future investigations into the varability of the tidal mixing regions due to spring and neap tidal changes, when there are no advective influences, would be helpful in understanding the contribution of these regions to the productivity of Cook Strait.

XI.2 Upwelling

The highly variable nature of the winds and topography of the central New Zealand shelf suggest the importance of upwelling in these waters. Several regions of upwelling were observed on the 1980 and 1981 cruises.

The surface distribution of nitrate-nitrite indicated a region of elevated nitrate-nitrite with a concentration of approximately 5 uM off Palliser Bay on leg 1 of the 1980 cruise during a period of no advection in the strait. The temperature and salinity data indicated that the source of the region of elevated nitrate-nitrite values was Southland Current water.

The period of strong to moderate southerly winds at the beginning of leg 1 reduced the advective flow of the D'Urville Current through Cook Strait Narrows and increased the transport and influence of the Southland Current in the eastern approaches of Cook Strait. This resulted in the encroachment of the Southland Current onto the steep shallow shelf off Palliser Bay. The upwelling that occurred was caused by water flowing over a decreasing depth.

The surface nutrient distributions for leg 2 of the 1980 cruise and leg 1 of the 1981 cruise indicated an advective flow from west to east in Cook Strait with an intrusion of water from the Taranaki Bight into Cook Strait Narrows.

The northerly and westerly winds on leg 2 of the 1980 cruise and leg 1 of the 1981 cruise will increase the transport of the D'Urville Current and result in an Ekman flow toward the northern and eastern coast of the

Taranaki Bight. A barotropic pressure gradient will be created that drives a slope current parallel to the bathymetry in the direction of Cook Strait Narrows.

Vertical sections of chemical, physical, and biological properties for a longitudinal transect of Cook Strait was produced from a series of hydrostations on leg 1 of the 1981 cruise. The vertical distributions of nitrate-nitrite, silicate, temperature and sigma-t indicated that water between 50 m and 200 m in Cook Strait Narrows was relatively homogenous and that above 50 m water from the central Taranaki Bight with low nutrients and high temperatures was present. The temperature, salinity and nutrient data indicated that the source of the homogenous water between 50 m and 200 m in the narrows was D'Urville Current water. The water advected into the Narrows by the slope current along the eastern Taranaki Bight was downwelled in the vicinity of Cape Terawhiti. The vertical distribution of chlorophyll 'a' also indicated the presence of the downwelled water in the Narrows with a relatively high constant concentration of chlorophyll 'a' to a depth of 275 m that had a high phaeophytin to chlorophyll 'a' ratio. The water downwelled and advected into the narrows was subsequently mixed with deep water residing in Cook Strait Canyon.

The water mixed in the Narrows was thereupon transported toward the shelf off Clifford Bay. This water was subsequently upwelled as a result of water flowing onto a decreasing depth on both leg 2 of the 1980 cruise and leg 1 of the 1981 cruise.

Vertical sections of the chemical and physical properties indicated the upwelling off Clifford Bay with all the isopleths bending upward toward the surface. The nutrient, temperature and salinity distributions indicated that the upwelled water mixes with water of Southland current origin overlying the Clifford Bay shelf.

A branch of the water transported out of Cook Strait Narrows appears to flow around Cape Terawhiti and upwell in the area of two shallow embankments, located on the shelf off Wellington and Palliser Bay, in the northeastern approaches of Cook Strait.

A region of cold, nutrient rich water was observed off Cape Farewell at the western approaches of Cook Strait on both the 1980 and 1981 cruises. Stanton (1971) attributed this cold temperature region to local intensification of a general wind induced upwelling off the west coast of the South Island during southerly winds. However, the upwelling region persisted during northerly winds, which would favor downwelling along this coast. This suggests that the cold, nutrient rich region is not dependent upon southerly winds producing a wind induced upwelling.

A vertical section through the Cape Farewell region on leg 1 of the 1981 cruise was produced from a series of hydrostations perpendicular to the coast. The vertical distributions of the chemical and physical properties showed all the isopleths bending upward toward the surface in the direction of Cape Farewell. This indicated that there was an onshore movement of bottom water along the transect that resulted in upwelling near the coast.

The distribution of surface properties indicated that the highest nutrients and the coldest temperatures were associated with the sharpest convex coastal bends and changes in bathymetry in the Cape Farewell region, although the winds favored downwelling during the sampling periods. The surface nitrate-nitrite distribution indicated concentrations of 6-7 uM located at the sharp coastal bends at Kahurangi Point and the base of Farewell Spit. This suggests that the upwelling was the consequence of a current flowing around a bend in the bathymetry.

XI.3 Plume

Surveys of the eastern approaches of Cook Strait were initiated on the 1980 and 1981 cruises to investigate the possible existence and the oceanographic properties of a plume of cold, nutrient rich water emanating from Cook Strait.

The surface distribution of nitrate-nitrite on leg 1 of the 1980 cruise indicated that there was no plume of elevated nitrate-nitrite values emanating from the eastern approaches. The strong to moderate southerly winds at the beginning of leg 1 apparently reduced the transport of the D'Urville Current into Cook Strait and increased the influence of the Southland Current over the eastern approaches of Cook Strait. As a result, there was no advective flow from west to east in Cook Strait and the predominant mechanism effecting nutrient distributions within the strait was tidal mixing.

An intermediate condition was indicated by the surface distribution of nutrients on leg 1 of the 1981 cruise. An advective flow from west to east in Cook Strait on leg 1 was indicated by the surface distributions of nitrate-nitrite and silicate. The period of light westerly to northerly winds increased the transport of the D'Urville Current into Cook Strait. A plume of elevated nutrient values appeared to be present on the coastal shelf around Cape Cambell. The temperature, salinity and nutrient data indicated that the source of the water with elevated nutrient values around Cape Cambell was the upwelling region off Clifford Bay. Apparently the influence and presence of the Southland Current in the eastern approaches of Cook Strait was not reduced sufficiently to permit the water that was upwelled off Clifford Bay to emerge as a plume from Cook Strait. It is thought that the light to moderate northerly and predominately westerly winds during leg 1 of the 1981 cruise did not adequately reduce the transport of the Southland Current and divert it offshore. As a result, the upwelled water off Clifford Bay was restricted to the coastal shelf and spread around Cape Cambell.

The surface distribution of nitrate-nitrite on leg 2 of the 1980 cruise indicated the presence of a plume of elevated nitrate-nitrite values emanating a distance of 120 km from Cook Strait during the sampling period. The nutrient, temperature and salinity data indicated that the source of the plume water appeared to originate from the area of Clifford Bay within southern Cook Strait. The maximum nitrate-nitrite concentration in the source region was approximately 6-8 uM. The upwelled water mixed to some degree with water of Southland Current origin, which overlaid the shelf off Clifford Bay. The resultant water mass was then transported eastward during a period of persistent strong northerly winds on leg 2.

The persistent period of moderate to strong northerly winds will reduce the barotropic component of the advective transport in the northward flowing Southland Current (Heath, 1972). The eastward displacement and reduced transport of the Southland Current results in a decrease in its influence over the eastern approaches of Cook Strait. It is thought that this reduced influence permitted the upwelled water off Clifford Bay, that was transported eastward, to emerge as a plume. The plume water flowed in a southeastward direction upon emerging from the strait. This denser cold temperature water began to sink as it flowed from the strait and mixed with Southland Current water along its southwestern boundary. The plume water flowed above the denser East Cape Current water, which was located in the northeastern area of the plume. This East Cape Current water appeared to reside at depth in the northeastern section of Cook Strait Canyon and offshore eastward beyond the coastal shelf.

Surface velocities of the plume were estimated from geostrophic calculations with a value of 48 cm sec^{-1} and from drogue trajectories with a value of 68 cm sec^{-1}.

The maximum chlorophyll 'a' concentration of 1.8 mg m^{-3} was located 125 km offshore at the seaward extent of the plume of elevated nitrate-nitrite values.

XI.4 Cape Farewell Eddy Structure

The surface distribution of nitrate-nitrite off Cape Farewell on the 1980 cruise suggests the presence of eddy formation and shedding in the upwelling region. The upwelling region was surveyed several times during the 1981 cruise to determine the processes responsible for the formation of large turbulent eddies in the Cape Farewell region.

The surface nitrate-nitrite distribution for the surveys of the upwelling region during a period of light northerly to westerly winds and neap tides on leg 1 of the 1981 cruise indicated that the upwelling region adhered closely to the coast. The maximum nitrate-nitrite and silicate concentrations on leg 1 were located at the sharpest convex bend at Kahurangi Point and the base of Farewell Spit. In addition, to the nearshore maxima in nitrate-nitrite values, there appeared to be several areas of higher nitrate-nitrite concentrations off Cape Farewell that form eddies associated with unstable meanders in the upwelling front. The surface nitrate-nitrite distribution also indicated the presence of a detached eddy in the western approaches of Cook Strait.

The silicate distribution in the Cape Farewell region appeared to be modified by several mechanisms. Significant amounts of silicate appear to be contributed by freshwater inputs and nearshore sediment fluxes, as indicated by the silicate highs in the nearshore areas. In addition, the change in nitrate-nitrite to silicate ratio as bottom water moves onshore and the increased surface silicate levels down-stream of the upwelling region suggests that there were significant contributions of silicate from the bottom sediments and regeneration in the water column off Cape Farewell.

The surface chlorophyll 'a' distribution for leg 1 of the 1981 cruise indicated that the maximum concentrations were located in the down-stream section of the plume of elevated nitrate-nitrite values in the western approaches of Cook Strait.

The surveys of nutrient distributions on leg 2 of the 1981 cruise off Cape Farewell coincided with a period of spring tides in Cook Strait and after a period of moderate southerly winds that subsequently shifted to a northerly direction. The nutrient and temperature data for the leg 2 surveys indicated that the extent of the region of cold nutrient rich off Cape Farewell had increased considerably compared to the leg 1 surveys. The plume of elevated nutrient values and reduced temperatures for the first survey of leg 2 extended well across the western approaches of Cook Strait toward Cape Egmont. This plume was detached from the coast of Cape Farewell north of Kahurangi Point with an apparent return flow of warm nutrient depleted oligotrophic water in the near-shore area. In addition, the area of intensified upwelling associated with the sharp convex coastal bend at the base of Farewell Spit, that was evident on the leg 1 surveys, was not observed on the leg 2 surveys. The area of intensified upwelling associated with the sharp convex bend at Kahurangi Point appeared to have increased in intensity from 7.0 uM on leg 1 to 8.0 uM on leg 2 indicating a greater upwelling depth and intensity. This data suggests that the period of upwelling favorable southerly winds just prior to the first survey of leg 2 increased the magnitude of the transport of the Westland Current and extended it to the north, while minimizing the indraught into Cook Strait known as the D'Urville Current (Brodie, 1960).

The subsequent surveys on leg 2 indicated a contraction of the upwelling region with a displacement to the south of the area of nitrate-nitrite maxima at Kahurangi Point and a decrease in the maximum surface values from 8.0 uM to 5.3 uM. The reduction in intensity and contraction of the upwelling region is probably a result of the persistent light northerly winds that occurred during the sampling period. A projected course of events as a result of prolonged northerly winds would be increased transport into Cook Strait and the reestablishment of the area of intensified upwelling associated with the sharp convex coastal bend at the base of Farewell Spit.

The contribution that the spring to neap tidal variation makes on the extent and configuration of the upwelling region cannot be determined from the present data set.

The nutrient and temperature data also indicated the presence of cyclonic eddies that were both detached from and imbedded in the upwelling region. The presence of three eddies, Eddy Leilani, Eddy Rhoanna and Eddy Karol was indicated by the nutrient and temperature data on the first survey of leg 2. This data indicated that the eddies were associated with unstable baroclinic meanders in the frontal boundary and were approximately 20 km in extent with a strong cyclonic rotation. In addition, the nutrient, temperature and density data indicated that Eddy Leilani had become senescent during the final survey. The extremeties of Eddy Leilani were fragmented due to frictional dissipation, with slumping of the isopleths, and the data suggested that mixing across the surface was taking place.

The dynamics of the eddies in the Cape Farewell region have been estimated by Bowman et al., (in press). The dynamics indicate that a strong jet is sustained at the front with a speed of 90 cm sec^{-1} with an upwelling velocity of 10 m day^{-1} and an onshore bottom flow of -23 cm sec^{-1}.

Cyclogensis, that formed the eddies, is produced by mechanisms that generate negative relative vorticity. The maximum contribution to the generation of relative vorticity will take place at the sharpest convex bends at Kahurangi Point and the base of Farewell Spit and in areas with sharp changes in depth such as Kahurangi Shoals. Eddies generated near Kahurangi Point will be supplied with relative vorticity as the eddies move northward toward the western approaches of Cook Strait, simultaneously the eddies will tend to lose vorticity by dissipation due to processes such as friction. The frictional processes that tend to dissipate the eddy will predominate when the eddy moves into the broad flat expanse of the western Taranaki Bight. The chemical. physical and biological data indicated that an eddy generated at Kahurangi Point that moved into the western Taranaki Bight had a detectable lifetime of approximately 1 to 2 weeks.

In addition to the low frequency larger scale variations in the upwelling region, that are probably due to changes in the transport of the Westland Current, there also appears to be high frequency small scale variations in the intensity of upwelling associated with meanders in the upwelling front and the related eddies. The temperature and nutrient data indicated that the meanders had a wavelength of approximately 28 km, a phase velocity of approximately 40 cm sec^{-1} and a period of 19 hours (Bowman _et al._, in press). The possible contributions of tidal and wind variations to the high frequency varability in the intensity of upwelling cannot be determined from the present data.

Nutrient uptake processes were important in determining nutrient distributions in the euphotic zone off Cape Farewell.

The reduced extent of the region of elevated nitrate-nitrite compared to the region of decreased temperatures off Cape Farewell indicated that substantial uptake of nitrate-nitrite was taking place. A graph of nitrate-nitrite concentration versus temperature for the first survey of leg 2, prepared by

Dr. P. Lapennas, indicated an exponential decrease in nitrate-nitrite concentration in relation to temperature. This suggests substantial uptake of nitrate-nitrite by phytoplankton.

The variability of the silicate distribution in relation to uptake and regenerative processes appeared to be more complicated than nitrate-nitrite in the Cape Farewell region. Nelson et al. (1981) states that studies of silicate uptake by natural marine phytoplankton indicate that silicate behaves differently from other primary nutrients in coastal upwelling regions and that each region studied is unique in relation to silicate dynamics.

Silicate limitation in regions where silicate values are low may play an important role in controlling the production cycle and phytoplankton species succession in an upwelling region (Nelson et al., 1981). Silicate values off Cape Farewell were generally low in recently upwelled waters and in the oligotrophic waters. Therefore, these relatively low values of silicate in the upwelling regions and the additional areas of subsurface silicate depletion indicate that silicate may be an important nutrient in controlling phytoplankton succession and composition in the Cape Farewell region.

However, primary production and species composition is controlled by a combination of several limiting factors, which include the physical mixing regime and interactions between the various limiting nutrients (Walsh, 1976).

Preliminary analysis of phytoplankton samples by Dr. P. Lapennas taken on leg 2 indicated that there were an increased number of diatoms within the upwelling region and the associated eddies. The diatoms appeared to be sinking and spreading as the water flowed northward toward the eastern approaches of Cook Strait. The sinking and spreading diatom population appeared to be replaced by an increased number of flagellated forms, such as dinoflagellates in the upper layers of the water column. In addition, the nearshore area, with an implied southward return flow on leg 2, appeared to have a phytoplankton population comprised predominantly of flagellated forms (P. Lapennas, pers. comm.).

The phytoplankton distribution and species composition are relatively consistent with the nutrient distributions and the physical mixing regime. The strong physical mixing regime and the higher nutrient concentrations in the recently formed eddies favor an increased number of diatoms. As the eddies move toward the western approaches of Cook Strait the nutrient values within the eddies decrease and the water column stability increases resulting in a sinking diatom population and an increased proportion of flagellated forms in the upper portion of the water column. Senescent eddies with high water column stability were depleted in nitrate-nitrite in the upper portion of the water column and had predominantly flagellated forms of phytoplankton in the surface layers. The subsurface layers above the thermocline were silicate depleted corresponding to the sinking diatom population. The changes in species composition associated with the eddies off Cape Farewell appears to indicate a phytoplankton succession similar to a seasonal succession taking place within the lifetime of the eddies. In the nearshore area off Cape Farewell, although the silicate concentration was apparently sufficient for diatom growth, the low values of nitrate-nitrite and the reduced mixing regime favored the flagellated forms of phytoplankton.

The relatively small increase in phytoplankton biomass compared to the amount of nutrients supplied suggests that phytoplankton losses due to sinking and grazing are high in the Cape Farewell region. The persistence of the upwelling region off Cape Farewell suggests that grazing stress may be high off Cape Farewell due to low habitat variability. Preliminary analysis of zooplankton samples taken on the leg 2 surveys by Dr. B. Foster indicated that the largest numbers of microzooplankton herbivores were associated with the cold temperature eddies, which also suggested high grazing stress.

Concentrations of arrow squid (*Notodarus solani*) appear to be especially abundant near the frontal boundaries of senescent eddies (Bowman *et al.*, in press). This suggests that the upwelling region off Cape Farewell and the associated eddies results in a reduction in the length of the food chain in the region and increases the amount of production available to the higher trophic levels. Therefore, the persistence of the upwelling region off Cape Farewell may result in a substantial contribution to the productivity of the western New Zealand coastal shelf.

The studies of the Cape Farewell upwelling region suggest the importance of further investigations of the changes in extent and configuration of the upwelling region off Cape Farewell and possible interactions with the upwelling region and eddies off Cape Foulwind observed by Stanton (1971). Information on the variability of the Westland Current and the possible effects of tidal difference on the Cape Farewell region are important in understanding the changes in the upwelling region.

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