

CSIRO
Division of Fisheries and Oceanography

REPORT 117

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with Periodic Deoxygenation**

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1980

COMMONWEALTH SCIENTIFIC AND INDUSTRIAL RESEARCH ORGANIZATION
DIVISION OF FISHERIES AND OCEANOGRAPHY
P.O. BOX 21, CRONULLA, NSW 2230

National Library of Australia Cataloguing-in-Publication Entry

Rainer, Sebastian.

Hydrology of an estuary with periodic deoxygenation.

(Commonwealth Scientific and Industrial Research
Organization. Division of Fisheries and Oceanography.
Report; no. 117)

Bibliography

ISBN 0 643 02567 7

I. Hydrology—New South Wales—Port Hacking.
I. Griffiths, F. B., joint author. II. Title. (Series)

551.46'578

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HYDROLOGY OF AN ESTUARY WITH PERIODIC DEOXYGENATION

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Aust. CSIRO Div. Fish. Oceanogr. Rep. 117 (1980)

Abstract

Two 24-hour studies of diel and tidal variability in hydrological, dissolved oxygen and chlorophyll *a* were made in a small tidal lagoon in Port Hacking, N.S.W. Ebb and flood tides were highly asymmetrical. The water column was strongly stratified during the neap tide study but only weakly stratified during the spring tide study. Exchange during neap tides was negligible. During spring tides the lagoon behaved like a front-dominated estuary with a high tidal exchange rate.

Oxygen-consuming processes predominated at depths below 5 m. At times of poor hydrological exchange, this results in the deoxygenation of bottom waters. High fluorescence levels in near-surface waters were associated with high photosynthetic activity. Very high fluorescence levels in anoxic bottom water were apparently due to chlorophyll degradation products.

INTRODUCTION

Cabbage Tree Basin is a small tidal lagoon in Port Hacking, N.S.W. at 34°05'S, 151°08'E (Fig. 1). It lies in an arm of a drowned river valley system cut into Hawkesbury Sandstone. It is situated within the boundary of the Royal National Park, with no direct road access and with boat access at high tide only, and is relatively free from urban influence. Previous work in Cabbage Tree Basin (Rochford 1953a, 1953b; Rochford and Spencer 1953, 1955) indicated that surface water temperatures were high in summer, that surface salinities were often low and that oxygen levels were often much reduced in the deeper waters of the basin. Cabbage Tree Basin thus appeared to have similar characteristics to the larger basins studied elsewhere

in Port Hacking (CSIRO, 1976; Godfrey and Parslow, 1976; Scott, 1978b).

Benthic communities in estuaries are subject to a wider range of environmental perturbation than those in deeper waters, but little work has been done to determine the ability of estuarine benthic communities to withstand environmental changes. Because of the small size of Cabbage Tree Basin and the wide range of temperature, salinity and dissolved oxygen found, the area was considered appropriate for a study of the responses of its benthic fauna to such changes (Rainer, unpublished data; Rainer and Fitzhardinge, unpublished data). No data were available on the magnitude of tidal and diel variability. A study of short-term hydrological variability,

together with measurements of the bathymetry and tidal exchange characteristics, is reported here.

Cabbage Tree Basin is about 35 ha in area, comprising an 8 ha basin and 27 ha of intertidal flats. The basin drains to the main body of Port Hacking by a sandy channel 2.1 km long which runs alongside a small area of housing towards its mouth. This channel enters Port Hacking some 2.5 km from the ocean. The channel is restricted 1.2 km from the mouth by a footbridge constructed in 1952-53. This footbridge, with rock abutments, forms the seaward boundary of Cabbage Tree Basin. Above the footbridge is an 11 ha sandflat that is usually immersed at high water. The sandflat is fringed by 4 ha of mangroves; on the eastern side, behind the mangroves, there are 12 ha of saltmarsh. Noticeable siltation in the Basin has occurred since the construction of the footbridge, and the channel to the Basin has been redirected and considerably lengthened.

The surrounding hills, up to 130 m high, are covered with dry sclerophyll eucalyptus forest and provide a total catchment of 450 ha. There are several temporary streams but Cabbage Tree Creek, at the head of the basin, provides the major freshwater input. Annual rainfall is about 1200 mm, and tends to be episodic rather than seasonal.

The earlier data from Cabbage Tree Basin included intermittent measurements at several stations of surface and bottom salinity, temperature and dissolved oxygen. These data are summarized in Fig. 3. Water temperatures in the basin were between 12.3-27.8°C at the surface and 12.5-23.2°C at the bottom. Water temperatures in the tidal channel were between 12.1-31.0°C. Salinity in the basin was usually about 35‰, although surface-bottom differences of more than 1‰ were common, and could be as high as 11‰. Oxygen levels in the bottom water were usually somewhat reduced. Severely

reduced oxygen levels occurred at any time of the year, with complete deoxygenation of the bottom water occurring consistently in autumn. This was not necessarily associated with reduced salinities.

Data from the two stations in the basin itself suggested that horizontal differences in hydrological properties were usually small compared with vertical differences and changes with time. A single sampling point was therefore selected for the present studies, and short-term differences with depth examined. Changes over a longer period have been examined separately, in conjunction with changes in the benthic fauna (Rainer, unpublished data; Rainer and Fitzhardinge, unpublished data).

EQUIPMENT AND METHODS

A tide pole was set up on the seaward edge of the Basin (Fig. 2) and a bathymetric survey was made. Tide heights were obtained by direct measurement from the fixed tide pole with subsequent adjustment to chart datum. Bathymetry was determined with a Furuno FG-11/200 Mk 3 echo sounder.

A station was established in the deepest part of the basin, about 100 m south of the tide pole (Fig. 2). Measurements were made during 29-30 March 1977 and 5-6 April 1977, of irradiance, water temperature, salinity, dissolved oxygen and fluorescence. Surface and subsurface irradiance was estimated using a Lambda quantum meter with a LI 192S underwater quantum sensor. Water samples were collected in 5 l Jitts bottles (Jitts 1964) at hourly intervals at 1 m depth intervals from the surface to the bottom. Probes were inserted in the Jitts bottle and temperature, salinity and dissolved oxygen readings made; a sample was then taken for on-deck fluorescence measurement, and Winkler oxygen determination. Occasional measurements of water temperature, salinity and dissolved oxygen were made at the tide pole.

Salinity and temperature were determined with a Hamon portable salinometer (Autolab Model 602), and dissolved oxygen measurements were made as percent saturation with an EIL Portable Oxygen Meter model 1520. The percent oxygen saturation values were corrected using the Winkler oxygen results, and expressed as $\mu\text{mol kg}^{-1}$. Fluorescence was measured with an *Impulsphysik Variosens 1* fluorometer, using excitation at 330-570 nm and measurement at 680-690 nm. An additional near bottom sample was usually taken if the distance from the last sample to the bottom was greater than 0.5 m. To avoid poisoning the platinum electrode, salinity and temperature measurements were not made on samples smelling of hydrogen sulphide.

The calibration of the salinometer was checked at the beginning and end of each 24-hour series, and reference was made to a salinity substandard at intervals. Chlorophyll *a* estimates were derived from the fluorescence data using a calibration curve based on a range of samples from the nearby South West Arm. The relationship between fluorometer response F , in mV, and chlorophyll *a* concentration Chl , in mg m^{-3} determined by the trichromatic method, was

$$F = 26.8 + 44.9 \ln \text{Chl} + 6.29 (\ln \text{Chl})^2,$$

with $r = 0.98$ and $N = 21$. The equation was derived using data within the range of $\text{Chl} = 0.76\text{-}5.87$.

RESULTS

Bathymetry and Tidal Curves

Bathymetry relative to chart datum is given in Fig. 2. The mean depth of the basin is 2.9 m below chart datum and the maximum depth 6.8 m below chart datum. The main freshwater input is from Cabbage Tree Creek to the south. Tidal exchange takes place over the sandbank to the north (Fig. 2).

Lowest low water at neap tide was 1.1 m above chart datum, and at spring tides 1.2 m above chart datum. The predicted and observed tidal amplitudes for neap and spring tides are given in Figs 4a and 4b respectively. Marked tidal asymmetry occurred during both studies, the flood tide lasting 2.8-4.6 hours and the neap tide 7.2-9.7 hours. Flood tides showed a short-term, approximately linear rise, followed on the ebb tide by a rapid drop to 0.2 m above low water, and then a gradual decrease until the tide changed.

Variable tidal delays are associated with the time required for external water levels to reach equilibrium with those in the basin. High tide at the entrance to Cabbage Tree Basin was delayed by about 0.5 h compared with Fort Denison. Most of this delay was attributable to the narrowness and shallowness of the channel below the footbridge, which is 1.3 km from the main channel in Port Hacking. A further tidal delay of up to an hour occurred at the footbridge itself, where the channel is effectively restricted to 9 m wide and 0.5 m deep. Slack high water in the basin occurred when the water levels on either side of the footbridge were equal, but lasted for less than 5 min. Ebb tide in the basin commenced within 5 min of ebb commencing at the footbridge.

Meteorological Observations

No rain fell during either sampling period. Creek flow was not measured, but was small during both sampling periods. During the neap tide study sampling took place in calm conditions from 0600 h to 1100 h. Between 1300-1600 h there was a NW breeze of $4\text{-}6 \text{ m s}^{-1}$ (Force 3). This died off gradually to calm conditions, and no wind was recorded between 2000 h and the end of sampling at 0600 h the following morning. During the spring tide study, ENE-NE winds of $1.5\text{-}6 \text{ m s}^{-1}$ (Force 2-3) were

present from the beginning of the sampling period until 2200 h, changing to calm airs or a light SE-SW breeze of $0.5-1 \text{ m s}^{-1}$ (Force 1) until 0900 h the following morning; light N-NW winds of $0.5-1 \text{ m s}^{-1}$ were present from 1000 h until the end of sampling at 1200 h.

Salinity (Figs 5, 6)

Salinities during the neap tide study were between $32.5-34.5$ ‰. The minimum salinity found was at the surface, shortly after high tide (32.5 ‰), at 1900 h, while the maximum salinity found was at 6 m depth (34.47 ‰, at 1200 h and 1500 h). A salinity inversion was present between 1-2 m depth at 1400 h (Fig. 5), while surface and sub-surface salinities at 1600 h indicated that some mixing had taken place, possibly due to wind stress. A more stratified salinity structure was gradually resumed after 1600 h. Salinities were generally higher during the spring tide study ($33.7-34.7$ ‰). Stratification was apparent during 2300-1200 h, between 0-2 m.

Water Temperature (Figs 7, 8)

Water temperatures during the neap tide study were between $21.5-23.8$ °C. Lowest temperatures were generally found at 5 m depth (mean temperature, 21.9 °C), with higher temperatures occurring towards the surface and nearer the bottom. The bottom 1.5 m was a fairly constant $0.5-1.0$ °C warmer than water found at 4-5.5 m depth. Stability was maintained because of the higher salinity of the bottom waters. Surface warming (0-3 m) took place between 0900-1800 h followed by cooling at night for both the neap tide and spring tide series.

Water temperatures during the spring tide study were between $21.4-23.6$ °C. Maximum temperatures at the surface occurred on the afternoon of 5 April, 23.5 °C at 1500 h, and at high tide on 6 April, 23.6 °C at 1200 h.

Temperatures below 5 m depth showed little diurnal variation, with a range of only 0.4 °C ($21.5-21.9$ °C). This contrasts with surface temperatures, where the range was 1.4 °C ($22.2-23.6$ °C).

Density σ_t (Figs 9, 10)

Density (σ_t) calculations were made from the salinity and temperature data. During the neap tide study there was a reasonably stable density pattern over the sampling period, with a tendency for decrease in sub-surface waters towards the end of the period. Surface waters (0-2 m depth) showed several short-term inversions (1400 h, 2200 h, 2400-0200 h). A similar range of σ_t values was found during the spring tide study. Few changes occurred over the sampling period in waters from 5 m depth to the bottom, but reduced surface densities were found in late evening and over the night, and again around high water on the second day.

During both sampling periods the σ_t values of water leaving the basin were similar to those at the monitoring station at 0-2 m depth. During the neap tide study, σ_t of incoming surface water, an hour before the daytime slack high water was less than that of surface water at the monitoring station. On the nighttime flood tide, σ_t of incoming water at 0500 h, at 1 m depth, was denser than bottom water at the monitoring station. During the spring tide study, incoming water at 1 m depth, about an hour before high water (2200 h), was denser than near-bottom water at the monitoring station. At 1000 h, about 1.5 h before high water, σ_t for incoming surface water was close to the σ_t values at 2 m and 3 m depth at the monitoring station.

Differences in the density of the incoming water at the tide pole from water at similar depths at the monitoring station were due to the combined effect of differences in temperature and salinity. During the

neap tide study, incoming water at the tide pole was about 0.2‰ less saline and up to 1.4°C warmer than near-surface water at the monitoring station at 1600 h, and up to 1.2‰ more saline and 1.8°C cooler at 0500h. During the spring tide study, incoming water at 2200 h and at 1000 h was about 0.6‰ more saline and up to 0.7°C cooler than near-surface water at the monitoring station.

Incident Light Measurements
Table 1)

Incident light was measured on three occasions during the spring tide study, at 1 m intervals from surface to near-bottom, between 0800-1200 h on 6 April. Above-surface light intensity was 1100-1600 microEinsteins $m^{-2} s^{-1}$, reducing to 500-1070 microEinsteins $m^{-2} s^{-1}$ immediately below the surface and to 4-11 microEinsteins $m^{-2} s^{-1}$ near the bottom (7-8 m).

The attenuation coefficient E was calculated from the relationship

$$\frac{Q_z}{Q_0} = e^{-Ez} \quad (\text{Scott 1978a}),$$

where Q_z and Q_0 are the downward irradiances in microEinsteins $m^{-2} s^{-1}$ and z is the depth in metres. For the entire water column E varied between 0.26-0.30 m^{-1} . Attenuation was highest near the surface, where E varied between 0.29-0.49, and least between 6-7 m depth, where E varied between 0.16-0.19. The pattern of light absorption was similar on each occasion. The 10% light penetration depth was 2.7-3.5 m, and the 1% light penetration depth was 6.7-7.8 m, slightly less than the depth of the water column at the monitoring station.

Dissolved Oxygen (Figs 11, 12)

During the neap tide study dissolved oxygen values were generally above 175 $\mu\text{mol kg}^{-1}$ from the surface to about 3 m depth, while a strong oxycline was present at 5-6 m depth. Mean oxygen concentrations were 118 $\mu\text{mol kg}^{-1}$ at 5 m depth and

25 $\mu\text{mol kg}^{-1}$ at 6 m depth. Water below 6 m depth was generally anoxic, with a strong sulphide odour. The highest oxygen concentrations, over 210 $\mu\text{mol kg}^{-1}$, were found between 1-2 m depth in the late afternoon and between 0-1 m depth in the early morning (0700 h).

During the spring tide study dissolved oxygen values were generally above 150 $\mu\text{mol kg}^{-1}$. The lowest dissolved oxygen values were at the bottom (122-180 $\mu\text{mol kg}^{-1}$), while the highest values were found at 3 m depth (172-194 $\mu\text{mol kg}^{-1}$); surface values were 152-178 $\mu\text{mol kg}^{-1}$. The highest values were generally restricted to 2-4 m depth. Occasional high surface values (1500 h, 1600 h, 1800-2300 h) and near-bottom values (1400 h, 1500 h) probably reflect wind- and tidally-generated mixing.

Significant changes in oxygen levels occurred during day and night periods during both studies. During the neap tide study, oxygen levels rose during the day (0800-1600 h) between the surface and 5 m depth, but fell at 5 m and 6 m depth; at night (1800-0600 h) reductions were found at all depths. Significant differences between day and night trends were found from the surface to 3 m depth. Highest rates of oxygen increase, 2.4-2.8 $\mu\text{mol kg}^{-1} h^{-1}$, were found at 2-3 m depth, suggesting considerable phytoplankton production at these depths. During the spring tide study, changes in oxygen levels showed a similar pattern. Pooled estimates showed a rise during the day between the surface and 5 m depth, while night-time levels generally fell. The highest rates of oxygen increase, 3.8-4.2 $\mu\text{mol kg}^{-1} h^{-1}$, were again at 2-3 m depth, at about the 10% light penetration depth. Decreases at night were generally less than during the neap tide study, but were significantly different from the daytime values at all depths between the surface and 4 m depth. Nearer the bottom, oxygen levels decreased at 1.3-7.0 $\mu\text{mol kg}^{-1} h^{-1}$ on the neap tide and 0.6-2.5 $\mu\text{mol kg}^{-1} h^{-1}$ on the spring tide.

Table 1. Incident light values ($\mu\text{Ei m}^{-2} \text{s}^{-1}$) between surface and near-bottom, 0800-1200 h on 6 April 1977, Cabbage Tree Basin.

Depth (m)	Time (h)		
	0800	1000	1200
Air	1100	1300	1600
0	500	950	1070
1	160	400	550
2	90	205	285
3	40	120	170
4	21	59	75
5	11	32	45
6	6	16	25
7	4	11	16
8	-	-	9.5

Chlorophyll a (Figs 13, 14)

The vertical distribution of apparent chlorophyll *a* differed between the two sampling periods. Mean values fell into three groups for each period, with surface water of relatively low chlorophyll *a* concentration overlying an intermediate layer of higher concentration. Apparent chlorophyll *a* concentrations in the bottom layer were very high during the neap, but were lower than the midwater concentrations during the spring tide study. Diurnal variability was low in the surface and bottom layers during both sampling periods.

A daytime increase in fluorescence was found between 2-4 m depth on 29-30 March and between 2-6 m depth on 5-6 April. The greatest change was at 3 m depth on both occasions, when the mean day values were 42% and 105% greater than the night values. The decrease from day to night values was fairly rapid on 29 March, occurring over several hours. On 5 April the decrease was gradual, occurring between mid-afternoon and late evening over seven or eight hours. An increase at dawn is apparent on both occasions. On 5 April, at 4 m depth, the chlorophyll *a*-equivalent values were 3.6 mg m⁻³ at 0600 h, 5.9 mg m⁻³ at 0700 h and 6.6 mg m⁻³ at 0800 h, a 1.8 times increase in two hours.

DISCUSSION

Hydrology

The general features of the hydrology of a basin connected to the sea by a shallow tidal channel have been described for other areas in Port Hacking (Godfrey and Parslow 1976). Cabbage Tree Basin appears to conform to this pattern. Water is vertically well-mixed in the tidal channel before entering the basin. If denser than the surface waters of the basin it sinks to a depth of equal density and spreads towards the head of the

basin; on the falling tide, water is skimmed off the top of the basin. Depending on the depth to which the incoming water sinks, residence time in the basin is variable and may be relatively short. Water below the level of incoming water will be largely isolated from exchange processes and will have a much longer residence time.

The basin waters were density-stratified during both the neap and the spring tide periods. The influence of insolation during the day was seen in a deepening of the surface and mid-depth isotherms towards evening, but there was little effect below 3 m. Changes in salinity were more marked, particularly in surface waters; these reflect in part changes due to the input of denser water during flood tides, but probably also reflect horizontal heterogeneity in the surface waters, due to the combined effects of wind-induced mixing and some freshwater inflow. During both sampling periods, instability in the salinity structure accompanied winds of 1.5-3 m s⁻¹ or higher, suggesting that wind-induced mixing may be a major factor in determining the stability and retention time of near-bottom water in Cabbage Tree Basin.

Tidal Exchange

Estimates of potential exchange rates were made by assuming a complete exchange of new water with previously-resident water. The net exchange for each tidal cycle \underline{r} was calculated as

$$\underline{r} = \underline{az}/\underline{aZ},$$

where \underline{a} is the area of Cabbage Tree Basin, \underline{z} the mean depth of the new water input, and \underline{Z} the mean depth of Cabbage Tree Basin (4.3 m).

The area of sandflats on the seaward side of the basin, about half the area of the basin itself, was usually covered to a depth of 15-20 cm at low water. This water, together with that retained in the channel, is water that was present in the basin

at the previous high tide and that will be returned to the basin on the next flood tide. Temperature and salinity data at the tide pole confirmed that new water from Port Hacking did not reach the basin until the tide had risen about 0.1 m. The combined effect of this and the reduced height of high water suggests that an exchange of water from Port Hacking with basin water can only occur when high water in Port Hacking is above 1.2 m above datum at neap tide and above 1.3 m above datum at spring tide.

Predicted heights for high water vary throughout the year between 1.1-2.0 m, suggesting values for \underline{z} of 0.0-0.7 m. Mean lower high water and mean higher high water at Sydney are 1.3 m and 1.6 m, for which the values of \underline{z} are 0.1 m and 0.3 m. Assuming an average value for \underline{z} of 0.2 m, \underline{r} will be 0.047, so that complete exchange would require 22 tidal cycles or about 11 days. At periods of minimum neap tides time for complete exchange would be considerably lengthened, and Cabbage Tree Basin may be regarded as having no effective exchange during such periods. At periods of maximum spring tides complete exchange would require about 10 tidal cycles (e.g., 2-6 May 1977 - Australian national tide tables 1977). Between the present neap and spring tide studies, the assumption of maximum exchange over the seven days gives $\Sigma \underline{z} = 4.6$ m, i.e., complete exchange.

Salinity changes between the neap and spring tide studies suggested that substantial exchange had occurred: mean salinity at 6 m on the neap tide ($34.08^{\circ}/\text{oo}$) was the same as the surface water on the spring tide seven days later. No rain was recorded over the seven-day period at Cronulla (Bureau of Meteorology, unpublished data). Freshwater input from Cabbage Tree Creek is dependent on rainfall, and will tend in any case to flow out of the basin with the ebb tide unless substantial wind-generated mixing occurs. Since Cabbage Tree Basin was stratified during both sampling periods, such

mixing was not considered important and freshwater input was disregarded in exchange calculations. Evaporation will also affect waters that would be largely lost with the ebb tide, and was similarly neglected over the period of stratification.

These arguments are not necessarily valid at times when stratification is absent, as after wind-mixing, or at times when the incoming water is less dense than the resident water, as in winter. While exchange seems to have been close to the maximum possible during the two sampling periods, this pattern cannot be considered typical of the basin under all conditions.

Oxygen Production and Consumption

Mean oxygen concentrations did not differ substantially between day and night periods. However, changes in dissolved oxygen levels at particular depths (Table 2) suggest that there was a net consumption of oxygen below 3-4 m depth.

Three factors are likely to have been important in the patterns of oxygen increase and decrease seen: phytoplankton production and consumption, sediment-related chemical and biological oxygen demand, and tidal exchange. Phytoplankton production was evidently important between the surface and 3-4 m on the neap tide and between the surface and 4-5 m on the spring tide. The high rates of oxygen decrease at the upper boundary of the anaerobic layer (5-6 m depth) on 29-30 March presumably reflect a combination of chemical and biological oxygen demand. Chemical oxygen demand may arise from the oxidation of substrates such as ferrous phosphate (Rochford 1974). Scott (1978b) found that recent biodebris was the principal material responsible for deoxygenation in the bottom waters of South West Arm. An accumulation of such material at the upper boundary of the deoxygenated layer could similarly account for most of the apparent oxygen utilization seen in Cabbage Tree Basin.

Table 2. Oxygen concentration ($\mu\text{mol kg}^{-1}$) in relation to elapsed time from beginning of selected day and night periods between surface and near bottom, Cabbage Tree Basin, 29-30 March 1977 and 5-6 April 1977. Coefficients are for a linear regression of oxygen concentration against time in hours, $y = a + bx$, so that \underline{b}_1 and \underline{b}_2 are estimates of net hourly oxygen addition or loss during day and night periods respectively; the standard error of the regression coefficient \underline{s}_b is given for each value of \underline{b}_1 and \underline{b}_2 . Regression estimates from the two daylight periods of 5-6 April were combined for comparison with the night period values. Probabilities were assessed for $H: \underline{b}_1 = 0, \underline{b}_2 = 0$ and $\underline{b}_1 = \underline{b}_2$. Significances are indicated as: * $^0 = 0.05 > p > 0.01$; ** = $0.01 > p > 0.001$; *** = $p < 0.001$.

Depth (m)	Day (0800-1600 h)			Night (1800-0500 h)			Difference in slope ($\underline{b}_2 - \underline{b}_1$)
	\underline{a}_1	\underline{b}_1	\underline{s}_b	\underline{a}_2	\underline{b}_2	\underline{s}_b	
29-30 March.							
0	203	0.6	0.5	209	-0.5	0.4	-1.0
1	200	0.9	0.6	213	-1.1***	0.1	-2.0***
2	191	2.4**	0.5	212	-1.1***	0.2	-3.5***
3	171	3.2***	0.4	206	-2.1**	0.5	-5.4***
4	163	1.6	1.1	180	-2.2	1.0	-3.9*
5	154	-4.0	2.0	132	-7.0**	1.8	-3.0
6	45	-3.4*	1.1	26	-1.3	0.7	2.1
5-6 April							
0	160	3.0*	1.0	176	-1.4*	0.5	-4.5
1	162	3.1	1.4	180	-1.9***	0.3	-5.0**
2	169	3.8*	1.1	168	1.1**	0.4	-2.7*
3	177	4.2**	1.0	187	-0.7	0.4	-4.9**
4	168	2.6*	0.9	182	-0.6	0.3	-3.2**
5	167	1.0	1.1	174	-0.3	0.3	-1.3
6	166	-0.7	0.8	170	-0.6	0.3	0.1
7	160	-2.5	3.0	168	-0.7	0.3	1.8

Tidal exchange was relatively unimportant during the day and night periods considered on 29-30 March, as high water occurred at dawn and dusk (Fig. 11). On 5-6 April high water occurred at midday and midnight (Fig. 12), and the injection of well-oxygenated water into the water column may account for differences in day and night rates of oxygen change between the neap and spring tide studies. A second effect of tidal exchange occurs by addition of new water near the bottom on the rising tide and withdrawal of water from near the surface on the falling tide. This is illustrated by the rise of the near-surface $175 \mu\text{mol kg}^{-1}$ isopleth during the night from 2-3 m depth to 1-2 m, and its further rise to 0-1 m the following morning (Fig. 12). This phenomenon would account for the overall rise in oxygen levels at 2 m depth during the night of the spring tide study, while there was a net decrease at all other depths.

Chlorophyll a

Considerable differences were found in the vertical and temporal distribution of *in vivo* fluorescence in Cabbage Tree Basin (presented as chlorophyll *a* equivalents, Figs 13, 14). The overall range of apparent chlorophyll *a* values for waters from the surface and 4 m depth (mean chl *a* = $1.7-4.3 \text{ mg m}^{-3}$) is similar to those recorded from other areas of Port Hacking (Scott 1976, 1978a).

The fluorescence values obtained for near-surface and near-bottom waters were similar within each 24-hour period. Mid-depth waters, on the other hand, had substantially greater values during the day than at night

(Table 3). The increase in fluorescence in mid-depth waters was not preceded by any increase in the near-bottom waters, suggesting that the increase was not due to upward migration from deeper water.

Synchronous cell division may occur in phytoplankton (Sweeney 1969), but an increase in chlorophyll *a* of the magnitude found seems unlikely to occur within only one or two hours. Accordingly, the increase in apparent chlorophyll *a* around 3 m depth is less likely to represent an increase in chlorophyll content than in the fluorescence response itself. The highest rates of daytime oxygen increase, and presumably of phytoplankton production, were also at 3 m. The coincidence in the depths of maximum oxygen increase and of fluorescence increase suggests that the latter has biological significance.

The region of very high apparent chlorophyll *a* content in the bottom water (6-7 m depth) during 29-30 March had dissolved oxygen levels of $25 \mu\text{mol kg}^{-1}$ or less. There was no significant difference between day and night levels of apparent chlorophyll *a*, indicating that the fluorescence was unlikely to be associated with an active photosynthetic system. The degradation products of chlorophyll *a* often found under anoxic conditions include the fluorescent compounds phaeophytin *a*, chlorophyllide *a* and phaeophorbide *a* (Higgins and Jeffrey 1976). *In situ* fluorometry is inadequate to differentiate these from chlorophyll *a*, but the anoxic condition of the bottom water suggests that these or similar compounds may have been the major source of the high fluorescence observed.

Table 3. Chlorophyll *a* equivalent concentrations (mg m^{-3}) during day and night periods, Cabbage Tree Basin, 29-30 March 1977 and 5-6 April 1977, at 1 m intervals from surface to near bottom. Significances were determined for $H_0: \bar{X}_1 = \bar{X}_2$ and are indicated as in Table 1; chlorophyll *a* values are given for each depth as the mean $\bar{X} \pm 1$ standard deviation $\hat{\sigma}$.

Depth (m)	Day (0800-1600 h) $\bar{X}_1 \pm \hat{\sigma}$	Night (1800-0500 h) $\bar{X}_2 \pm \hat{\sigma}$	Difference $(\bar{X}_2 - \bar{X}_1)$
29-30 March			
0	1.6 \pm 0.1	1.6 \pm 0.1	<0.01
1	1.6 \pm 0.1	1.7 \pm 0.1	0.05
2	2.7 \pm 0.2	2.2 \pm 0.1	-0.56*
3	4.6 \pm 0.2	3.2 \pm 0.2	-1.35***
4	4.9 \pm 0.1	4.2 \pm 0.2	-0.67*
5	5.5 \pm 0.3	6.8 \pm 0.3	1.30*
6	7.9 \pm 0.3	8.1 \pm 0.3	0.13
7	7.4 \pm 0.1	8.8 \pm 0.8	1.38
5-6 April			
0	2.2 \pm 0.1	2.2 \pm 0.1	-0.02
1	2.5 \pm 0.2	2.2 \pm 0.1	-0.33
2	4.0 \pm 0.4	2.3 \pm 0.2	-1.74***
3	5.1 \pm 0.2	2.5 \pm 0.3	-2.62***
4	5.2 \pm 0.3	2.6 \pm 0.2	-2.53***
5	4.3 \pm 0.2	2.7 \pm 0.1	-1.61***
6	3.3 \pm 0.1	2.9 \pm 0.1	-0.41*
7	3.0 \pm 0.1	3.0 \pm 0.1	-0.08

CONCLUSIONS

(1) Tides in Cabbage Tree Basin are asymmetrical, with short flood periods and extended ebb periods. Tidal excursions in Port Hacking below 1.2 m above chart datum do not affect water levels in Cabbage Tree Basin; during neap tide periods when high water is 1.2 m above datum or less there may be no exchange of water in Cabbage Tree Basin with water from Port Hacking.

(2) Thermal and salinity stratification was present during both studies. Tidal exchange occurs by the subsurface input of water during flood tides and withdrawal from the surface layer during ebb tides, a pattern typical of front-dominated estuaries.

(3) Increases in oxygen concentration occurred during the day between the surface and about 5 m as a result of primary production; the increases were greatest at about 2-3 m, at around the 10% light penetration depth. Diurnal increases in fluorescence occurring at mid-depths and particularly at around 3 m, suggested a positive relationship between fluorescence and photosynthetic activity.

(4) Oxygen-consuming processes predominated below 5 m depth during both the neap and spring tide studies. The combination of these processes and the poor net exchange during neap tides resulted in deoxygenation of the bottom water. High fluorescence found in the anoxic bottom water appeared not to be associated with an active photosynthetic system but was probably rather due to chlorophyll degradation products.

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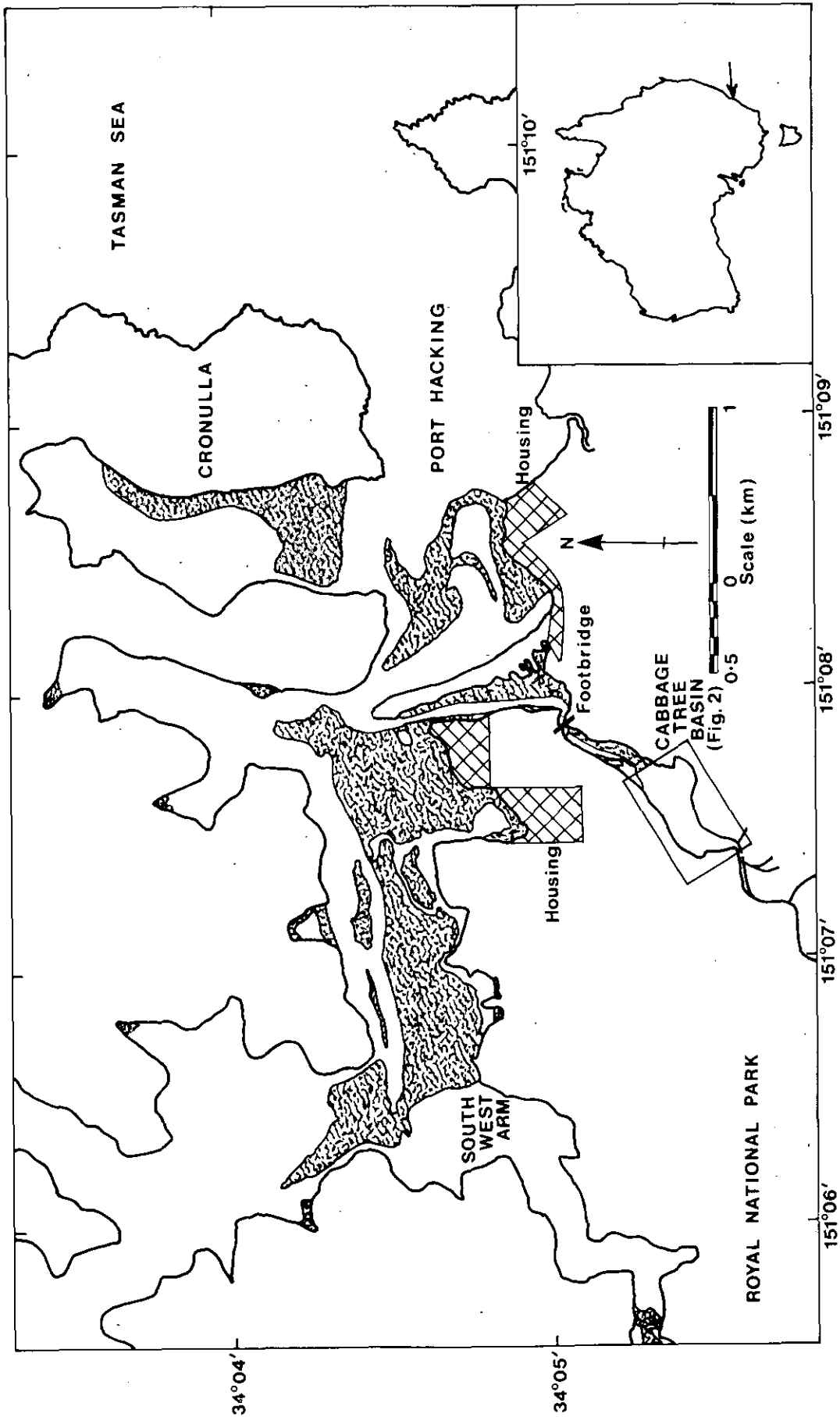


Figure 1. Port Hacking, New South Wales. The enclosed area of Cabbage Tree Basin is enlarged in Fig. 2. Stippled areas indicate sand bars exposed at MLWS, hatched areas indicate areas of housing.

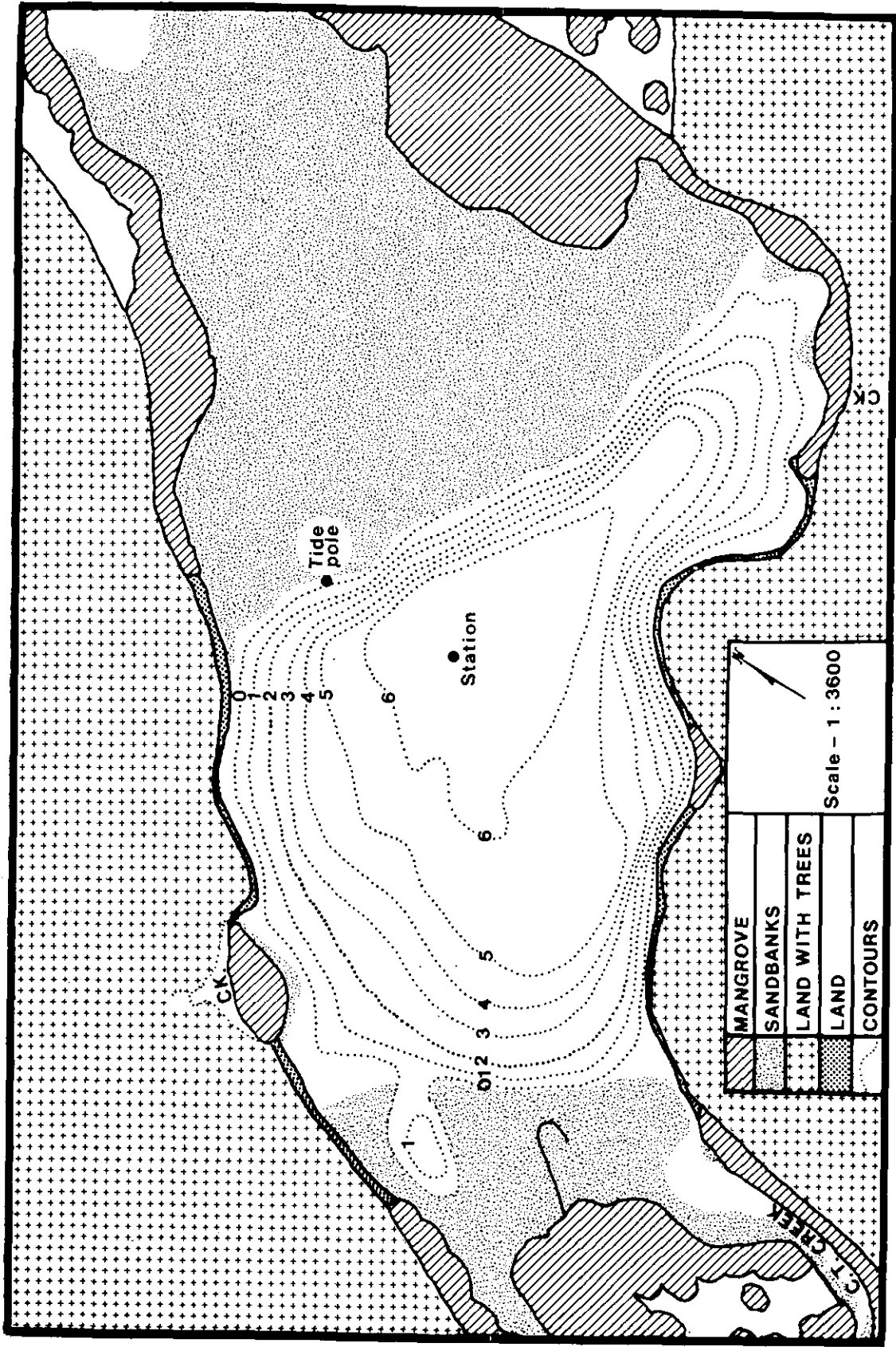


Figure 2. Cabbage Tree Basin: bathymetry. Contours are at 1 m intervals, relative to chart datum for Port Hacking; the positions of the tide pole and monitoring station are indicated.

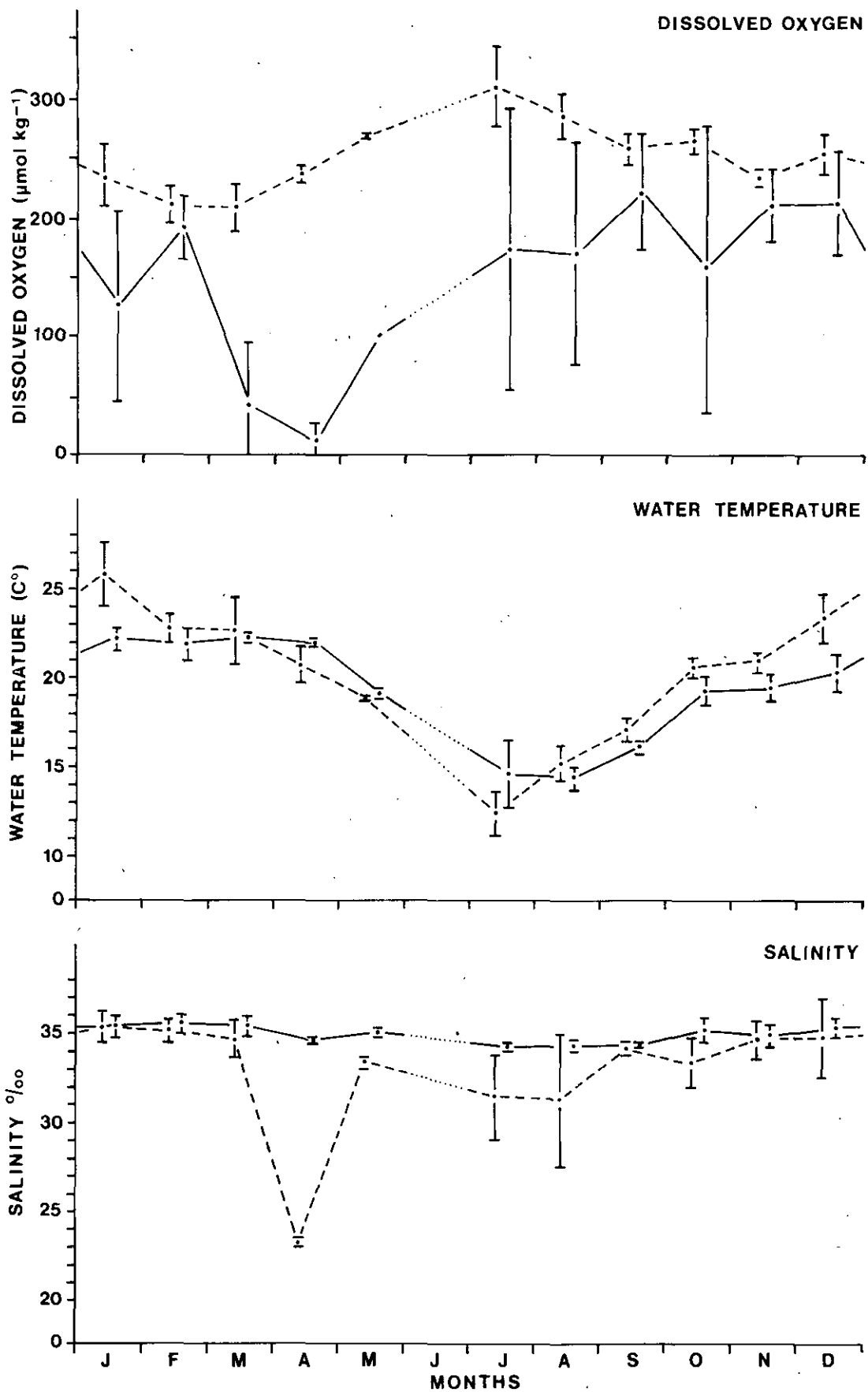


Figure 3. Dissolved oxygen, water temperature and salinity, Cabbage Tree Basin, 1951-1953. Surface (dashed line) and bottom (continuous line) values, given as the mean \pm 1 standard deviation (data from Rochford 1953a, b; Rochford and Spencer 1953, 1955).

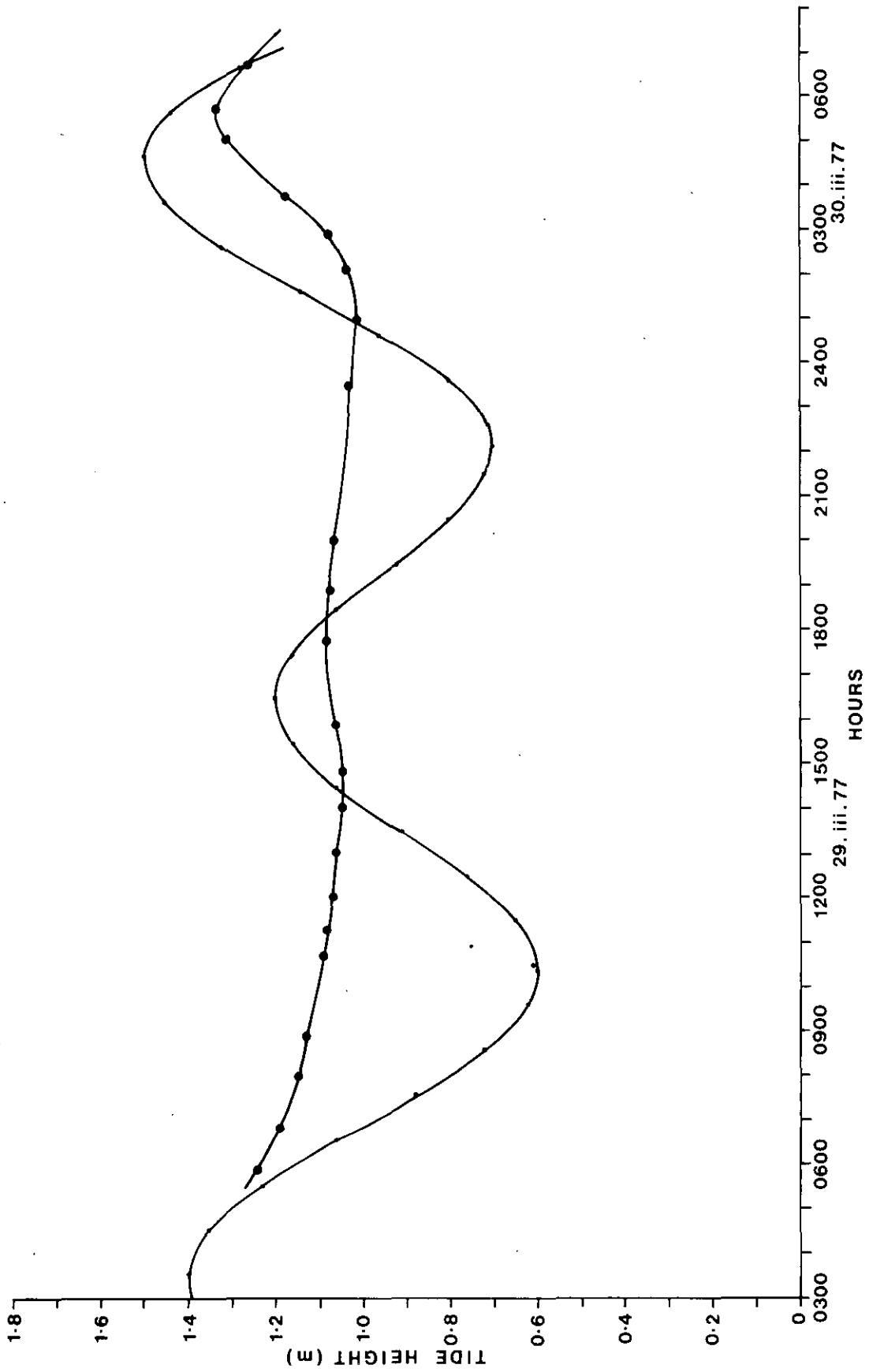


Figure 4a. Tidal curves observed in Cabbage Tree Basin (x---x) and predicted for Port Hacking (---): (neap tides, 29-30 March 1977). The curves for Port Hacking are based on predicted times for Fort Denison plus 0.5 h; heights are relative to chart datum of Port Hacking.

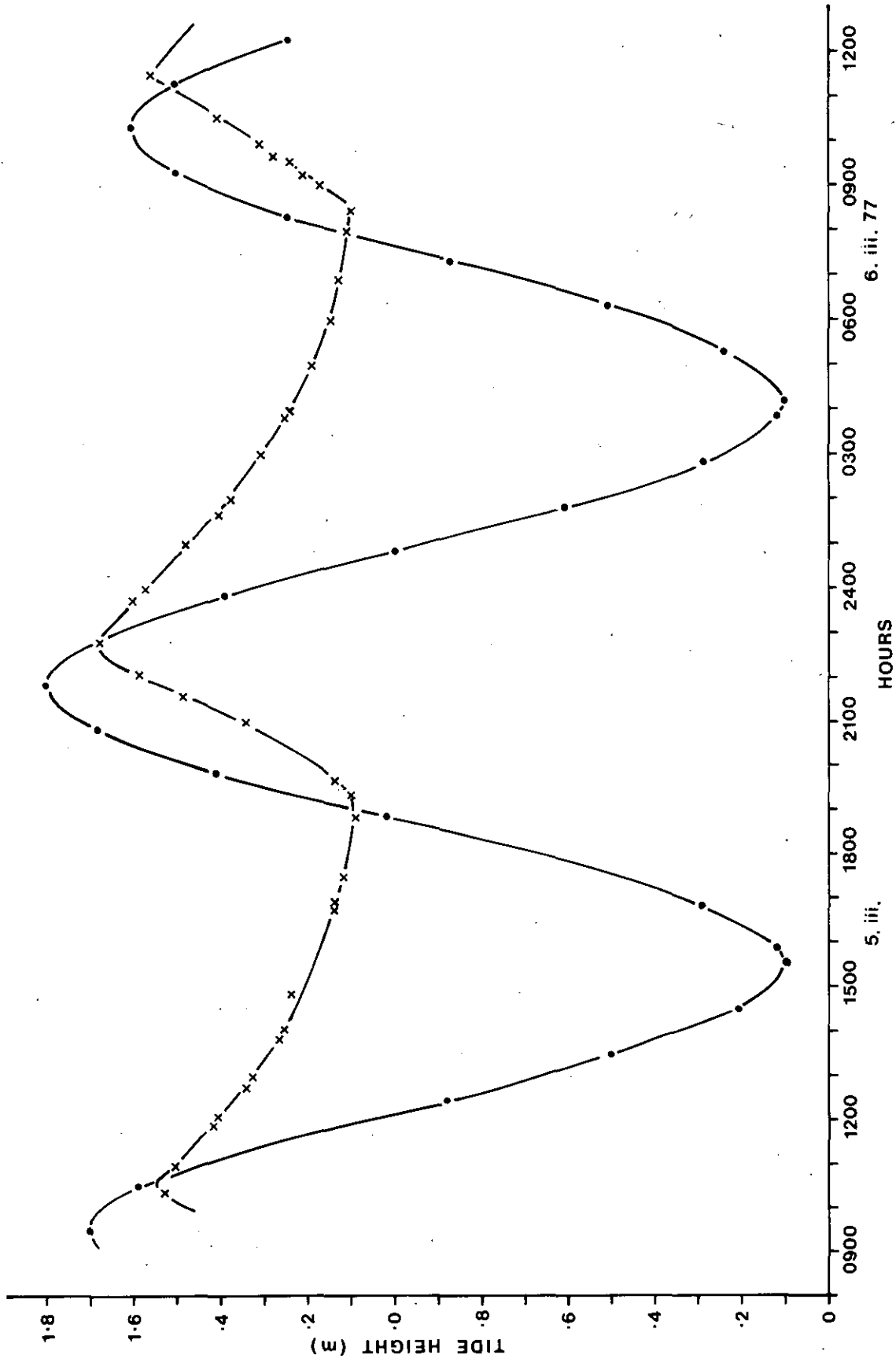


Figure 4b. Tidal curves observed in Cabbage Tree Basin (x—x) and predicted for Port Hacking (—): (spring tides, 5-6 April 1977). The curves for Port Hacking are based on predicted times for Fort Denison plus 0.5 h; heights are relative to chart datum of Port Hacking.

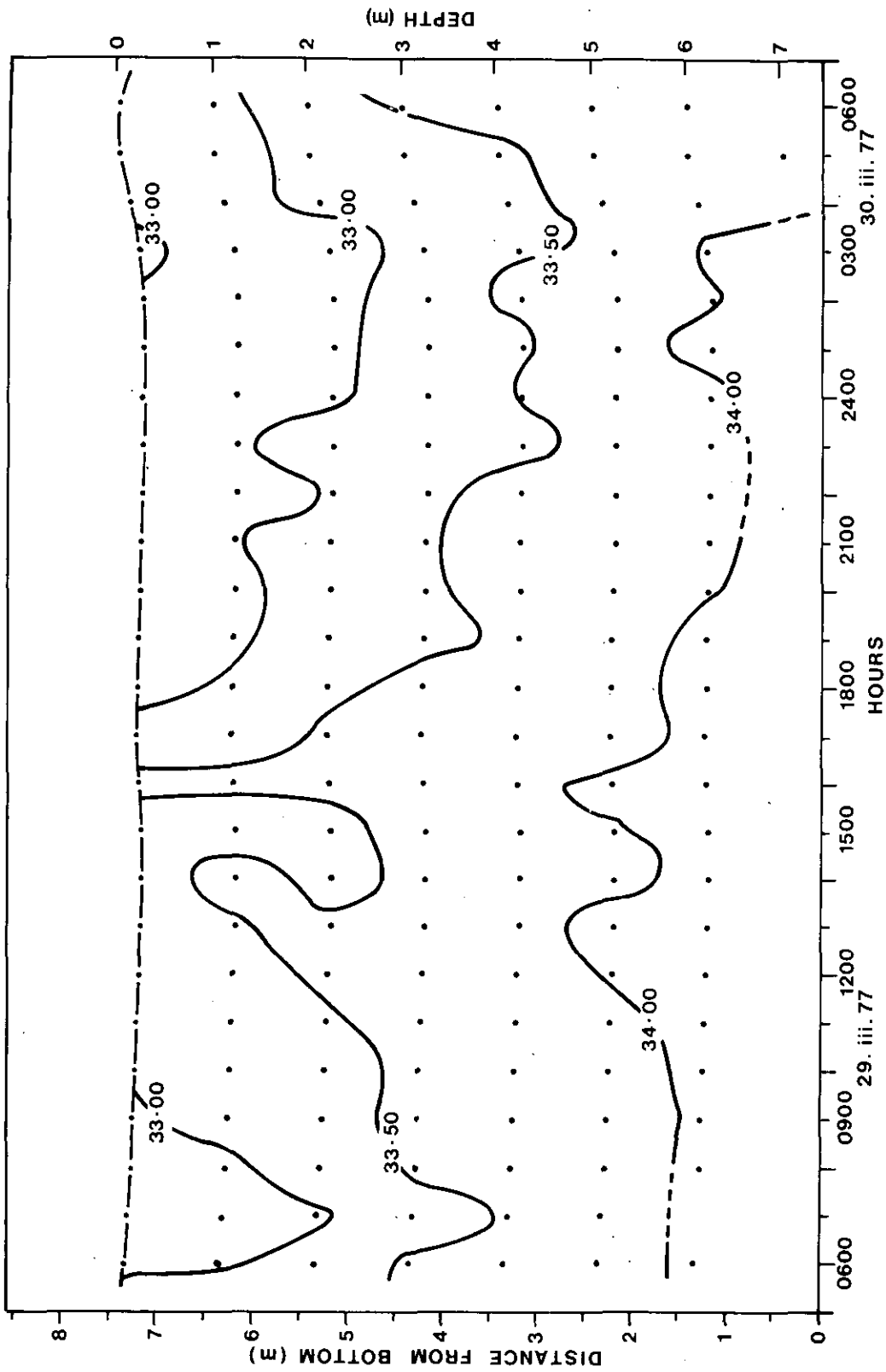


Figure 5. Salinity (‰): Neap tides, 29-30 March 1977. Isohalines are at intervals of 0.5‰ . Sample values are plotted relative to a fixed baseline at the bottom; samples taken at constant depth therefore vary with the stage of the tidal cycle in their distance from the bottom. Distance from the bottom is indicated on the left of the figure. Isobaths are parallel to the water surface and are indicated on the right of the figure, which gives the depth of the last samples in the study. Dashed isohalines are used where data are absent from a particular hourly series.

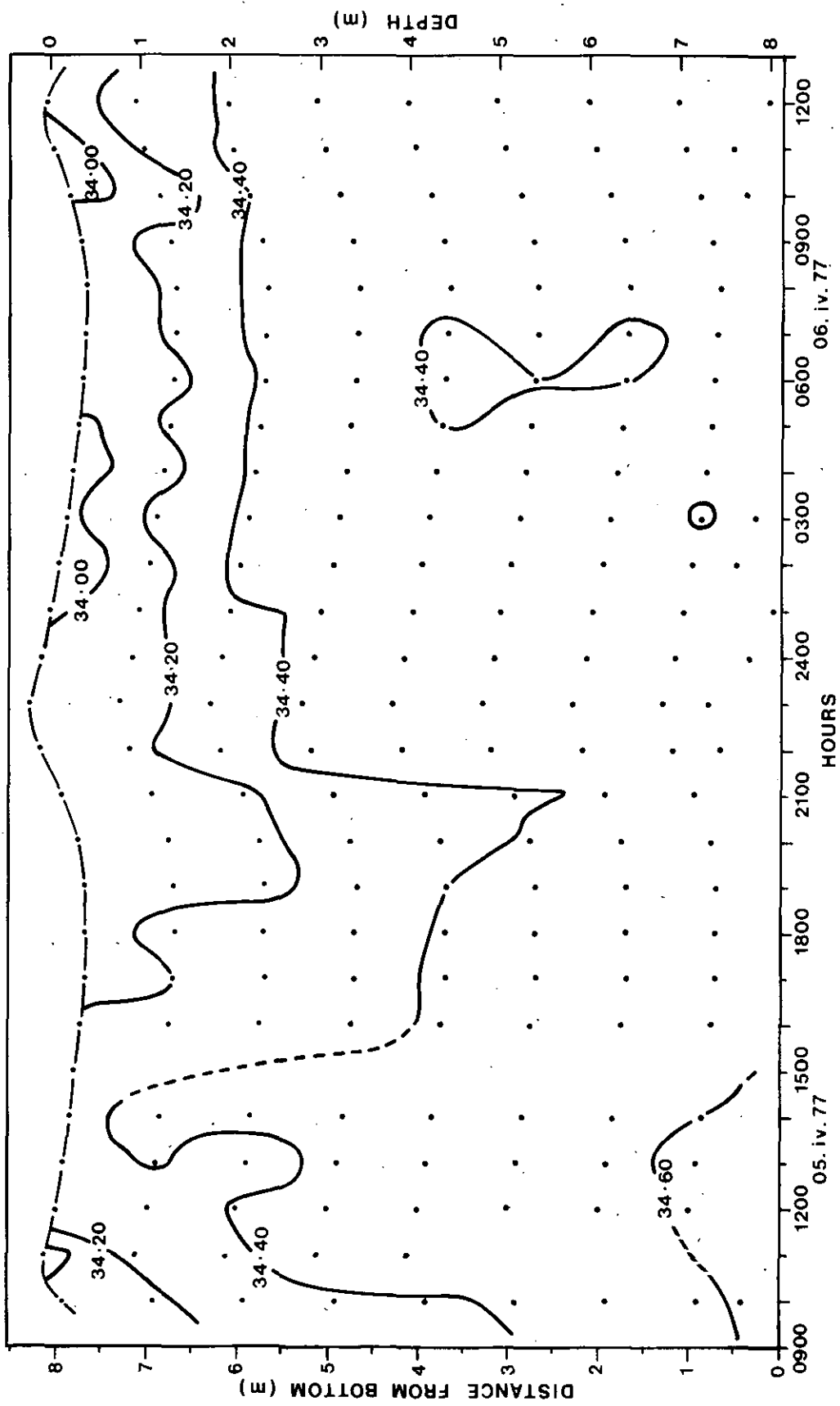


Figure 6. Salinity ($^{\circ}/_{\infty}$): spring tides, 5-6 April 1977. Isohalines are at intervals of $0.2^{\circ}/_{\infty}$; depths and dashed lines are as in Fig. 5.

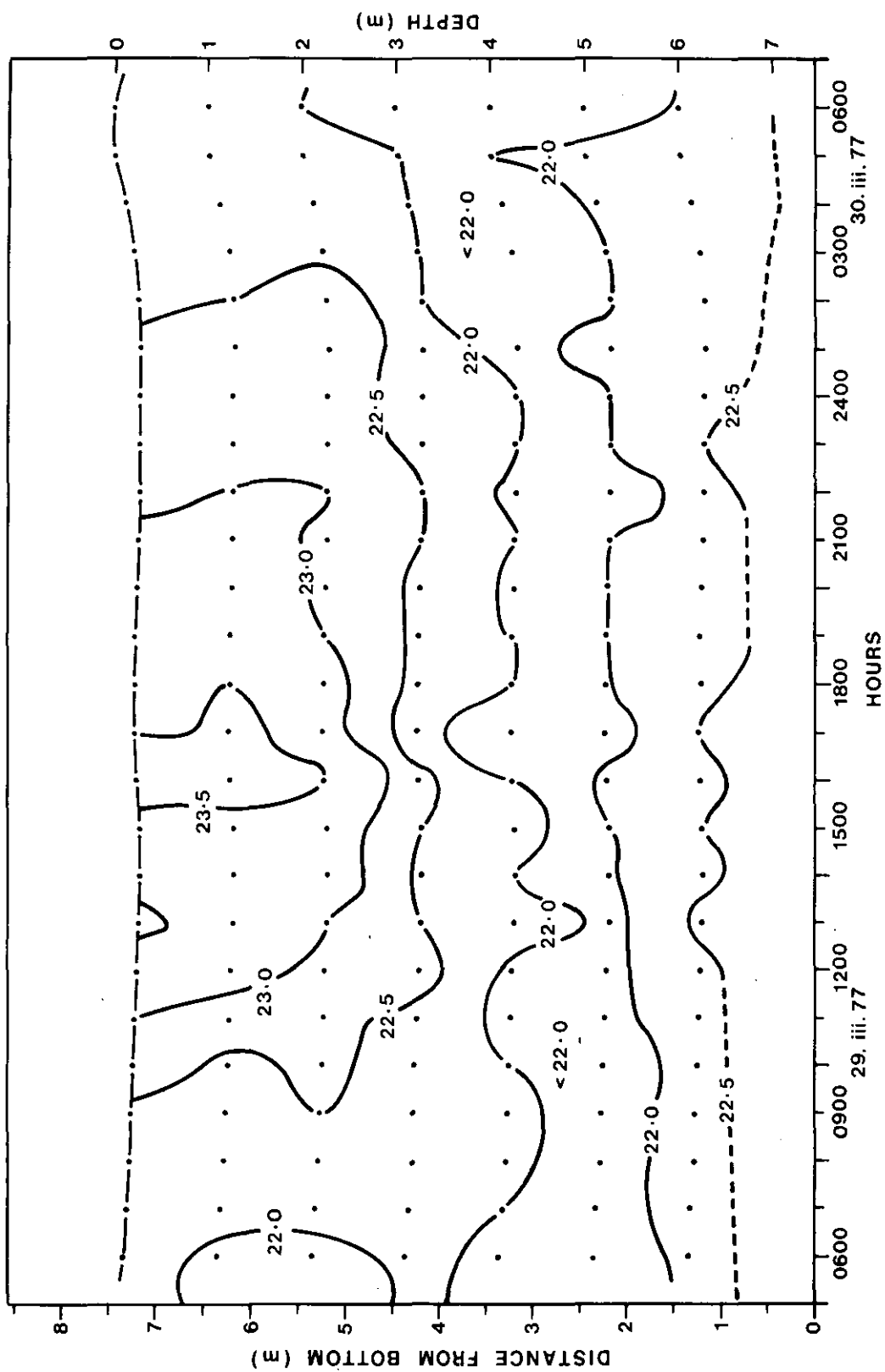


Figure 7. Water temperature ($^{\circ}\text{C}$): neap tides, 29-30 March 1977. Isotherms are at intervals of 0.5°C ; depths and dashed lines are as in Fig. 5.

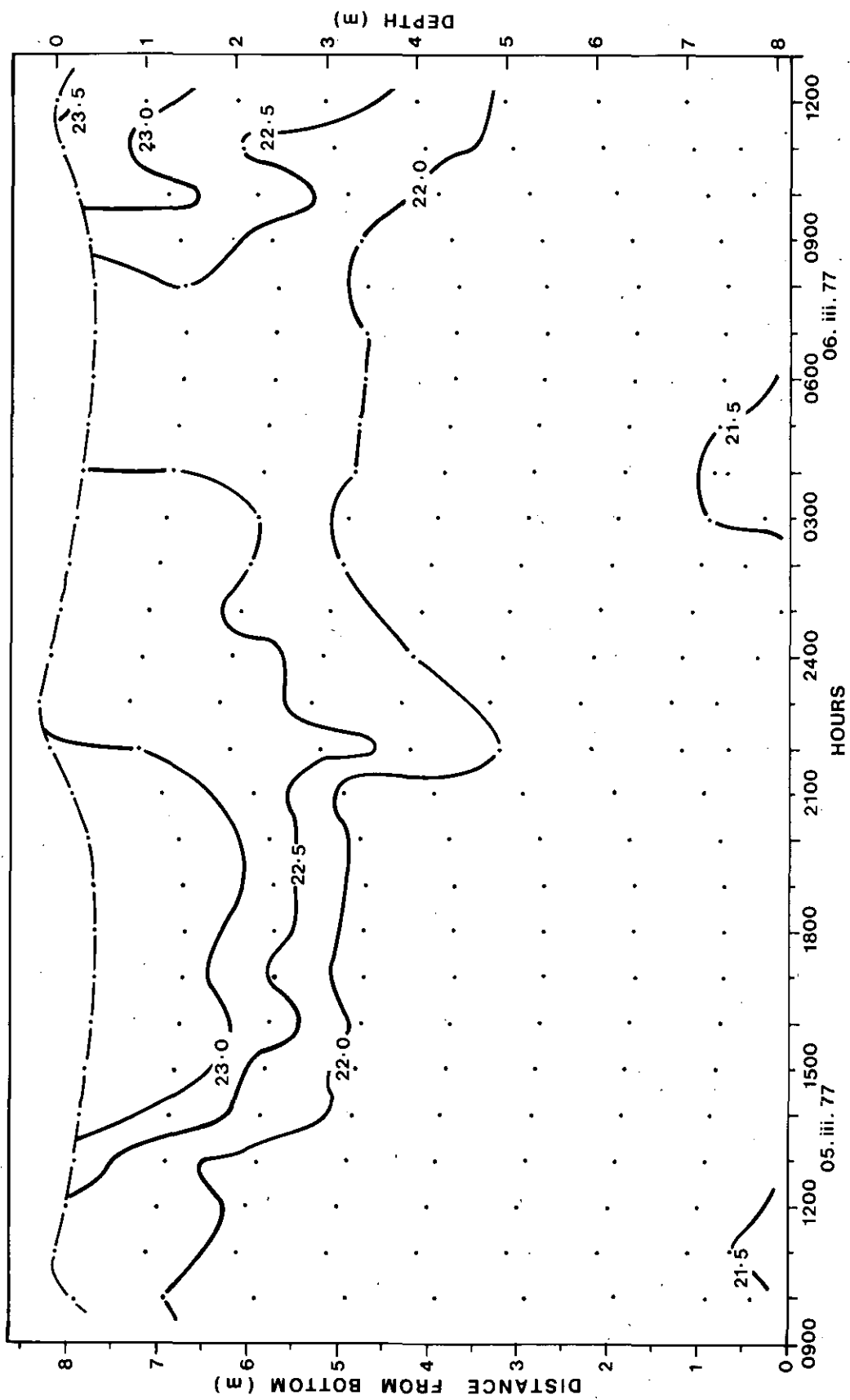


Figure 8. Water temperature ($^{\circ}\text{C}$): spring tides, 5-6 April 1977. Isotherms are at intervals of 0.5°C ; depths and dashed lines are as in Fig. 5.

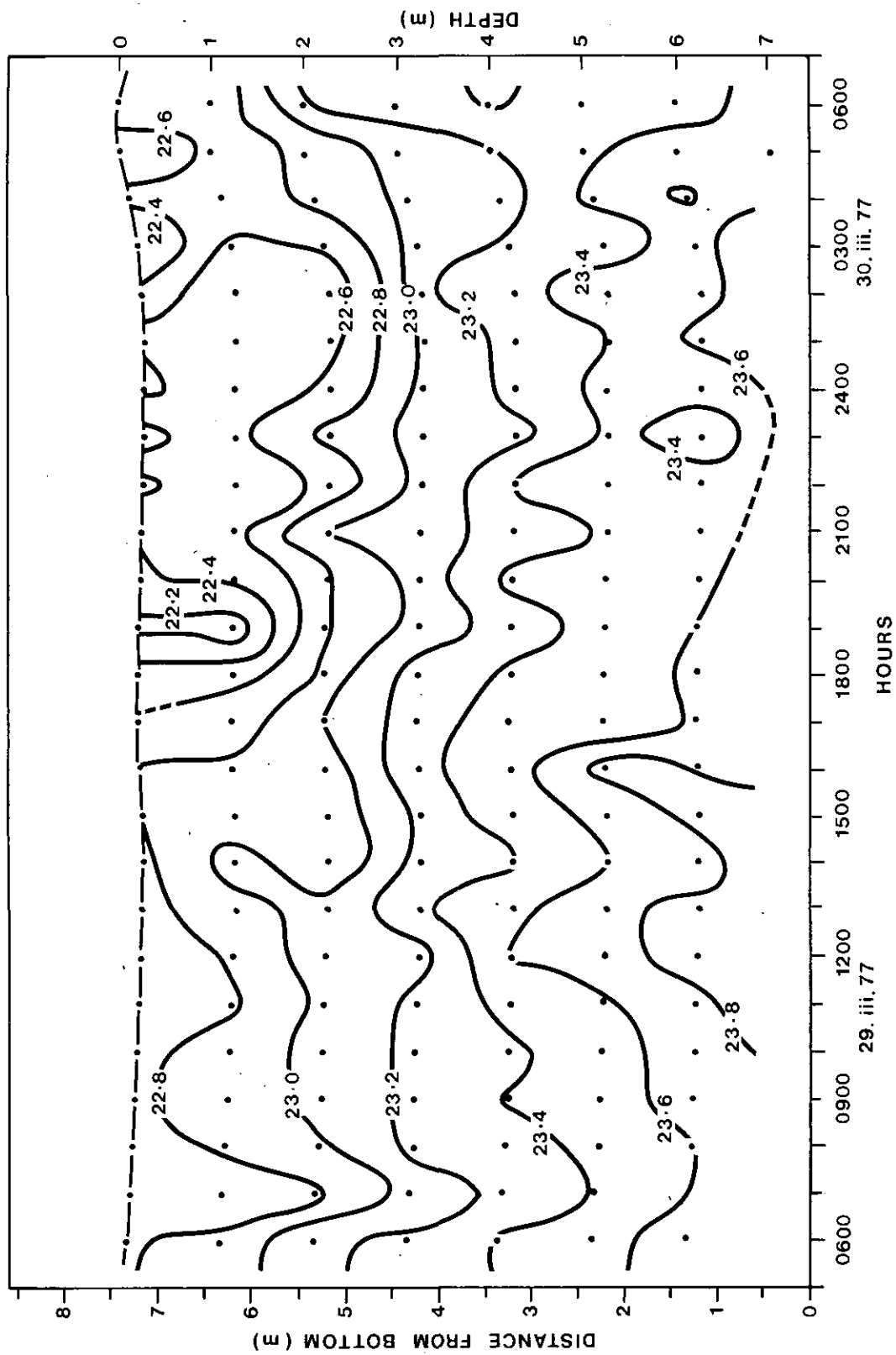


Figure 9. Density σ_t : neap tides, 29-30 March 1977. Density isopleths are at intervals of 0.2 σ_t ; depths and dashed lines are as in Fig. 5.

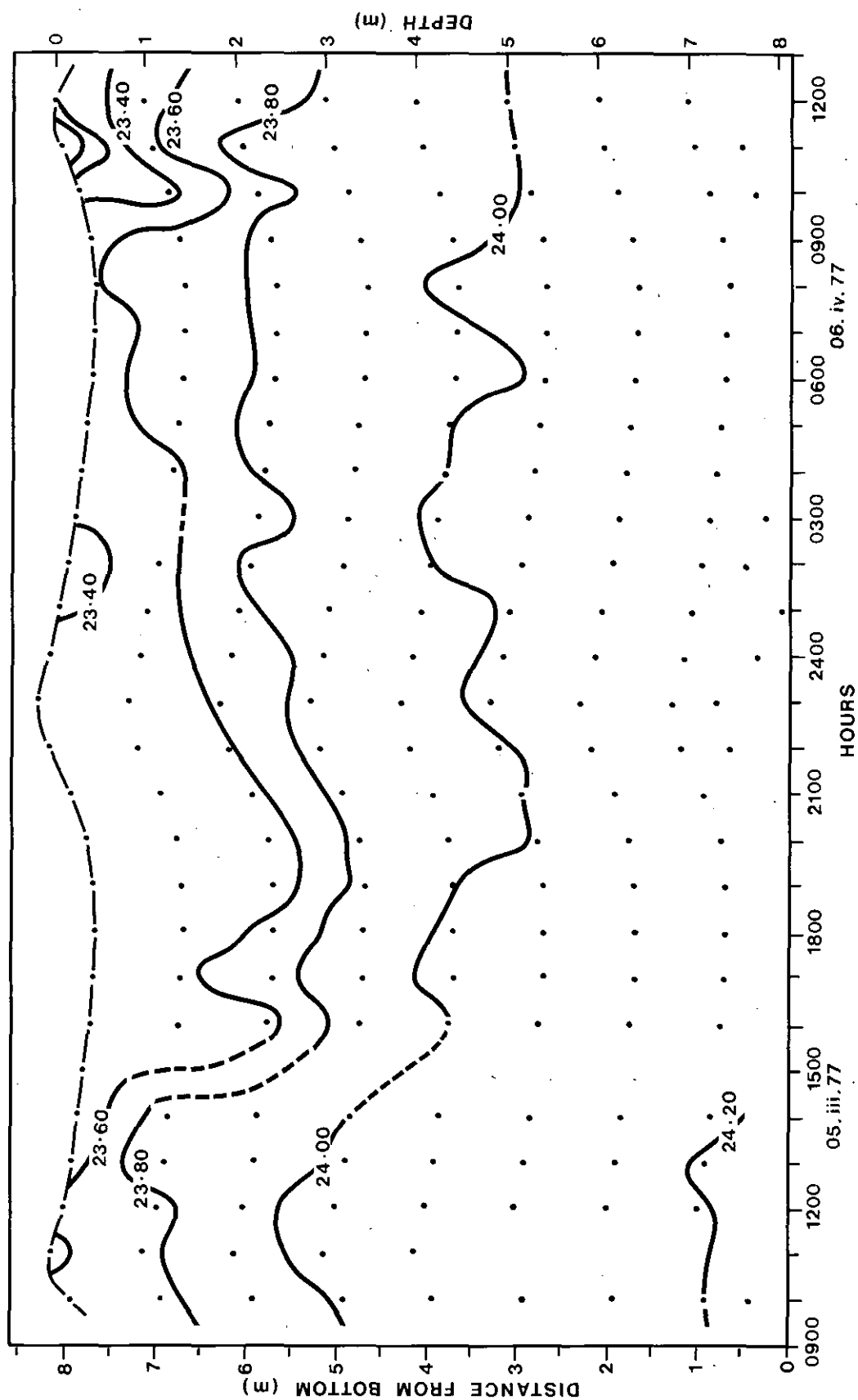


Figure 10. Density σ_t : spring tides, 5-6 April 1977. Density isopleths are at intervals of $0.2 \sigma_t$; depths and dashed lines are as in Fig. 5.

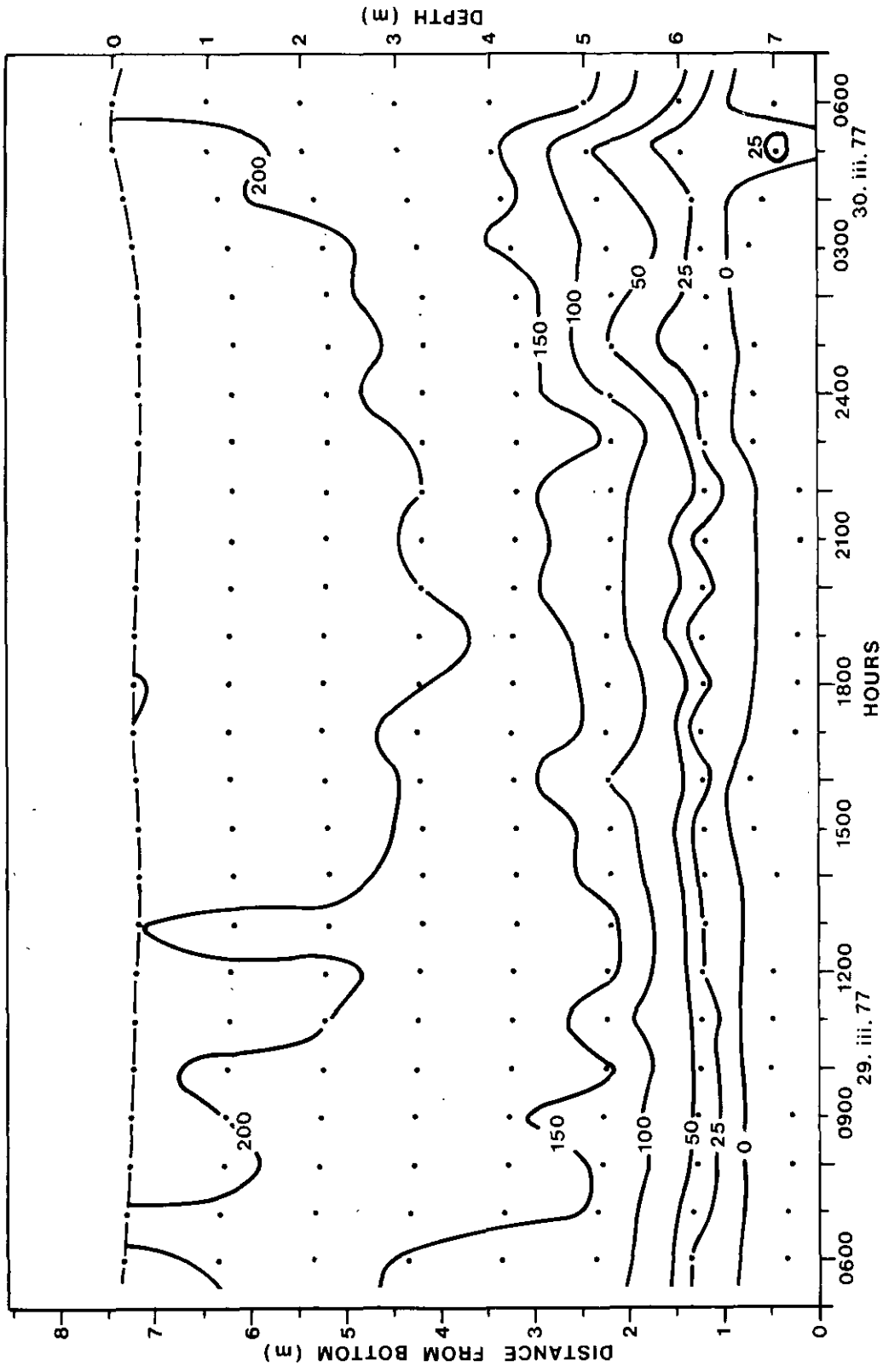


Figure 11. Dissolved oxygen ($\mu\text{mol kg}^{-1}$): neap tides, 29-30 March 1977. Oxygen isopleths are at 0, 25, 50, 100, 150 and 200 $\mu\text{mol kg}^{-1}$; depths are as in Fig. 5.

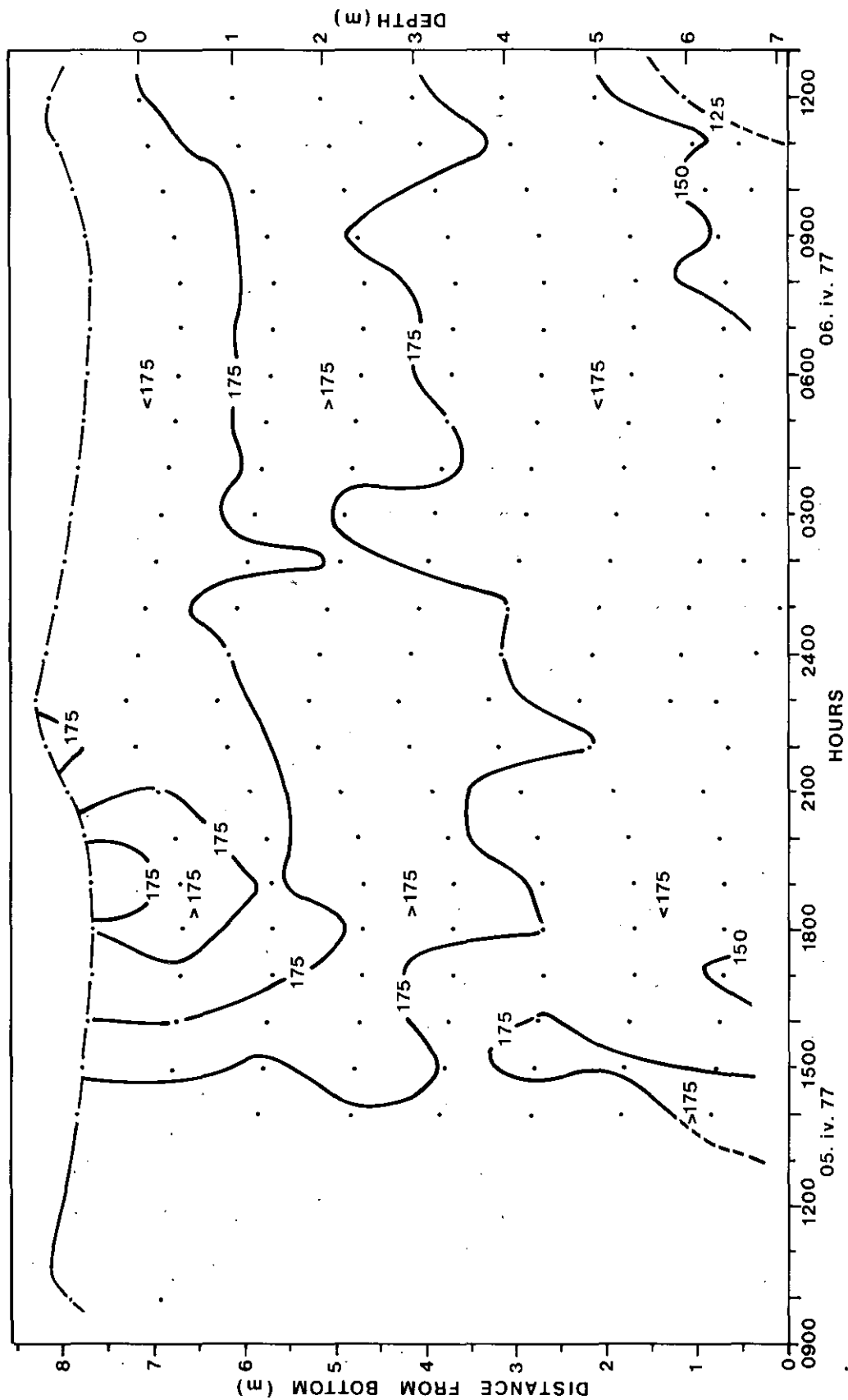


Figure 12. Dissolved oxygen ($\mu\text{mol kg}^{-1}$): spring tides, 5-6 April 1977. Oxygen isopleths are at intervals of $25 \mu\text{mol kg}^{-1}$; depths and dashed lines are as in Fig. 5.

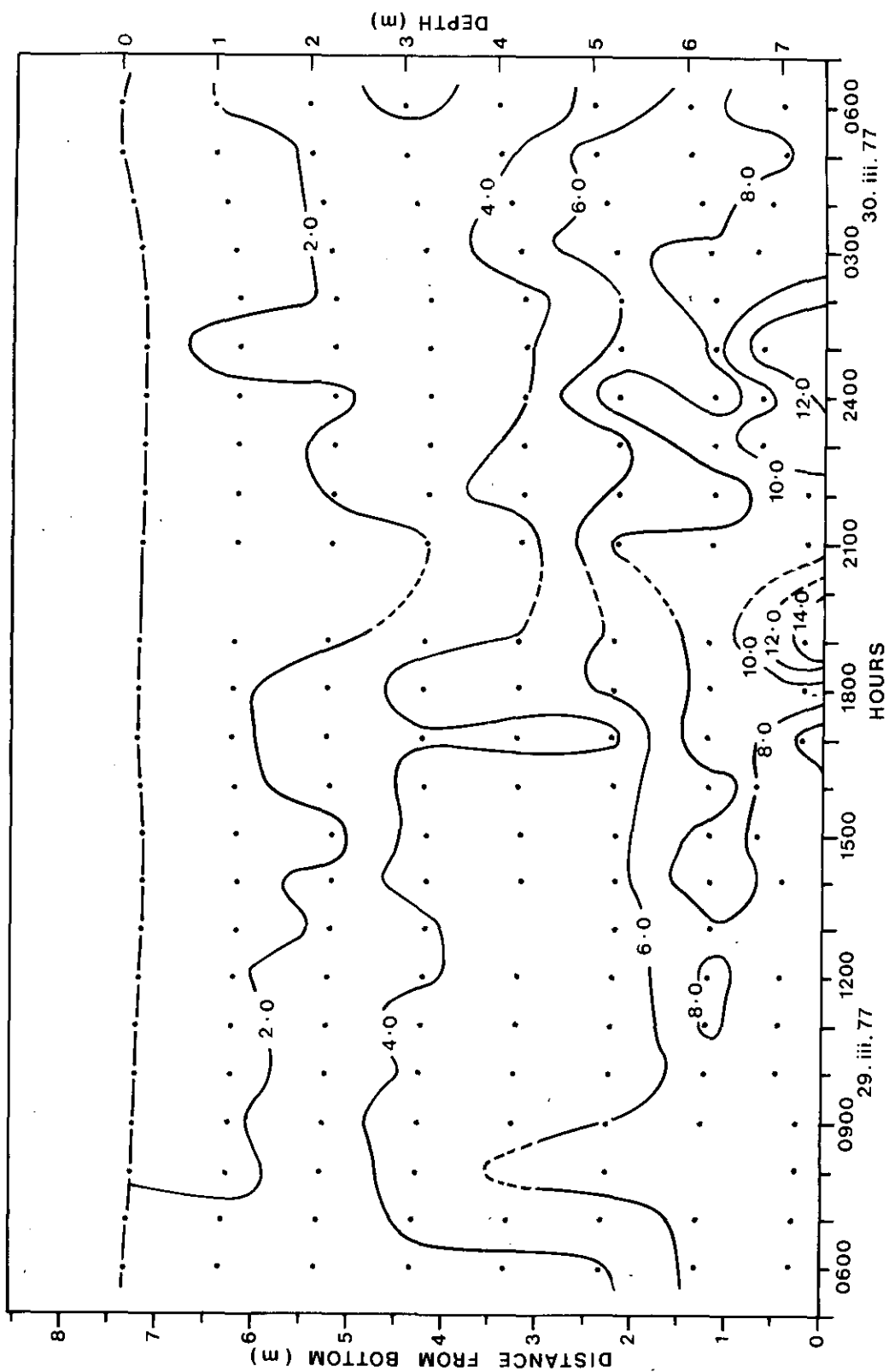


Figure 13. Apparent chlorophyll *a* concentration (mg m⁻³): neap tides, 29-30 March 1977. Chlorophyll *a* isopleths are at intervals of 2.0 mg m⁻³; depths and dashed lines are as in Fig. 5.

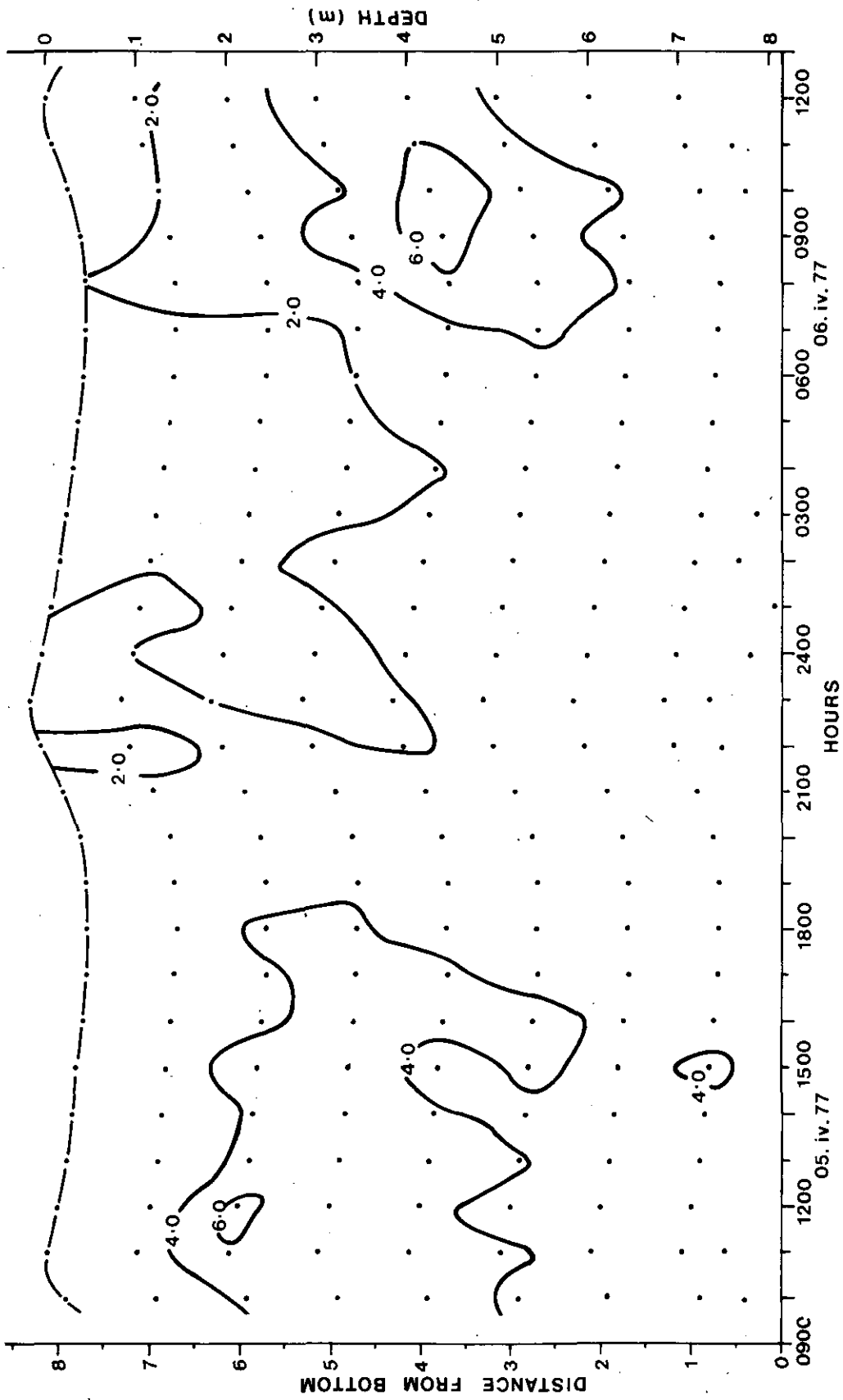


Figure 14. Apparent chlorophyll *a* concentration (mg m^{-3}): spring tides, 5-6 April 1977. Chlorophyll *a* isopleths are at intervals of 2.0 mg m^{-3} ; depths are as in Fig. 5.

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