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THERMAL STRATIFICATION AND THE DISTRIBUTION OF DISSOLVED OXYGEN IN BILLABONGS OF THE ALLIGATOR RIVERS REGION, NORTHERN TERRITORY (FINAL REPORT)

prepared by

T.D. Walker, J. Waterhouse and P.A. Tyler

Department of Botany, University of Tasmania, Hobart

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Supervising Scientist for the Alligator Rivers Region

A LIMNOLOGICAL SURVEY OF THE ALLIGATOR RIVERS REGION, NORTHERN TERRITORY. 2. THERMAL STRATIFICATION AND THE DISTRIBUTION OF DISSOLVED OXYGEN IN THE BILLABONGS.

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T.D. Walker

J. Waterhouse

and

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SUMMARY

The recognition of stratification in tropical waterbodies poses more problems than in the temperate zone. First, the small temperature changes involved demand careful attention to accurate measurements and, second, the large diurnal variation must be taken into account. Most limnologists have, with difficulty, adopted various arbitrary criteria based on a finite temperature change per unit depth. In this study it has been more useful to consider biological relevance, and recognize a de facto stratification from attendant ecological events, specifically oxygen depletion. Such a notion does not demand lasting rigorous hydraulic separation of water masses, only a sufficient barrier to mixing to allow progressive oxygen depletion. It is consistent with the considerable localized and limited vertical mixing common to tropical lakes, and with the view of a billabong as a heterogeneous and dynamic mosaic of water cells.

Based on these criteria the billabongs of the Alligator Rivers Region form a continuum of stratification behaviour. At one end of the spectrum lies Kulukuluku, and perhaps Woolwonga, with several months of de facto stratification. Leichhardt has less sustained periods of hypolimnetic anoxia, separated by periods of mixing. The sum of these limited periods means that bottom waters are anoxic for a considerable time during the year. Jabiluka occupies a middle position, with regular alternation of holomixis and brief episodes of stratification. It is a classical example of a tropical, polymictic lake. At the other extreme of the spectrum are Bowerbird, with its continual flow, and the shallow backflow billabongs. The position any billabong occupies in this continuum depends on such factors as morphometry, shelter and orientation with respect to prevailing winds.

Since heavy metal mobility and the susceptibility of the native fauna to toxins are both enhanced at low oxygen tensions the clear implication for the Magela system, where long term anoxia does not occur, is that the most critical time is the first few weeks of the Dry, the most critical billabong Leichhardt. The implications for the Nourlangie system are more

serious. Not only may anoxia be persistent in bottom waters but also it may extend for periods throughout the whole water column of billabong and floodplain.

1.0 INTRODUCTION

Within the catchments of the South and East Alligator Rivers, Northern Territory, lie four uranium deposits - Ranger, Jabiluka, Koongarra and Narbarlek. Government approval for the mining and milling of these deposits is largely dependent on adherence to environmental guidelines formulated by the Ranger Uranium Environmental Inquiry (Fox et al. 1977). Recognising that the waterways downstream of mining and milling operations could be subject to perturbation, this inquiry recommended the formulation of an effective biological and chemical monitoring program for these areas. It was evident that such a program must be founded on a detailed understanding of aquatic ecology of the Region. At the time of that report, little was known of aquatic ecology in tropical Australia and it was clear that considerable general limnological research would be required. The present study is part of a broadly-based investigation into the aquatic ecosystems, co-ordinated by the Supervising Scientist for the Alligator Rivers Region.

This series of reports presents the results of a limnological study into a number of small waterbodies, locally called billabongs, in the catchments of the South and East Alligator Rivers. The billabongs, left behind as the floodwaters of the rainy season recede, assume immense ecological importance as the refuges of birds and aquatic life during the prolonged dry season. The picture of each billabong given is based upon temperature and oxygen data (this report), optical conditions (Walker and Tyler 1985a), water chemistry (Walker and Tyler 1985b), nutrient status (Walker and Tyler 1985c), phytoplankton populations (Kessell and Tyler 1985; Ling and Tyler 1985; Thomas 1983) and phytoplanktonic productivity (Walker and Tyler 1985d). An extended introduction to the Alligator Rivers Region and its billabongs is given at the beginning of this report. For ease of reporting, much of the data presentation has been organized into Appendices.

2.0 STUDY AREA

2.1 Geography

The Alligator Rivers Region is located immediately to the west of the Arnhem Land Plateau, a rugged sandstone formation covering much of the north-eastern corner of the Northern Territory (Figs. 1-4). A general description of the Region is given by Christian and Aldrick (1977) and Fox et al. (1977).

All the major streams have their headwaters in the plateau and run in a generally north-westerly direction. On leaving the plateau they cross the lowlands, and during the wetter months, spread over extensive floodplains. Only the large rivers maintain a continuous stream channel through the floodplains. The lowlands merge with tidal flats along the estuaries and on the northern coastline.

During the dry months, the floodwaters recede, leaving a large number of small lentic waterbodies. Locally, these small lakes are called billabongs. In South Africa they would be called pans. Pedantically, a billabong is a distinctive type of waterbody, an oxbow or meander cut off by fluvial processes (Bayly and Williams 1973; Hutchinson 1957). However the word is entrenched in local usage in the Northern Territory for almost any small, riverine waterbody.

In previous publications on the limnology of the Region several billabong classifications have been proposed (Davy and Conway 1974; Hart and McGregor 1980; Walker and Tyler 1979) based primarily on geography, morphometry and hydrology. All the classifications proposed adopt three major taxonomic units - backflow, channel and floodplain billabongs. Placed within the context of Hutchinson's (1957) lake classification (Table 1) backflow billabongs appear to be lateral lakes (type 52), while floodplain billabongs may be either type 56 or 57. Channel billabongs appear not to fit this classification.

2.2 Climate

The climate of the Region is of the winter-dry, tropical climate type (Aw) of the Koeppen-Geiger climatic classification. This system is based on mean monthly temperature and precipitation. Aw climates are characterised by distinctly seasonal rains (the 'Wet') (Fig. 5), a pronounced dry period

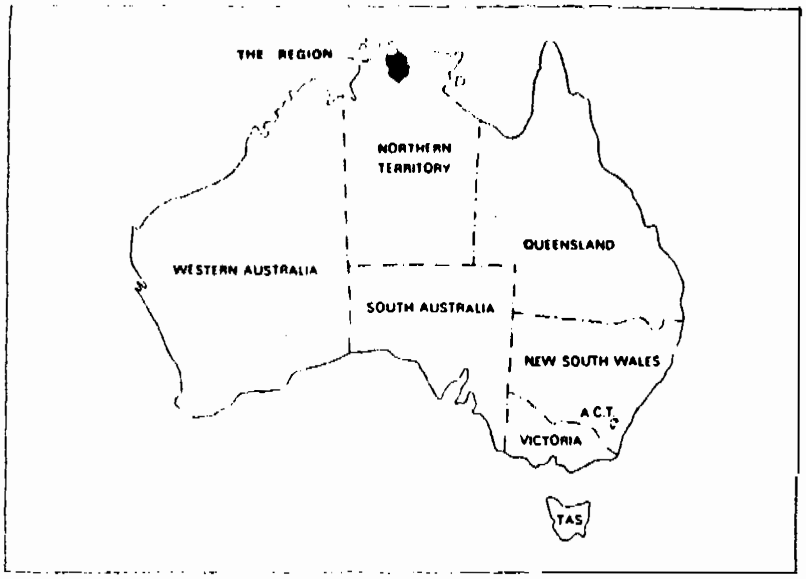


FIG 1. Location of the Alligator Rivers Region, Northern Territory (taken from Fox 1977).

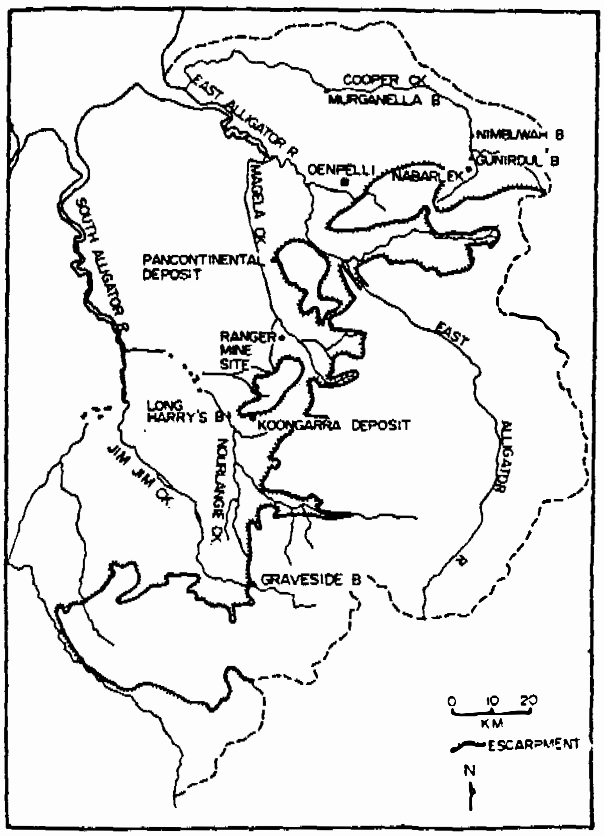


FIG 2. Study areas in the Alligator Rivers Region.

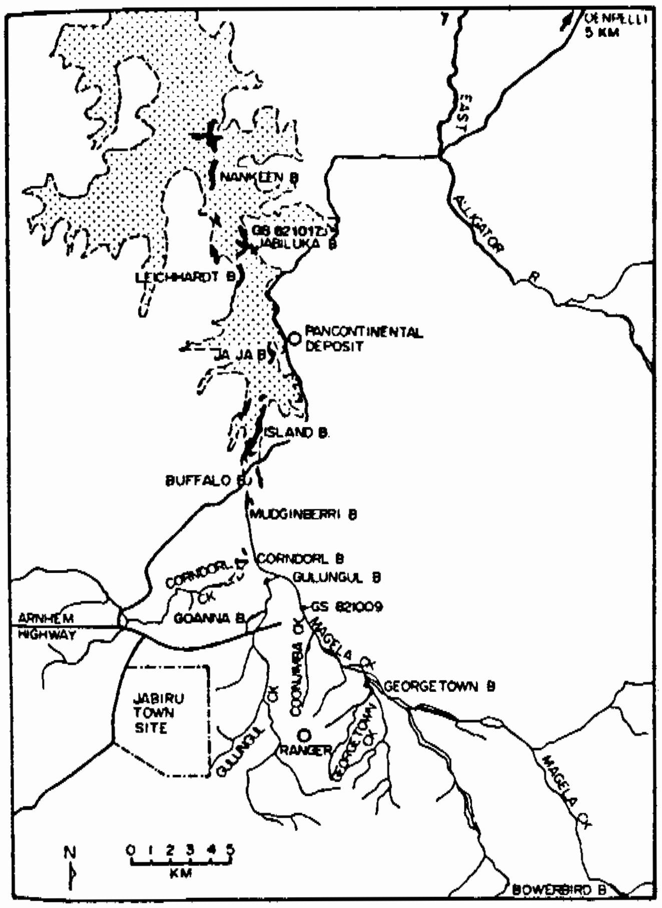


FIG 3. Location of the Magela Creek billabongs, stream gauging stations (GS821009/17), and two uranium deposits.

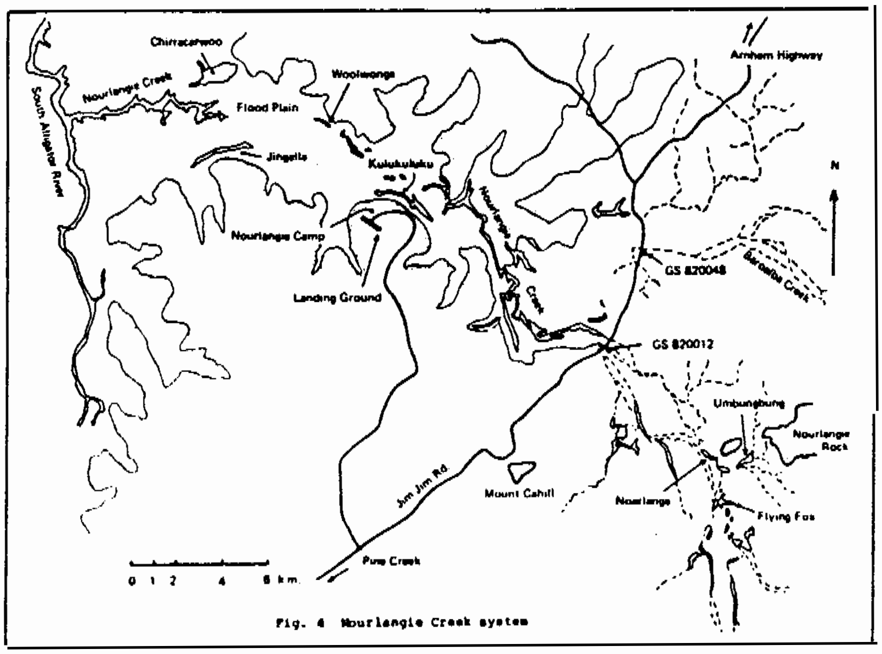


FIG 4. Location of the Nourlangie Creek billabongs and stream gauging stations (GS82002/48).

TABLE 1: The usual classification of Alligator Rivers billabongs compared with Hutchinson's (1957) classification of lakes.

BILLABONG CATEGORY	HUTCHINSON CATEGORY	BILLABONG CHARACTERISTICS
Backflow	Type 52 - lateral lake. Formed when the sediments of the main stream, deposited as levees, back water up a tributary stream.	Shallow; shelving banks; fine sediments.
Channel	Not described - located wholly within stream channel.	Deep; steep banks; coarse sediments.
Floodplain	Type 56 - lakes in depressions on floodplains caused by uneven aggradations during floods.	Shallow; shelving banks; fine sediments.
	Type 57 - lakes in abandoned channels on floodplains.	Comparatively deep; steep and shelving banks; predominantly fine sediments.

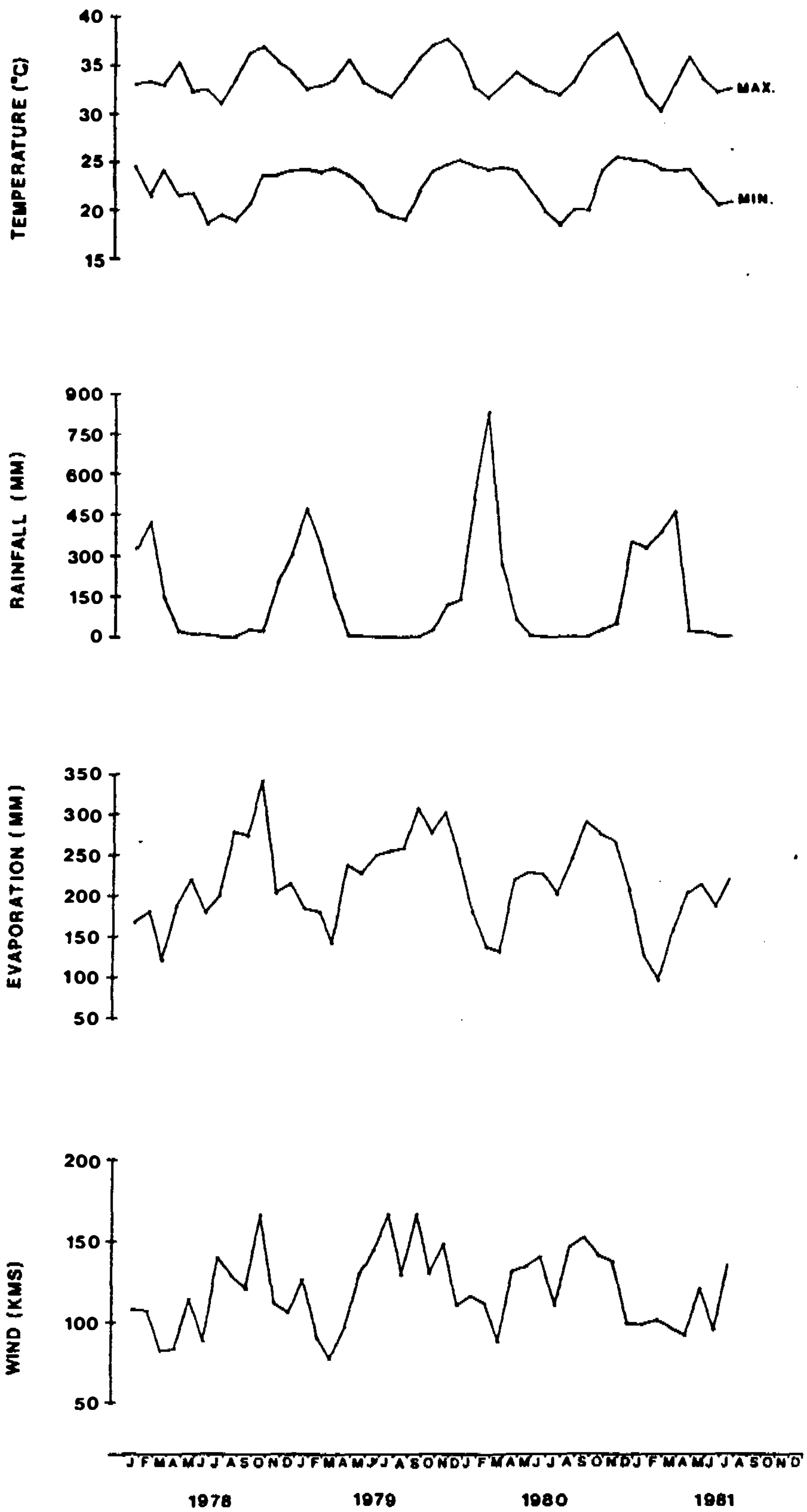


FIG 5. Meteorological data for Jabiru over the study period: mean monthly maximum and minimum atmospheric termperatures; monthly totals of rainfall; monthly totals of evaporation and monthly wind anemometer readings. (courtesy Ranger Uranium Mines).

(the 'Dry'), and a considerably reduced seasonal range of mean monthly temperatures compared with temperate climes (Riper 1971). Thus at Jabiru, both mean monthly maximum and mean monthly minimum temperatures have a seasonal amplitude of only about 7°C (Fig. 5). The lowest mean daily temperatures occur in the middle of the Dry, during the months May-August (Fig. 5). The difference between mean maximum and mean minimum of air temperature is greatest at this time (16°C), and least (8°C) during the Wet.

The pronounced climatic seasonality experienced in this low latitude zone is caused by a reversal of wind direction each Dry and Wet (Fig. 5,6), the wind during the Dry blowing from the arid Australian hinterland, being dry and stable, whereas the Wet winds from the sea are humid, unstable and conducive to precipitation. These humid winds come first from the north during a period (October-November) known locally as the "Build-up". Despite high humidity, rainfall is sparse until the winds veer north-westerly at the onset of the Wet. Thus, in apparent contrast to many other tropical climes, where this seasonal wind reversal, or monsoon, is a sudden event, here the wind shift is gradual (Fig. 6).

Despite the slight increase in daylength following the winter solstice (Fig. 7), the daily hours of sunlight decrease considerably (Fig. 7) as the winds tend northerly and introduce cloud to the clear skies characteristic of the cooler months. Despite this, the net solar radiation impinging on the ground at first increases (Fig. 7) with the increasing angle of the midday sun. However, by the Dry/Wet interchange the density and duration of cloud cover is sufficient to limit severely both sunlight hours and net radiation (Fig. 7) and air temperatures drop significantly (Fig. 5). Thus the highest yearly air temperatures are recorded prior to, not at, the summer solstice.

Not surprisingly, pan evaporation is maximal late in the Dry (Fig. 5) at the time of highest temperatures and maximum net incoming radiation. During this study, annual pan evaporation at the Jabiru meteorological station exceeded annual precipitation by 800-1200mm.

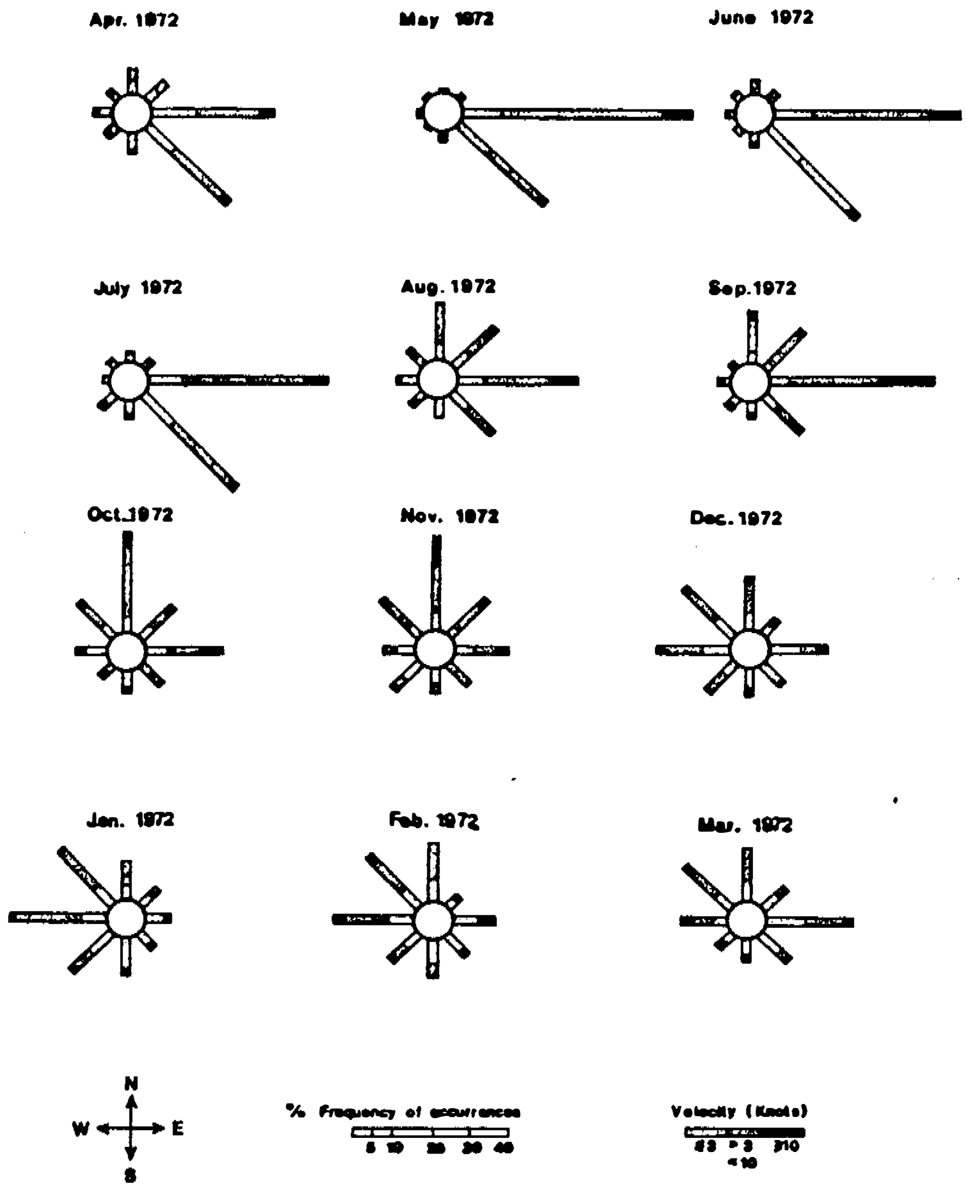


FIG 6. Wind roses for Jabiru, December 1971 to November 1972. The months have been rearranged to assist seasonal interpretation. It is assumed in the text that the year is typical. (Redrawn from Noranda Australia Ltd., 1978).

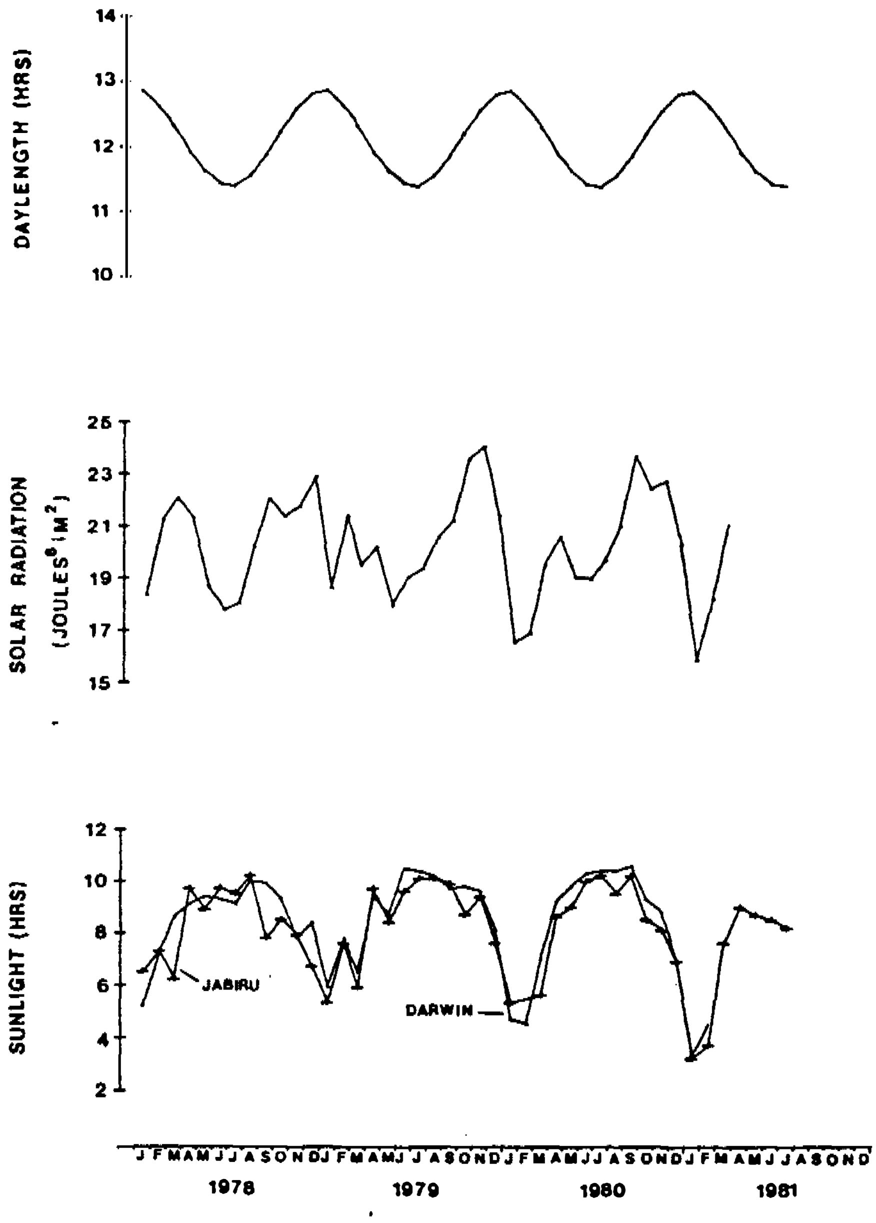


FIG 7. Meteorological data for Jabiru (and/or Darwin) over the study period: day length (courtesy Dr Hirst, Bureau of Meteorology, Melbourne), monthly totals of net solar radiation at Darwin Airport (courtesy Bureau of Meteorology, Melbourne), and mean monthly hours of sunlight at Darwin Airport (courtesy Bureau of Meteorology, Melbourne) and Jabiru (courtesy Ranger Uranium Mines).

During the Wet, five major weather-producing systems operate (Christian and Aldrick 1977). Widespread rain results from equatorial or monsoonal troughs and organised convection. Intensive rain with restricted distribution is produced by tropical cyclones, and localized thunderstorms and showers result from local convection systems. The climatic variables of the Region are summarised in Figure 8, showing the extent to which "seasons" can be recognized.

2.3 Hydrology

Any investigation into the limnological behaviour of standing waterbodies requires full cognizance of their hydrological regime. Since precipitation is distinctly seasonal, a comparable seasonality of flow occurs in the many water courses of the area. During the Wet, flow fluctuates widely in the rivers and their tributaries, with floodpeaks following heavy rain. In the Dry, except for upstream areas fed by perennial springs and seepages, and lower sections of main rivers and their estuaries which retain water throughout the year, flow ceases and lowland creek systems dry up. Then, the only water remaining is in plateau rock pools and the billabongs and swamps of lowland and floodplain regions.

The most dramatic hydrological event of the year is the initial influx of floodwaters at the start of the Wet. Pancontinental Mining Ltd. (1981) carried out an intensive sampling program on the effects of these inflows on channel and floodplain billabongs of Magela Creek. It showed that the cool inflows from the creek intruded beneath 'old' water in the channel billabongs, with the mixing induced by the turbulent inflow gradually extending downstream along the billabong. Thus, the first inflows appear not to push the old water downstream on a wide front. Rather, vertical mixing dilutes the old water, and as throughflow is established, the diluted water is displaced. The first flood enters the floodplain billabongs by a different mechanism. There, the absorption of heat by the shallow sheet of floodwater, as it moves across the floodplain, raises its temperature above that of the billabongs. The flow then slides across the surface of the billabong, and significant mixing only occurs when filling is complete and throughflow is established.

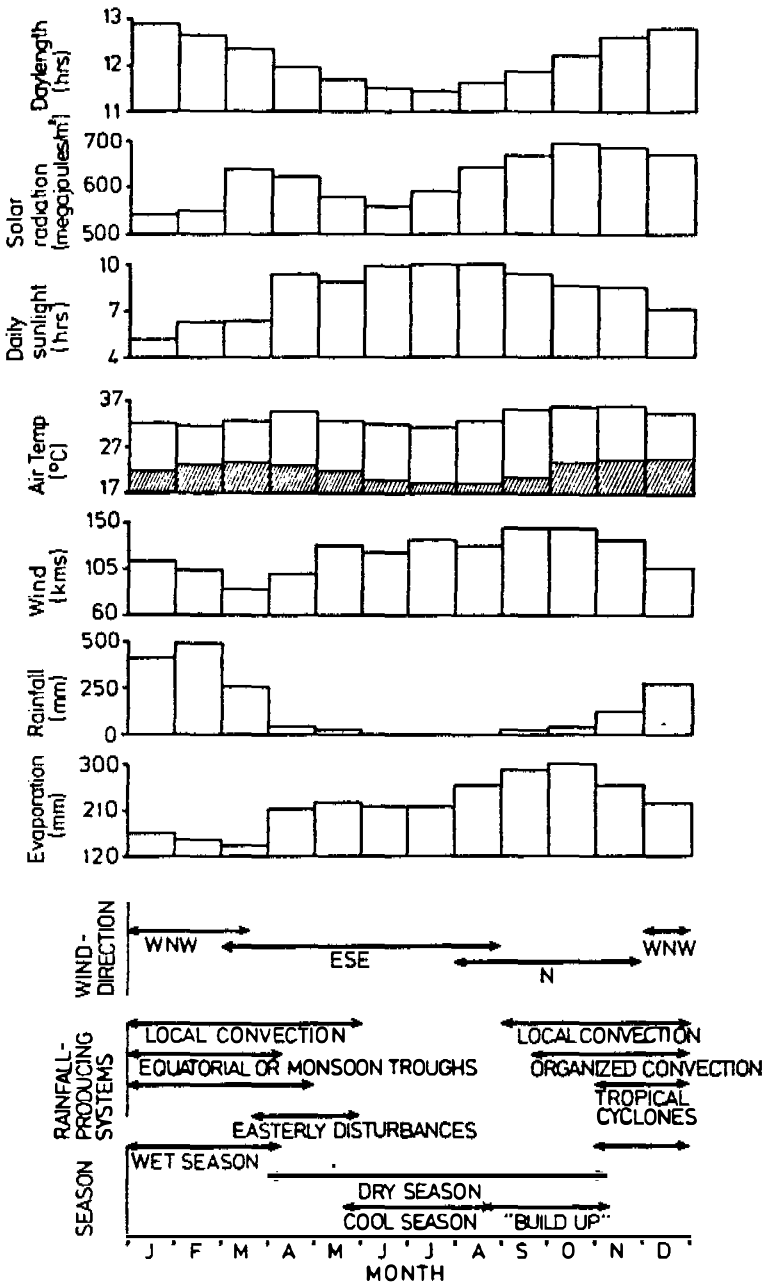


FIG 8. Synopsis of seasonal meteorological attributes of the Alligator Rivers Region (data from various sources).

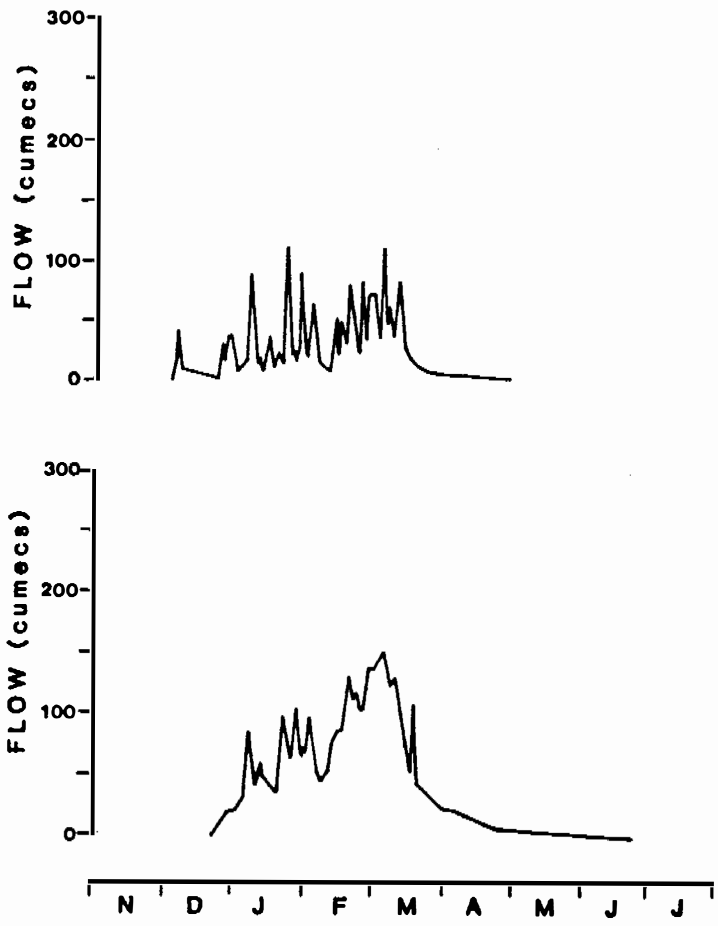


FIG 9. Flow in the Magela Creek past Jabiru (Gauging Station 821009) and Jabiluka billabong (GS821017) during the 1978/79 wet. (courtesy water Division of the Northern Territory Department of Transport and Works).

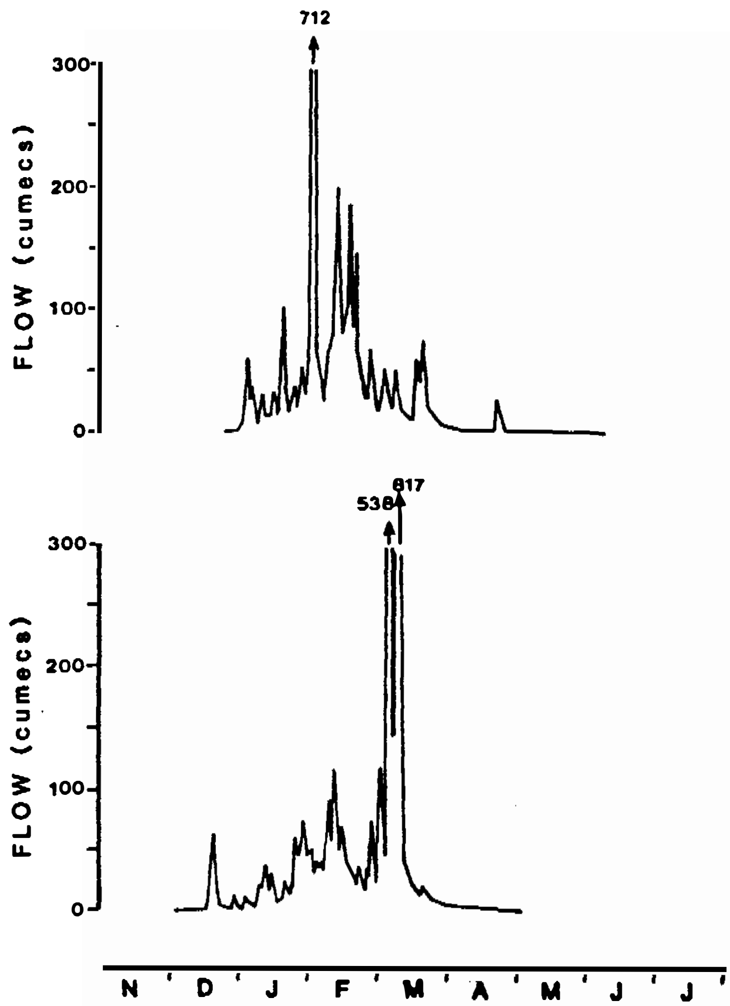


FIG 10. Flow in the Magela Creek past Jabiru (GS821009) in the 1979/80 wet (A) and the 1980/81 wet (B). (courtesy water Division of the Northern Territory Department of Transport and Works).

After the first flush of water down the creeks, Wet season flow is characterized by a base flow upon which floodpeaks are superimposed. There is considerable variability in this flow pattern from year to year (Figs. 9,10). According to Young (1980) erratic flow fluctuations at upstream gauging stations are smoothed progressively downstream until, on the floodplains, the effects of rainstorms on the plateau are hardly detectable. However, this is not always so. During the 1977/78 Wet major flow increases at upstream gauging station GS 821009 were readily and immediately detectable at the floodplain gauging station GS 821017 (Fig. 2 in Hart and McGregor 1980). This appears to be a regular event (Fig. 9).

Cessation of flow in the lowland creeks marks the end of any significant surface water input to the billabongs until the following Wet, though limited influx of groundwater may occur see Chapter 4. Water levels then drop through the Dry as more than 2 metres of water evaporates (Fig. 8). The distinctive character of the hydrological cycle then, is the marked seasonality. In the Wet the billabongs become part of a vast sheet of moving floodwater. In the Dry, they remain as isolated stagnant pockets, undergoing progressive change as intense evaporation concentrates their waters.

3.0 THE BILLABONGS

The locations of the billabongs studied are indicated in Figs. 2-4. Their major features are given in Table 2. All are small bodies of water, the largest (Island billabong) being only 2 km long and 200 m across at its widest point. Most are a fraction of the size of Island. Surface area and volume diminish during the Dry.

3.1 Channel billabong

These billabongs are located within the actual flow-channels and are virtually depressions in the stream bed. They are comparatively deep and characteristically have steep well-vegetated banks supporting mainly Pandanus sp. with some freshwater mangrove (Barringtonia sp.). The depth of these billabongs is an indication of the current velocity experienced during the Wet, so the more languid the stream, the shallower

TABLE 2: Classification and characteristics of Alligator Rivers Region billabongs.

BILLABONG CLASSIFICATION	CATCHMENT	BILLABONG NAME	DEPTH RANGE (m)	SEDIMENTS
Channel	Magela	Mudginberri	5.5-9	Sand
		Buffalo	3-5	Sand & silt
	Nourlangie	Noarlanga	6.9	Sand
	Coopers	Nimbawah	2.5-4	Unknown
"/Escarpment rockpool	Magela	Bowerbird	5-8	Rock & sand
"/Backflow	Baroalba/ Magela	Goanna	0-3	Silt & clay
"/Floodplain	Magela	Island	3.5-6.5	Sand with silt & clay
	Nourlangie	Kulukuluku[1]	6.5-10	Fine grey clay
Backflow	Magela	Georgetown	0-3	Fine silt & clay + localised sand
		Coonjimba	0-2	Fine silt & clay
		Gulungul	0-3	Fine silt & clay
		Corndorl	0-2.5	Fine silt & clay
	Nourlangie	Umbungbung	0-2.5	Fine silt & clay
Floodplain	Magela	Ja Ja	2.8-5.5	Silt & clay
		Mine Valley	0.2-2.5	Silt & clay
		Leichhardt[1]	3.5-6	3
		Jabiluka	3.5-6	Silt & clay
		Nankeen	3.5-6	Silt & clay
	Nourlangie	Woolwonga[1]	4-6	Unknown
		Jingalla	2-4	Unknown
	East Alligator	Red Lily[2]	2-4	Unknown

[1] Kulukuluku, Leichhardt and Woolonga all have floating meadows along their banks. In Kulukuluku, these meadows are comprised of *Hymenachne* and nut grass (local name, genus unknown) and in Leichhardt of *Hymenachne* and *Leersia*. Their composition in Woolwonga is unknown.

[2] Red Lily derives its name from the red lotus lily (*Nelumbo nucifera*) which may cover 80% of the billabong by the late Dry.

[3] In the large northern basin, a highly organic coarse sediment overlies a fine, grey compacted clay. In the smaller southern basin, sediments are as in the other floodplain billabongs (Thomas and Hart, 1981).

the billabong occurring within it. Generally, channel billabongs have sandy sediments, but in streams not draining sandstone (e.g. Goanna) clay sediments may occur.

It appears that channel billabongs with sandy sediments receive seepage input from aquifers for some time after surface flows have ceased. Even Goanna, with its clay sediments, may receive seepage from an elevated water table (Davy and Conway 1974). Because of their depth, steep banks, and the coarse nature of their sediments, they do not exhibit the marked increases in turbidity during the Dry, brought about by wind-induced resuspension of sediments, which is shown by most other billabongs. Goanna, with its clay sediments, does become turbid.

A number of billabongs are classified in Table 2 as hybrids. Whilst predominately displaying characteristics of channel billabongs they show some affinity with other categories. Thus, Goanna occasionally receives backflowing water from Gulungul Creek, Kulukuluku and Island are both located at the junctions of floodplain and the stream channels, and Bowerbird is an elongated rockpool in the escarpment through which water flows all year around.

3.2 Backflow billabongs

These billabongs are shallow, with shelving banks, and have clay and/or silt sediments. Located where small feeder streams join a larger creek, they are separated from the latter by a low sandy levee deposited by the main creek. The term 'backflow' refers to a hydrological event during the Wet when water from the main creek backs up in the tributary by overtopping the levee bank. The billabong is initially filled by this backflow at the commencement of the Wet, with the first floods from the large upstream catchment of the main creek. This happens considerably earlier than significant flows in its own feeder stream. Once the billabong is at high water level, the direction of flow over the levee bank is determined by the relative levels in the billabong and the main creek. At this time extensive low-lying areas of paperbark (Melaleuca leucadendron) forest surrounding the backflow billabongs may be inundated, whilst dense macrophyte beds colonise the shallow open water. Subsequent to the Wet/Dry interchange, the waters begin to contract through intense evaporation, and the macrophyte beds senesce. With this reduction of both macrophyte cover and water depth, wind-induced turbulence can penetrate to the billabong floor and resuspend the fine sediments, so that turbidities rise to very high levels. By the end of a long Dry, backflow billabongs may dry up completely.

3.3 Floodplain billabongs

This is more a category of convenience than the previous two, for several types of billabong occur on the floodplains (Table 1). Of the floodplain billabongs studied (Table 2) one (Mine Valley) is merely a shallow depression in which water level is maintained throughout the drier months by seepage input (Brown 1979), whilst the others are remnants of deep channels on the floodplains. Their banks are steep in some places, shelving in others, depending on flow patterns in the Wet. Sediments are composed generally of coarse silt and various clays, with varying amounts of organic material. The extent of fringing vegetation, mainly Barringtonia and Pandanus, is variable, depending on the location of the billabong on the floodplain, and which floodplain. However as a rule, the floodplain billabongs are the most exposed of all, and during the Dry, extensive resuspension of their sediments may occur, raising turbidities to very high levels. During the Wet, the floodplain billabongs lose their identity to a large extent, as water spreads over the floodplain and covers them.

4.0 PERTURBATION OF THE AQUATIC ENVIRONMENT

The Ranger Uranium Environmental Inquiry (Fox et. al. 1977) recognised that, in recommending that mining should proceed, some environmental perturbation was inevitable, with the aquatic ecosystem likely to be the most adversely affected. The source of such impacts would be the mining and milling operations themselves, and the regional township (Jabiru).

Aside from the more obvious physical effects of mining and milling operations, these activities have, via the release of heavy metal and radionucleide (radium) contaminated water, the potential to influence vast areas of downstream wetlands subject to seasonal flooding. Elucidation of dispersal characteristics and biological implications of intentional or accidental release of such water-borne contaminants is clearly a major priority. Release of water high in suspended solids from retention ponds into natural waterways could also have deleterious impact; an increase in the annual sediment load could influence aquatic dynamics by reducing water clarity, as well as acting as transport medium for some contaminants (Hart 1980).

Two groups of contaminants will enter the waterways from the regional township. Effluent from oxidation lagoons treating domestic sewage, and urban runoff will add nitrogen and phosphorus, perhaps initiating eutrophication of downstream environments. The other contaminant group, pesticides used for protecting fence posts and dwellings, have already been detected in nearby streams, perhaps inducing the abnormally high incidence of malformation in certain frog species in these habitats (Hart 1980).

Assessment of the potential impacts of these contaminants must be made in the context of an advanced state of understanding of current environmental conditions and dynamics (Fox et. al. 1977; Harris 1980). The limnological scheme presented in these reports contributes significantly to such an understanding, additional to the provision of specific monitoring advice for some contaminants.

5.0 MATERIALS AND METHODS

5.1 Sample sites

In all billabongs, one sampling site was established, marked by a permanent buoy located at, or near, the deepest point. In two billabongs, Leichhardt and Island, three additional buoys were installed (Figs. 11,12) to check whether events at the primary site were representative of the whole billabong. Additionally, in May 1979, sampling was carried out along a transverse transect across Leichhardt (Fig. 11) for the same purpose.

5.2 Methodology

Water temperatures were measured initially with a thermistor. However, the instrument, which was perfectly suitable for temperate studies, proved to be inadequate for the Northern Territory. Its calibration drifted slightly as its

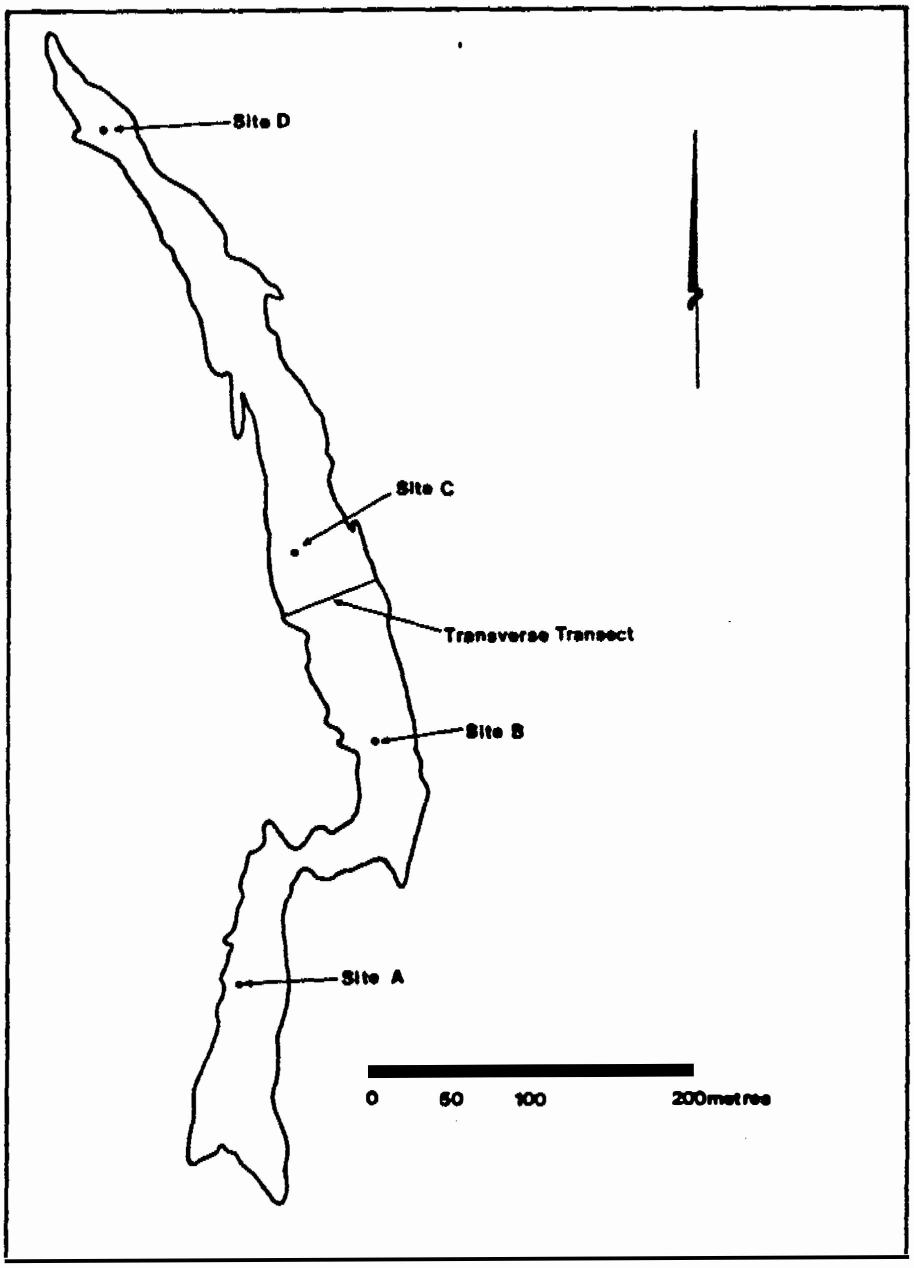


FIG 11. Map of Leichhardt billabong showing the position of the transverse transect, and sites A-D for logitudinal transect studies.

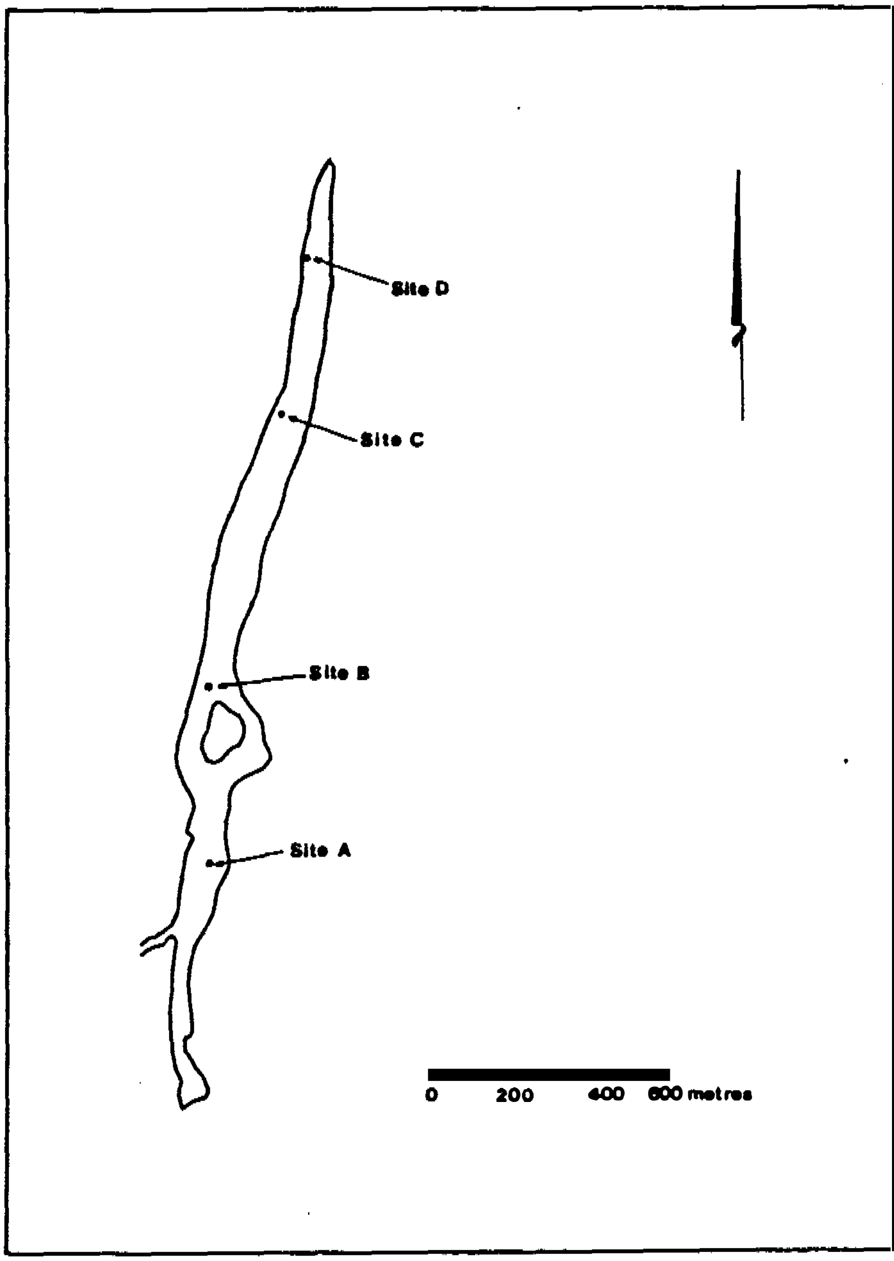


FIG 12. Map of Island billabong showing the position of sites A-D for longitudinal transect studies.

components experienced a considerable temperature variation between calibration in an air-conditioned laboratory and several hours under hot, field conditions. For any one set of measurements, which require only a few minutes, the magnitude of temperature change detected between, say, top and bottom waters, would be correct, but not necessarily accurate in absolute terms. Since the recognition of thermal stratification or its absence in tropical waterbodies rests on detection of very small temperature changes (0.1^{o}C), the thermistor was abandoned in the 1979/80 Wet in favour of a submersible pump (Rule 400) which pumped water from selected depths past an accurate mercury thermometer in a flow through cell.

Dissolved oxygen concentrations were measured by the Alsterberg azide modification of the Winkler technique (APHA 1975). Initially the samples were taken with a Van Dorn sampler, later with the submersible pump. During 1980 some measurements were made reliably with a Delta Dissolved Oxygen Meter calibrated each day in the field against the Winkler method.

5.3 Sampling rationale

Most billabongs were visited once each month, although a higher sampling frequency was thought desirable. However the frequency was largely determined by both the large number of billabongs in the study and their ease of access, and during the Wet upon the availability of helicopter and airboat. For some billabongs, intensive sampling was carried out during the Dry/Wet interchange, from the time when the first floodwaters entered the billabong until complete flushing had occurred. At each visit to a billabong, temperature and oxygen profiles were determined in the early morning at the sampling buoy. For the more intensively sampled billabongs, this was repeated in the late afternoon.

The rationale behind early morning sampling (06.00-08.30) was that any thermal gradient detected must have persisted overnight, indicating lasting hydraulic stratification. Later in the day a thermal gradient could have resulted from that day's heating. Furthermore, photosynthetic oxygen evolution would scarcely have commenced. Therefore, early morning sampling should coincide with minimum temperatures and minimum oxygen concentrations. The desirability of dawn sampling in tropical limnology has been widely recognised, for a variety of reasons (e.g. Beadle 1974; Schmidt 1973; Seaman et al. 1978). The afternoon sampling (15.00-16.00) was more of a compromise. Though solar heating had ended by this time, oxygen production would continue until 17.00-18.00 (Walker and Tyler 1979). Therefore, our sampling strategy is likely, first, to give a good estimate of the daily range of temperature, second to give a good indication of minimum dissolved oxygen, but an underestimate of maximum dissolved oxygen, and finally, to permit proper interpretation of thermal phenomena. The sampling strategies for each of the study billabongs are shown in Table 3.

6.0 RESULTS - SURFACE WATER TEMPERATURES IN THE BILLABONGS

6.1 Diurnal variation

The diurnal range of surface water temperatures in the Dry could be quite considerable. Table 4 shows the variation in surface water temperature recorded for a number of billabongs over a 24 hour period, and indicates that the early morning and late afternoon sampling rationale adopted did give a reasonable estimate of the daily range of temperature. Depending on the length of the solar day, and the weather conditions on a particular day, heating may or may not have commenced when the morning samples were taken, and may or may not have ceased by the afternoon sampling. Within this constraint, Table 5 shows the range of daily variations, for some surface waters during 1978-81. A seasonal pattern of diurnal variation was difficult to discern. However, some general comments may be made.

First, the most extensive diurnal temperature fluxes occurred in the very shallow, turbid billabongs (backflow billabongs, Mine Valley) during the middle or late Dry. Deeper billabongs of similar turbidity (Jabiluka, Ja Ja, Nankeen) also experienced considerable variations. Hart and McGregor (1980) also noted that largest day time temperature rises occurred in the most turbid billabongs. Occasionally, large rises occurred in relatively clear, protected billabongs, such as Noarlanga on 22nd August 1979, when the daytime increase was 5.4^{o}C.

TABLE 3: Sampling rationale for Alligator Rivers billabongs

BILLABONG	PERIOD STUDIED	NATURE OF SAMPLING
Mudginberri	1978	1a(Dry); 1d(Wet/Dry interchange;Wet);2
	1979	1c
	1980-early 1981	1b(Dry); 1d(Wet/Dry interchange;Wet)
Buffalo	1978-early 1979	1a
Noarlanga	1979	1a
	1980-early 1981	1b
Nimbawah	late 1980-early 1981	1b
Bowerbird	1978-early 1981	1a,c
Goanna	1978	1a
	1979	1c
	1980-early 1981	1b
Island	1978-1979	1a
	1980-mid 1981	1a,3
Kulukuluku	late 1979	1a
	mid 1980-late 1981	1b,4
Georgetown	1978	1a(Dry); 1d(Wet/Dry interchange)
	1979	1c
	1980-early 1981	1b(Dry)
Coonjimba	1978	1a,2
Gulungul	1978	1a
	1979	1a
	1980-mid 1981	1a(Dry); 1d(Wet/Dry interchange;Wet)
Corndorl	1978	1a
Umbungbung	1979	1a
	1980-early 1981	1b
Ja Ja	1978	1a
	1979	1c
	1980-early 1981	1b(Wet and early Dry)
Mine Valley	1979	1a
	1980-early 1981	1b
Leichhardt	1978	1a
	1979	1a;5
	1980-early 1981	1a,3
Jabiluka	1978	1a,2
	1979	1a
	1980	1a(Dry);1d(Wet/Dry interchange);2
Nankeen	1978	1a
	1979	1c
	1980-early 1981	1b
Woolwonga	1980-early 1981	1c
Jingalla	1979-early 1980	1a,1b
	late 1980-early 1981	1b
Red Lily	late 1979-early 1981	1a,1b

KEY

1a. Monthly ^{o}C and D.O. profiles at one site (morning and late afternoon).

b. Monthly ^{o}C and D.O. profiles at one site (morning)

c. Infrequent (<monthly) ^{o}C and D.O. profiles at one site.

d. Frequent (>monthly) ^{o}C and D.O. profiles at one site (morning).

2. Some diurnal ^{o}C and D.O. profiling in early Dry.

3. Occasional studies of ^{o}C and D.O. at four sites over several days in Dry.

4. Ten consecutive day sampling in August 1981 of ^{o}C and D.O. profiles at one site.

5. Occasional transverse transects across billabong of ^{o}C and D.O. profiles during early Dry.

TABLE 4: Diurnal variation of temperature (°C) in surface waters of four Magela Creek billabongs

BILLABONG	DATE	TIME	°C	BILLABONG	DATE	TIME	°C
Coonjimba	25-26/4/78	0915	26.4	Ja Ja	14-15/4/78	0900	28.7
		1114	27.9			1115	29.4
		1315	28.7			1315	30.4
		1530	30.0			1515	29.6
		1715	29.0			1715	29.4
		1930	28.7			1930	29.3
		2200	27.6			2115	29.0
		0000	27.0			2315	28.7
		0420	25.7			0115	28.6
		0745	25.7			0715	28.6
Mudginberri	28-29/4/78	0730	27.4	Jabiluka	13-14/5/81	0915	27.4
		1105	28.3			1120	28.2
		1330	29.0			1330	28.5
		1600	30.1			1530	28.9
		1830	29.6			1720	28.8
		2200	28.5			2225	28.1
		0445	27.4			0220	27.7
		0730	27.2			0625	27.5
						0815	27.5

TABLE 5: Diurnal range (max. - min.) of temperature (°C) in surface waters of selected billabongs.

BILLABONG	YEAR	JAN	FEB	MAR	APR	MAY	JUN	JULY	AUG	SEPT	OCT	NOV	DEC
Bowerbird	1978						1.5	1.7	1.6		1.2	2.3	
	1979							1.3					
	1980					1.4		1.9		1.7		1.6	
Georgetown	1978	2.5[1]				2.5	3.7	3.3	3.2	3.0	5.4	3.7	2.6
Gulungul	1978					1.8	4.4	2.2	1.9	7.4	6.1	4.9	
	1979	-0.9				2.8	2.7	6.2	5.4		7.5		
	1980			2.1	3.5	1.4	3.2			4.9	6.2		
	1981		1.9	2.8	3.6	2.6							
Corndorl	1978	2.7[1]				1.7	3.2	4.2	3.7	6.5	4.7	3.8	2.3
Coonjimba	1978	3.6[1]			2.3		3.2	6.1	4.6	6.2	9.0	8.6	5.0
Mudginberri	1978	3.1[1]			2.5		1.1	3.1	1.5	3.3	1.5	3.0	
Buffalo	1978					1.3	3.1	2.2	1.5	3.0	1.8	2.2	-0.3
Island	1978				2.2		0.4	3.0	1.3	2.9	0.5	2.8	
	1979	4.3				2.0		2.0	3.2		3.0	1.9	
	1980				1.0	2.1		2.9	1.8		2.5		3.1
	1981		2.4	2.0	2.4	2.6							
Mine Valley	1979					0.3	1.9	3.4	6.0	8.8			
	1980				0.9	2.6	5.3						
Leichhardt	1978							4.3	1.1	0.9	1.5	2.3	-0.7
	1979					2.1	2.8	5.0	4.1		3.1	2.7	
	1980				1.2	1.7	3.7	2.1	2.3	1.9	2.6	2.0	3.3
	1981			2.5	2.0	1.5							
Jabiluka	1978					1.3	2.7	2.5	1.8	2.4	2.1	-0.1	
	1979	-0.2				2.4	3.8	4.8	6.4		2.2	4.0	
	1980				0.9	0.9	1.3	1.6	3.8	4.8	1.6	1.1	
	1981			2.1	4.4	1.1							
Nankeen	1978					0.5	0.6	1.2	1.2	0.8		3.8	
Noarlanga	1979					2.4	2.3	1.7	5.5		2.3		2.4
Umbungbung	1979					4.9	4.2	7.2					
Red Lily	1980			1.0	3.2	1.2			2.5		0.9		4.1
	1981	2.7		3.5									

[1] Values for January, 1979.

TABLE 6: Diurnal variation in temperature at selected depths in Coonjimba in April 1978.

DEPTH (m)	TIME 0915	1115	1315	1530	1715	1930	2200	0000	0420	0745
0	26.4	27.9	28.7	30.0	29.0	28.7	27.6	27.0	25.7	25.7
1	26.0	26.2	26.4	26.4	26.4	26.4	26.4	26.5	25.7	25.7
2	25.8	25.8	25.8	25.8	25.8	25.8	25.8	25.8	25.7	25.7

Despite the apparent effect of turbidity on diurnal temperature variation and despite the fact that turbidity increased in all billabongs towards the end of the Dry (Walker and Tyler 1985a), a clear pattern of increasing diurnal flux at this time could not be demonstrated, probably for two reasons. Firstly, though at that time turbidity was rapidly increasing, the amplitude of daily air temperature variation was decreasing (Fig 2), the two opposing factors cancelling one another. Secondly, the meteorological conditions on any sampling day had a profound influence on daily variation.

The prevailing hydrological regime may also have influenced diurnal temperature flux. During the Wet the temperature of influent water could have a marked influence on billabong temperatures, especially when retention times were low. Thus, cool inflows could produce an inverse daytime temperature change (e.g. Gulungul on 11.1.79 where a drop of 0.9^{o}C was recorded between 09.15 and 16.45).

Aquatic macrophytes could also have influenced water temperatures, by first, limiting water movement and, second, submerged plants near the surface absorbing and, presumably, reradiating heat. This could explain considerably higher temperatures in dense stands than in nearby open water. Thus, on the afternoon of 10.5.79, surface temperature in the clear, comparatively deep water in the centre of Gulungul billabong was 31.4^{o}C, whereas in the littoral zone (0.5m deep), choked with Najas tenuifolia and Utricularia sp., surface temperature had risen to 37.3^{o}C, a difference of 5.9^{o}C.

6.2 Seasonal range

In the temperate zones it is commonly found that epilimnetic temperatures of large, deep lakes follow the seasonal trend of mean air temperatures. In shallow waterbodies of tropical regions however, such a relationship is difficult to demonstrate unless the large diurnal temperature variation is taken into account. An obvious strategy would be to sample each billabong just before sunrise. In this way, the seasonal daily minima of temperature would be recorded. This was seldom practicable but since sampling was normally within an hour of the onset of the day's solar heating, temperatures at a depth of 2 m were unlikely to have changed from the overnight minimum. This supposition is entirely vindicated by the results of diurnal measurements in Coonjimba billabong (Table 6).

Figure 13 shows that these daily minimum temperatures lie approximately midway between the monthly mean maximum and monthly mean minimum air temperatures. In general, the air and water temperature curves are bimodal with the minimum occurring in the cool period, the middle Dry. It is possible to recognise a 'cooling phase', when water temperatures fall, from the beginning of the Wet until the mid-Dry, followed by a 'heating phase' for the remainder of the Dry.

7.0 RESULTS - SURFACE OXYGEN CONCENTRATIONS IN THE BILLABONGS

7.1 Diurnal variations

The concentration of oxygen in surface waters is dependent upon the rate of consumption relative to production by photosynthesis, and upon exchange at the air/water interface. In practice, diffusion of oxygen from air to water or the reverse is slow, unless assisted by surface agitation which increases the diffusive area. Consequently the consumption/production ratio assumes major significance in surface waters of stagnant billabongs and the distribution of oxygen throughout the water column is regulated by mixing, stratification phenomena, and the distribution of algae and aquatic macrophytes.

Diurnal studies of four billabongs (Table 7) revealed that oxygen concentrations scarcely change for some time after their dawn minimum, but that the afternoon sampling would often underestimate the day's oxygen maximum. Not only does photosynthesis continue as long as there is daylight but the lowered temperatures of late afternoon may actually favour it (cf. Ganf and Horne 1975). Further, oxygen produced by aquatic plants may not be released immediately, causing a lag period in oxygen evolution (Goldman 1968). For these reasons, significant oxygen production often took place after the normal afternoon sampling. Table 7 indicates that this could be as much as 10-20% of saturation values. Even so, a day's photosynthesis and gas

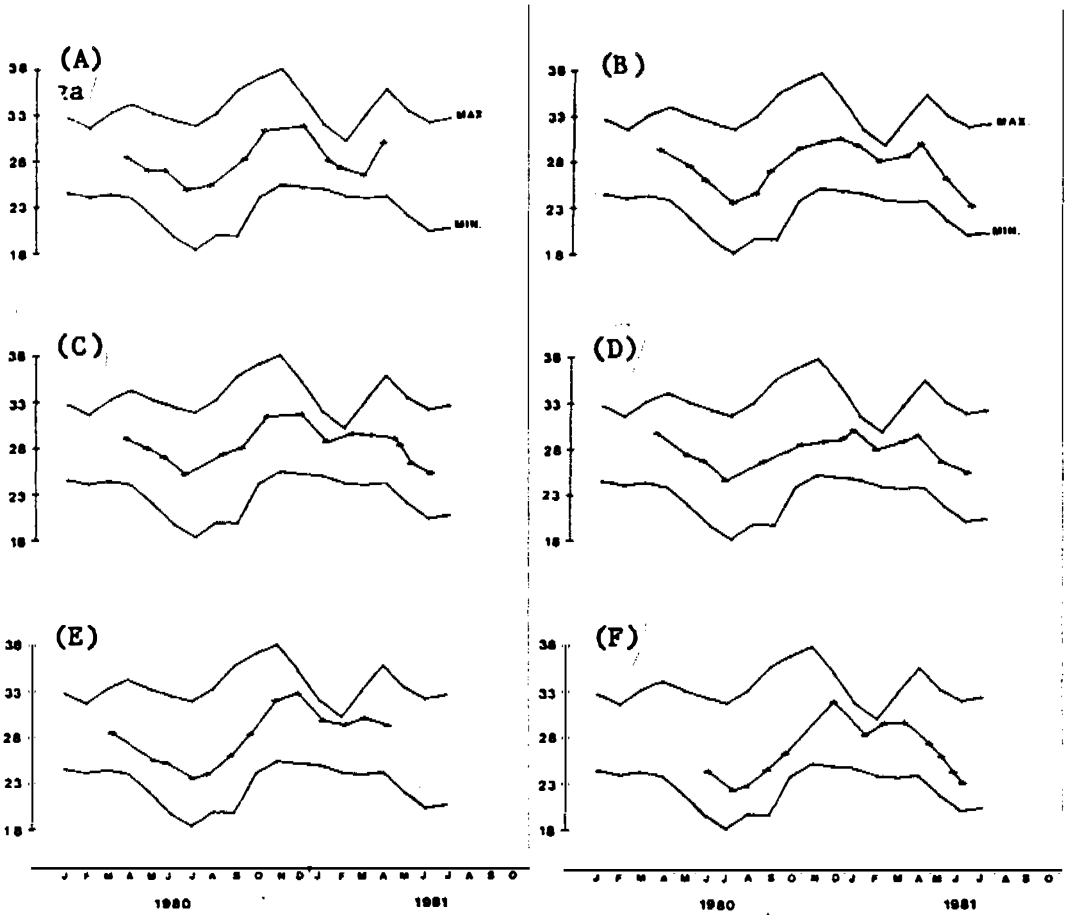


FIG 13. Seasonal variation in mean monthly maxima and mean monthly minima of air temperatures (°C) at Jabiru, and spot measurements of water temperatures at 2m depth in Mudginberri (A), Leichhardt (B), Island (C), Jabiluka (D), Noarlanga (E) and Kulukuluku (F) billabongs.

TABLE 7: Diurnal variation of dissolved oxygen (% saturation) in surface waters of four Magela Creek billabongs.

BILLABONG	DATE	TIME	% SAT.	BILLABONG	DATE	TIME	% SAT.
Coonjimba	25-26/4/78	0915	23	Ja Ja	14-15/4/78	0900	11
		1115	28			1115	16
		1315	41			1315	21
		1530	57			1515	25
		1715	75			1715	29
		1930	77			1930	32
		2200	59			2115	35
		0000	56			2315	27
		0430	35			0115	15
		0745	18			0715	11
Mudginberri	28-29/4/78	0730	72	Jabiluka	13-14/5/81	0915	55
		1105	76			1120	62
		1330	86			1330	63
		1600	90			1530	65
		1830	87			1720	68
		2200	79			2225	65
		0445	76			0220	61
		0730	70			0625	63
						0815	61

TABLE 8: Diurnal range (max. - min.) of dissolved oxygen (% saturation) in surface waters of selected billabongs.

BILLABONG	YEAR	JAN	FEB	MAR	APR	MAY	JUN	JULY	AUG	SEP	OCT	NOV	DEC
Bowerbird	1978						5	12	12		5	9	
	1979							10					
	1980					11		8		5		19	
Georgetown	1978					16	20	11	14	9	15	17	18
Gulungul	1978					23	28	54	22	41	15	-4	
	1979	32				46	24	48	42				
	1980			19	22	17	40		40		45		
	1981		13	9	26	25							
Corndorl	1978	14[1]				12	22	45	20	9	43	10	-5
Coonjimba	1978	3[1]			53		59	47	41	49	48	67	30
Mudginberri	1978	6[1]			18		16	15	28	17	16	16	
	1980		5[2]				34		5				
Buffalo	1978					18	30	23	24	29	28	35	3
Island	1978				64		21	39	32	36	13	35	31
	1979	22				33	30	20	43		23	45	
	1980			0[3]	19	21		39	23		31		21
	1981		5	15	62	50							
Mine Valley	1979					64	35	33	41		3		
	1980			24[3]	20	53	82						
Leichhardt	1978							36	64	24	20	62	56
	1979					30	24	49	92	52	48	33	
	1980			18[3]	22	20	22	61	22	58	43	26	33
	1981			10	32	22							
Jabiluka	1978					1	18	22	17	21	21	1	
	1979	0				23	21	27	34		3	20	
	1980			16[3]	8	7	19	24	38		16	2	
	1981			8	21	10							
Nankeen	1978					8		5	13	13	11	22	
Noarlanga	1979					12	0.8	17	18		21		
Umbungbung	1979					82	85	73					
Red Lily	1980			23	34	26			32		46		
	1981	69		40									

[1]Values for January, 1979

[2]Values for February, 1981

[3]Approximate values only because of inaccurate temperature measurement.

exchange with the atmosphere was generally insufficient to produce oxygen saturation.

Further data on diurnal fluctuations of oxygen are given in Table 8. While there was no clear seasonal or geographical pattern a number of events warrant mention. First, there was frequently a mid-Dry maximum of diurnal variation, as in Jabiluka, Island and Gulungul. This appeared to coincide with near-maximum phytoplankton chlorophyll levels (see chlorophyll plots in Walker & Tyler 1985a). Variations on this general theme were common. Island, in addition to its mid-Dry peak, could experience another at the Wet/Dry interchange. Leichhardt showed a capricious pattern no doubt related to the equally capricious fluctuation of phytoplankton populations (see Kessel and Tyler, 1985).

In some billabongs (Bowerbird, Georgetown, Nankeen, Noarlanga) the magnitude of diurnal oxygen variation scarcely changed throughout the Dry and moreover, it was small (20% - Table 8). In the case of all except Nankeen, this can be explained by lack of macrophytes and very low chlorophyll levels. In contrast, shallow Coonjimba displayed little change in diurnal oxygen flux throughout the Dry, but, consistent with its persistent macrophyte population, the magnitude of these changes was great. It is not clear why Nankeen did not experience the seasonal fluctuation in diurnal oxygen of its neighbour Jabiluka.

During the flow periods of the Wet, diurnal flux in most billabongs was low but the few which rarely experienced strong flows and which retained dense macrophyte stands could exhibit prodigious diurnal fluxes well into the Wet (e.g. Red Lily 29/1/81).

7.2 Seasonal range

As in the examination of the seasonal face of surface water temperatures, special significance is attached to the early morning sampling for oxygen, for several reasons. First diurnal variations confuse interpretation of seasonal trends. Second, early morning is the time for the daily minimum of oxygen, the daily maximum of ecological stress for aerobic organisms, and third, oxygen concentrations scarcely change for some time after dawn (see Table 7 in section 7.1).

In contrast to many temperate lakes where epilimnetic waters remain close to oxygen saturation throughout the night, most billabongs at dawn were considerably undersaturated, often more than 50% or so (Figs. 14,15). At tropical temperatures, absolute dissolved oxygen values at 50% saturation are no more than 3.5-4 mgl^{-1}, considerably less than the 9-12.5 mgl^{-1} common in the saturated epilimnia of temperate lakes. Presumably, the native aquatic biota is adapted to withstand periodic low oxygen concentrations. During this study surface oxygen concentrations of less than 10% of saturation values (<0.8 mgl^{-1}) were frequent at certain times of the year, but even Kulukuluku, with oxygen concentrations at the surface sometimes less than 2%, no fish kills were recorded. On these occasions, however, the fish were very active at the surface.

There was distinct seasonal pattern in the values of dissolved oxygen at early morning, with some variation from year to year (Figs. 14,15). A major, annual feature was the minima in surface oxygen early in the Dry (about April-June) (Figs. 14,15). The principal cause was almost certainly the heavy oxygen demand of the rapid decomposition of macrophytes in littoral regions at this time. Dramatic growth of macrophytes occurs in the late Wet in shallow waters surrounding creeks and billabongs, and on the floodplains. Falling water levels at the Wet/Dry interchange lead to senescence and decay of major macrophyte stands, an event known to cause severe oxygen deficits (Wetzel 1975) which may extend some distance into the open water (Thomas 1960, cited by Wetzel 1975).
The effect of macrophytic decomposition appeared to be particularly marked in the billabongs on the Nourlangie floodplain. During the early Dry, 1981, all billabongs studied in this locality experienced very low surface oxygen values ($\simeq$ 5% saturation), and were generally anoxic below 1 metre depth. A notable feature of the swamps and floodplain surrounding these billabongs at this time was the pungent odour of H_2S, indicative of the intense decomposition in these

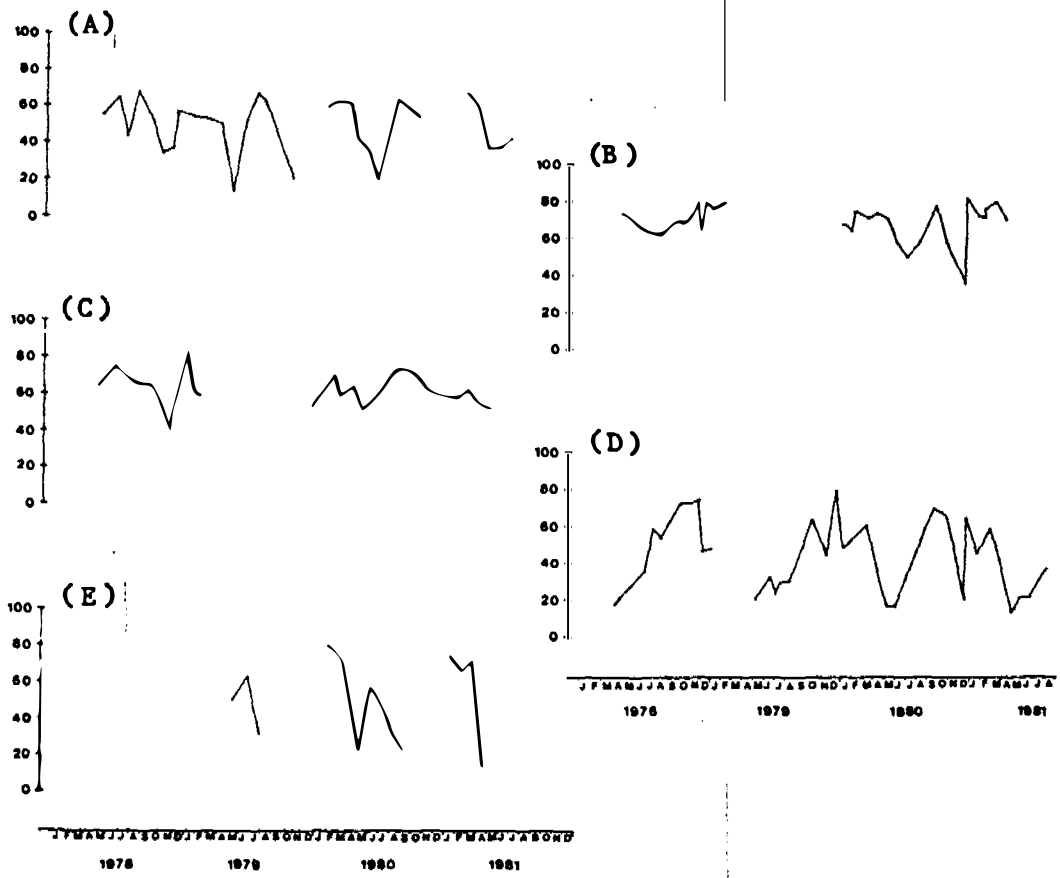


FIG 14. Surface values of dissolved oxygen (% saturation) for the study period in Gulungul (A), Mudginberri (B), Georgetown (C), Island (D) and Umbungbong (E) billabongs.

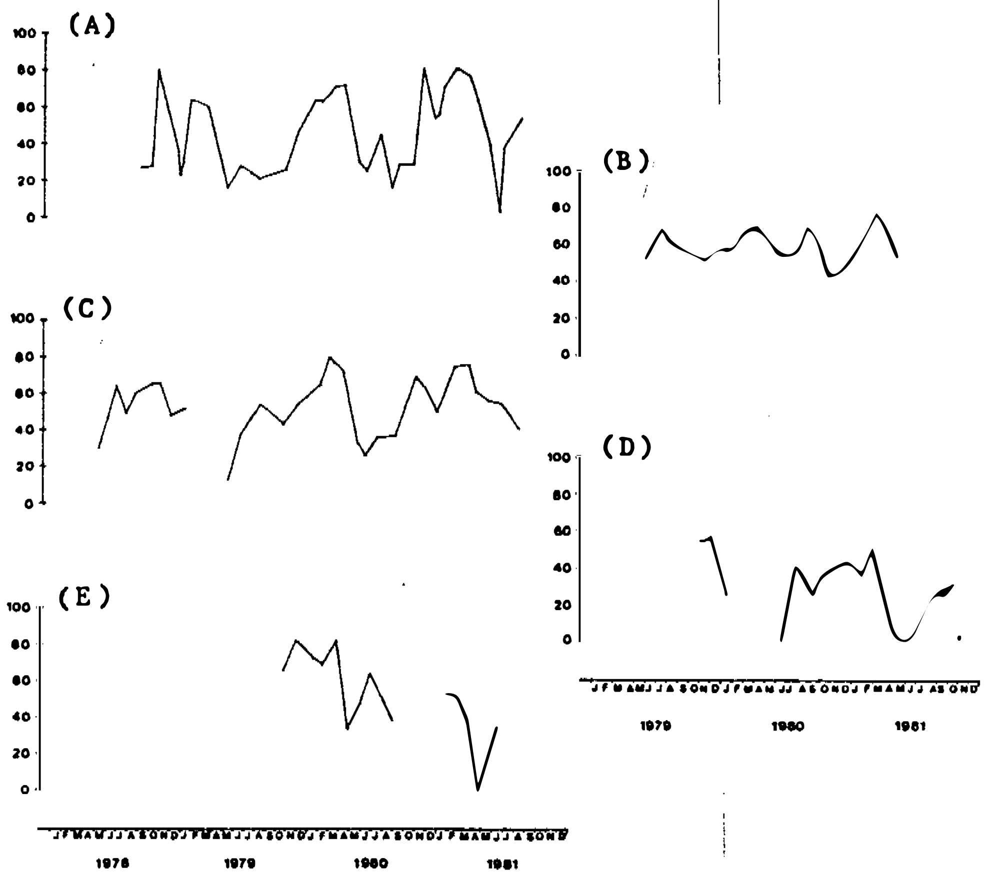


FIG 15. Surface values of dissolved oxygen (% saturation) for the study period in Leichhardt (A), Noarlanga (B), Jabiluka (C), Kulukuluku (D) and Jingalla billabongs.

rapidly-drying areas. Though oxygen levels in Jingalla had recovered somewhat by June, Kulukuluku and Woolwonga were still depleted of oxygen. Since for these two billabongs the results of the previous year were remarkably similar, this appears to be a regular event.

After the macrophytes have decayed, billabong circulation patterns and the dynamics of phytoplankton populations are likely to play major roles in the determination of oxygen levels throughout the remainder of the Dry. The dynamic nature of phytoplankton populations, and their close relationship to surface oxygen levels, is graphically illustrated by the sequence of results obtained by Hart for Island Billabong (Fig. 16). However, high phytoplankton levels do not necessarily imply high oxygen levels, since such factors as self-shading, high turbidity, metabolic inhibition and senescence can markedly reduce phytoplanktonic photosynthesis.

8.0 STRATIFICATION IN THE BILLABONGS

8.1 Preamble

The phenomenon of thermal stratification is well known and understood for the temperate zones, and rarely is there difficulty in recognizing when stratification exists. Usually there are two distinct water bodies, the epilimnion (upper layer) and hypolimnion (lower layer) separated by a zone of temperature and density change, the metalimnion. Often the lower stratum, the hypolimnion, without contact with the atmosphere, is depleted of oxygen. The breakdown of stratification, the overturn, is readily perceived as isothermy accompanied by ventilation and reoxygenation of the lower strata.

Elucidation of the stratification behaviour displayed by the billabongs is crucial to an understanding of their aquatic ecosystems and their ability to survive disturbance, since stratification, or hydraulic partitioning of the water column, often has pronounced biological and chemical consequences. Most such consequences attend the progressive depletion of oxygen in the hypolimnion, which may lead to anoxia and the production of hydrogen sulphide (H_2S). Changes in redox potentials

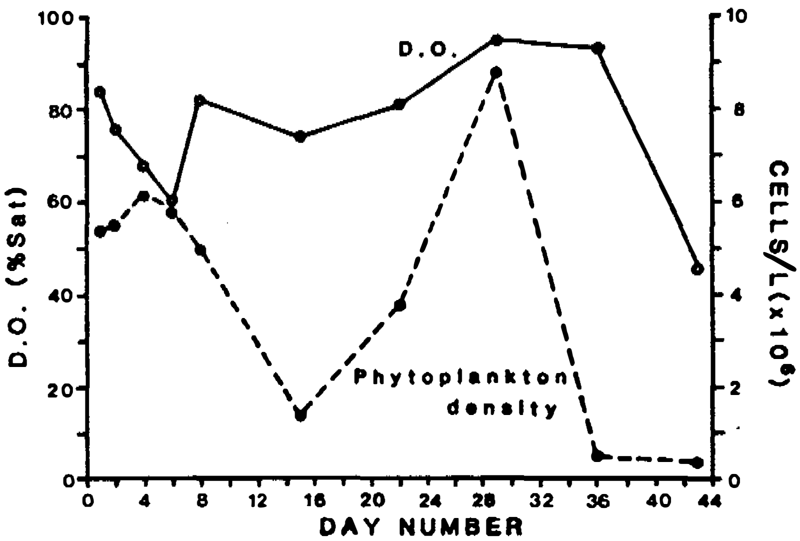


FIG 16. Variation in dissolved oxygen and phytoplankton density for Island billabong over a 44 day period (November/December 1980). (Data after Hart unpubl.).

accompanying these events may result in the release of inorganic ions (e.g. Fe^{2+}, Mn^{2+}, PO_4^{3-}) previously locked in insoluble complexes in the sediment. Redox changes also affect the solubility, mobility and speciation of heavy metals and other toxic substances, and may therefore influence the impact of toxic effluents on aquatic organisms.

Biological consequences of stratification include the progressive exclusion of obligate aerobes such as fish and invertebrates, as dissolved oxygen levels fall to zero in the hypolimnetic waters. Only facultative and obligate anaerobes can survive the anoxic conditions of this zone. Later, overturn may result in a burst of biological production as phosphate (PO_4^{3-}) is mixed throughout the water column.

It is sometimes necessary to adopt an arbitrary criterion of thermal stratification, and in temperate zones this has long been accepted as a metalimnetic thermal discontinuity (thermocline) of 1°C per metre (Birge 1897). There has been less agreement on an arbitrary definition for tropical lakes where comparable changes in water density attend much smaller temperature gradients (Ruttner, 1963). Talling (1969) claims that "... much smaller discontinuities (<<1°C/m) may control the overall division of the water mass." Viner (1970) adopted 1.5°C for Lake Volta, and Coche (in Balon and Coche 1974) defined a tropical thermocline as exceeding 0.2°C per metre. Lewis (1973), on the other hand, did not adopt a numerical criterion but claimed that small temperature differences "served to indicate the de facto isolation of water masses in the lake." Clearly, most authors have had difficulty in determining whether or not tropical waterbodies are stratified. For this reason stratification is not recognized here in thermal terms alone, and using the term in a connotative way, a billabong is deemed to be stratified only if the observed thermal discontinuity is accompanied by independent evidence of apparent isolation into discrete strata. The concentration of dissolved oxygen may provide the least equivocal corroborative evidence.

The billabongs of the Region vary considerably in their morphometry, orientation and degree of shelter, all factors which affect their hydraulic behaviour. Accordingly, in their stratification behaviour they exhibit a continuum of type, which defies rigorous classification. While opposite ends of the spectrum are obvious, the distinction between neighbours in the continuum may be slight. At one end is stratification with five months of relative stagnation of deepwaters (Kulukuluku) but with it appears, some vertical entrainment of surface water across the thermocline. From this point there is a continuum of increasing frequency and extent of such incursions, leading to increasing transience of stratification, until, at the other end of the spectrum, stratification is broken down each night, or never occurs.

The billabongs are arranged below approximately in decreasing order of their degree of stratification, irrespective of their geographical position. At intervals along the continuum, seminal billabongs (Kulukuluku, Leichhardt, Jabiluka, Island and Gulungul) have been treated in greater detail than others. To avoid interruptions of the text, most of the numerous figures and tables are grouped as Appendices and referred to by the prefix A.

8.2 Kulukuluku (refer to Appendix 1)

The thermal profiles (Fig. A1) show that

1. During the Wet, morning profiles were isothermal (Figs. A1.11-13), indicating complete night time mixing and/or water flow. Daytime heating sometimes produced slight thermal gradients in upper strata (Fig. A1.3).
2. For the first half of the Dry, intense heating of the upper strata could produce exponential thermal profiles by the afternoon (Fig. A1.15). Convective and/or wind induced mixing occurred each night, so that morning profiles were again isothermal or nearly so (Figs. A1.4, 14, 15).
3. For the latter half of the Dry, there was a persistent, tripartite thermal structure, with a

thermocline which was not destroyed by nocturnal circulation (Figs. A1.5-9, 18-20),

suggesting uninterrupted stagnation of the bottom waters during this period. The thermal data also indicate that during this stratification period

1. the depth of the thermocline increased from 2 m to 4.5 m (Figs A1.5-9, 18-20), as nocturnal mixing occurred to progressively deeper levels.
2. the temperature of the bottom (hypolimnion) waters increased, in harmony with seasonal changes in atmospheric temperatures.

The dissolved oxygen data substantiate the picture, deduced from the thermal data. A complete flushing, with the Wet, indicated by isothermy, is borne out by the even distribution of oxygen. During the first half of the Dry in both years, the billabong, as well as being isothermal, was iso-oxic (Figs A1.4,14-17). It was iso-oxic in a remarkable way - it was uniformly anoxic (see section 7.2), with a suspicion of a smell of H_2S at the bottom, but not throughout the water column. The isothermy and the absence of H_2S strongly suggests that frequent mixing was occurring, and that the anoxic condition was caused by high oxygen demand, not stagnation. The rain of debris from floating macrophyte meadows (Table 2) undoubtedly created a demand, throughout the year.

Later in the Dry the persistent thermocline was accompanied by a persistent oxycline (Figs A1.5-9, 18-20). In early November 1979, the end of the presumed stratification period, there was a strong oxycline (Figs A1.1-2), but the hypolimnion contained 2% of saturation value, increasing to 5% by the end of the month. Throughout the stratified periods of 1980 and 1981 the hypolimnion was anoxic and contained H_2S. Whilst in a temperate lake, this would be taken to indicate classical stratification, the hypolimnetic temperature increased by about $8^{\circ}C$ during the 1980 stratification period. If geothermal heating is discounted as an unlikely explanation, three alternatives exist, viz:-

1) Occasional nocturnal overturns occur, destroying the thermocline, distributing heat throughout the profile and ventilating the hypolimnion, followed by rapid re-establishment of the thermocline and hypolimnetic anoxia.
2) Solar heating below the thermocline.
3) Limited vertical incursions of warmer, oxygenated water into the hypolimnion, without disrupting the integrity of the thermocline and without effecting wholesale oxygenation designated here as "de-facto" stratification.

To resolve this issue, Kulukuluku was visited repeatedly (15 times) early in the morning for four weeks during October/November 1983. Profiles of temperature, oxygen and light penetration appear in Figs 17-19. Examination of this data reveals:-

1) The billabong was strongly stratified (see also Table 10), with a thermoclinal gradient of $5^{o}C$; in a temperate lake the corresponding density change would be mirrored, for example, by a temperature gradient of $10.6^{o}C$ from $8^{o}C$ to $18.6^{o}C$. The billabong waters below 3.0 m remained anoxic for the duration of the study.
2) Convective currents generated by nocturnal cooling (free convection), perhaps augmented by some wind - induced mixing (forced convection) penetrated each night to a depth of 2.5-3.5 m.
3) During the month there was preferential heating of hypolimnetic, and particularly metalimnetic, regions. Some recruitment of the upper metalimnion into the circulating epilimnion was apparent, with consequent sinking of the thermocline. For much of this period, epilimnetic early morning temperatures were static.
4) Solar heating is unlikely to have accounted for increasing temperatures in the deepwater regions. The euphotic depth, corresponding to the level to which 1% of surface radiation penetrates, was constant at

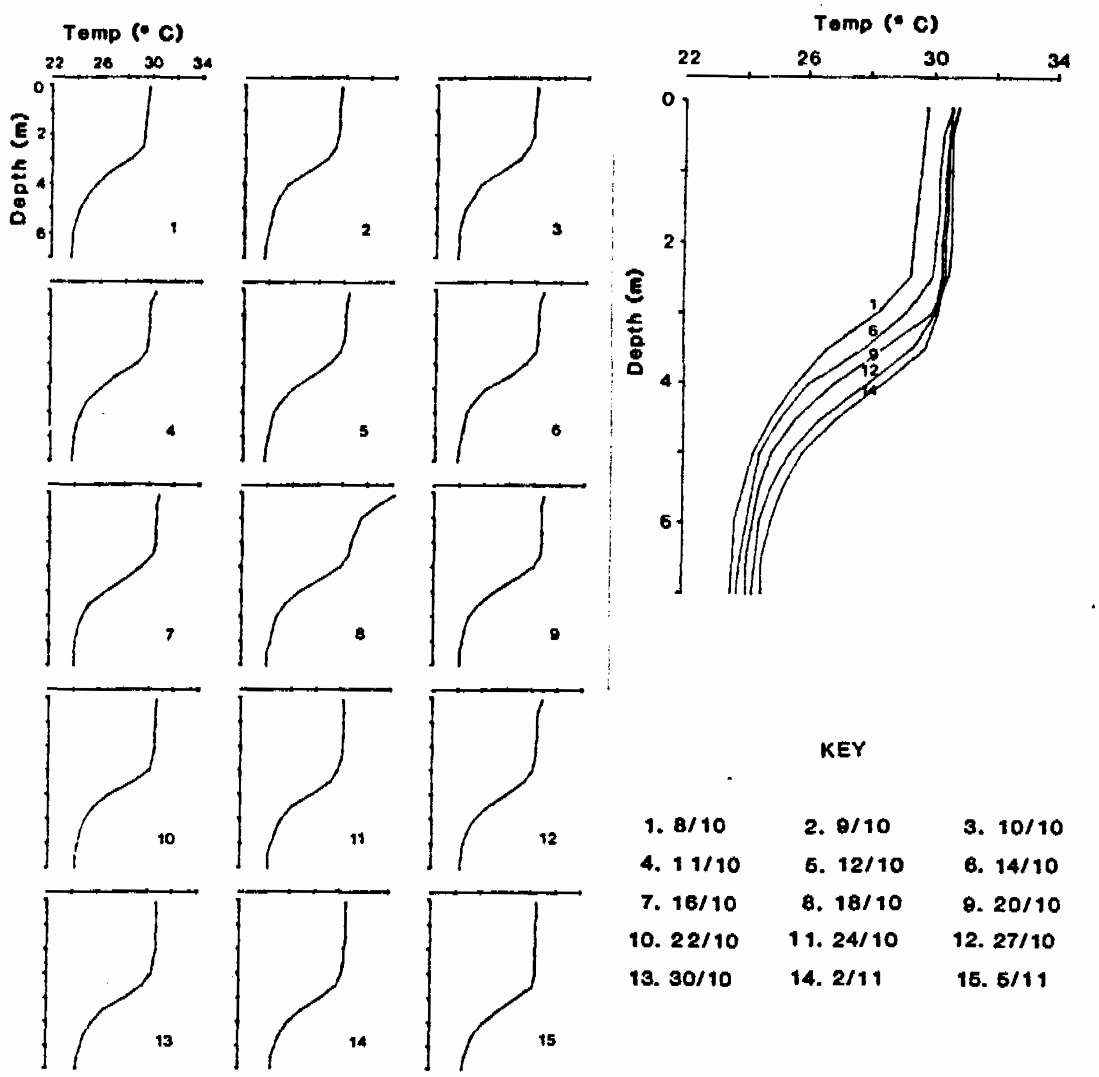


FIG 17. Vertical temperature profiles in Kulukuluku billabong during October/November 1983).

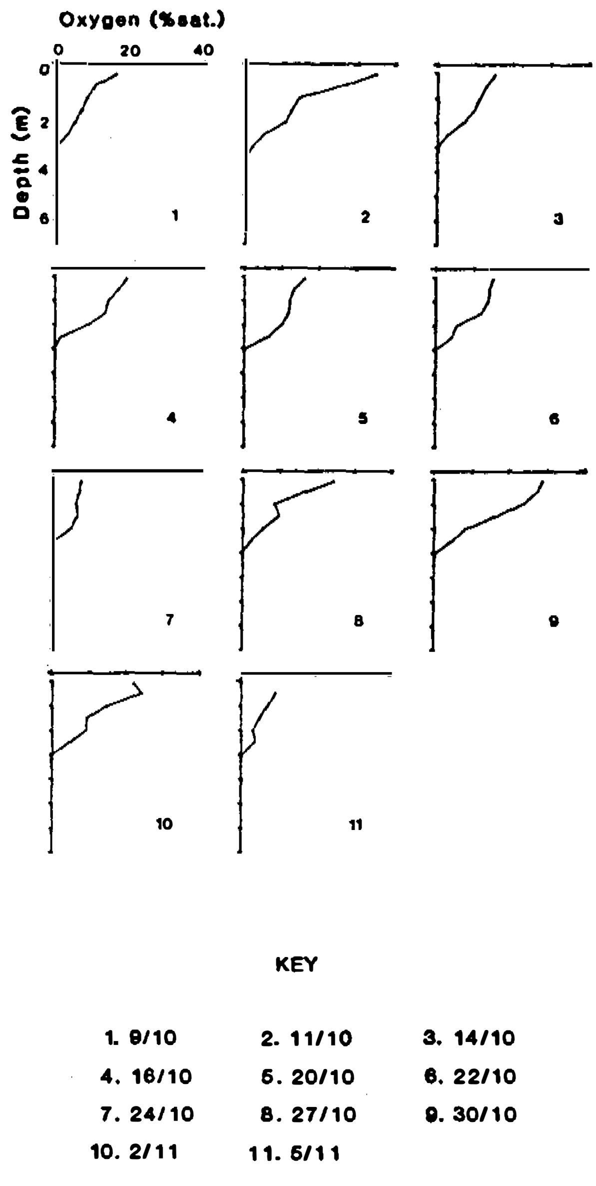


FIG 18. Depth profiles of dissolved oxygen in Kulukuluku billabong during October/November 1983.

TABLE 9: Hypolimnial temperature in Kulukuluku billabong during October/November 1983, compared with the volume-weighted mean temperature of the billabong i.e. the isothermal temperature induced by overturn, assuming no inflow or outflow of heat. The mean temperature was calculated according to a modified version (Ferris and Burton, unpubl.) of the LIMNO program (Merritt and Johnson 1977, quoted by Johnson et. al., 1978).

DATE	TEMPERATURE		DATE	TEMPERATURE	
	Hypolimnion	Mean		Hypolimnion	Mean
8/10	23.6	28.2	20/10	24.05	29.2
9/10	23.6	28.1	22/10	24.15	29.2
10/10	23.7	28.3	24/10	24.2	29.0
11/10	23.7	28.6	27/10	24.3	29.3
12/10	23.7	28.6	30/10	24.4	29.6
14/10	23.8	28.8	2/11	24.55	29.5
16/10	23.95	29.0	5/11	24.6	29.6

TABLE 10: Heat content (caloriea) of a $1m^2$ water column of Kulukuluku in relation to temperature difference between top and bottom water.

DATE	DEPTH	TEMP. RANGE °C	TEMP. DIFFERENCE °C	HEAT CONTENT ($x10^8$)
12/8/80	6.5	24.2-22.9	1.3	1.49
11/9/80	6.5	26.8-24.7	2.1	1.62
8/10/80	6.0	28.5-26.5	2.0	1.65
18/5/81	8.0	26.4-26.4	0	-
17/6/81	8.0	23.8-23.3	0.5	1.81
11/8/81	7.5	25.6-24.0	1.6	1.81
19/8/81	7.5	26.5-24.1	2.4	1.87
18/9/81	7.5	28.3-25.5	2.8	2.01
19.10.81	7.5	29.3-26.7	2.6	2.13
22/11/81	6.5	30.7-30.2	0.5	1.80

autumnal cooling phase of temperate lakes. In the latter case, the thermocline sinks as convective and wind-induced turbulence progressively erode the interface by vertical entrainment. This culminates in overturn when such mixing extends to the bottom (Mortimer 1974). In Kulukuluku, the thermocline also sunk progressively (Fig. A1.5-9, 18-20) but over a period when there was net heat gain by the water column (Table 10), including appreciable hypolimnetic heating by vertical entrainment. Hypolimnetic heating has been recorded elsewhere in the tropics (Falconer et al. in Beadle 1974; Magis 1962), and in Lake Asijere, Nigeria (Egborge 1977), and Barron Bonita reservoir, Brazil (Matsumura-Tundisi et al. 1981), is associated with downward displacement of the thermocline, as in Kulukuluku.

8.3 Woolwonga (refer to Appendix 2)

The limited data for Woolwonga (Appendix 2) suggests that it behaved in a similar manner to Kulukuluku. Until late June, though the billabong was not strictly isothermal, there was no identifiable thermocline, and the whole water column was anoxic or nearly so. Later, thermal gradients increased in magnitude, and on 26/6/80 (Fig A2.2) a definite thermocline was present, accompanied by an oxycline with 25% of saturation in the epilimnion and anoxic, sulphurous conditions below. Unfortunately, during the period when Kulukuluku was stratified, Woolwonga was sampled only once, in August 1980 (Fig A2.3) when not only were all levels of the billabong anoxic but seemingly so were shallow waters of the floodplain. These were choked with macrophytes, and H_2S could be smelled from a helicopter at 500 m. This emphasizes the importance of macrophytes in creating an oxygen demand.

8.4 Red Lily (refer to Appendix 3)

Red Lily was a non-conformist billabong, and unique among those sampled in that was apparently stratified and anoxic for all the Wet as well as for much of the Dry.

Its stratification pattern was intimately related to the seasonal distribution of the lotus lily (Nelumbo nucifera). Early in the Dry the lily died back, leaving the water surface clear until the late Dry. Regrowth then occurred and by the end of the Dry the large floating leaves formed an almost continuous

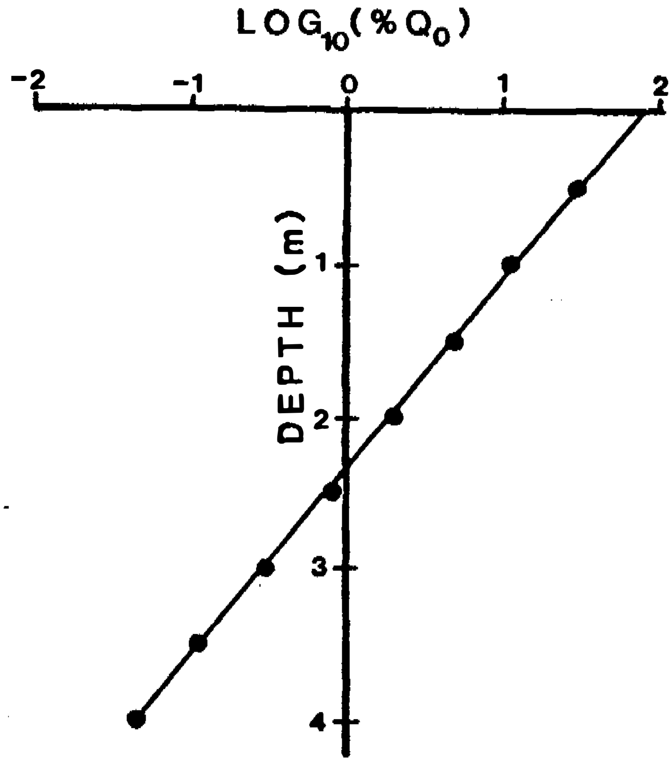


FIG 19. Attenuation of PAR in Kulukuluku billabong on 11/10/83.

around 2.5 m, and little solar heating below this level is probable.

5) The upper boundaries of the anoxic zone and the metalumnion were virtually coincident for much of the study, indicating that only slight barriers to mixing were necessary to permit deepwater depletion of oxygen. As it was, even in the epilimnion oxygen concentrations were very low.

6) Not only did the intensity of the sampling schedule virtually eliminate the possibility of undetected nocturnal overturn, but also, at these temperatures, overturn would have induced considerably more deepwater heating than was apparent here (Table 9).

It seems therefore likely that the notion of de-facto stratification is a valid one in this context, and that hypolimnetic heating was brought about by limited incursions of warm water. The oxygen demand of the hypolimnion must have been sufficient to consume any oxygen introduced, since there was no change in hypolimnetic anoxia over the sampling period. Such partial mixing, without overturn, has been recognized previously in the tropics (e.g. Beadle 1974; Magis 1962; Viner 1970).

The considerable dynamism implicit in the above interpretation, when considered with the horizontal temperature variation observed in other billabongs (e.g. Leichhardt and Island), provides a possible explanation for another perplexing problem, that of a slight decrease in bottom water temperatures between early morning and late afternoon on some Dry season days (Figs. A1.1,2,7,8)* . If limited entrainments of warm water raised hypolimnetic temperature locally, hydraulic readjustments would have caused cooler water from unaffected areas to flow in, causing the observed drops in temperature. The hypolimnion may thus be viewed as a mosaic of water cells whose dynamic interchanges caused frequent turbulence. The same notion, extended to include the whole billabong, is consistent with a picture of dynamic, heterogeneous waterbodies (see sections 8.4 and 8.10, and Kessell and Tyler 1985).

For much of the period during which Kulukuluku was stratified its thermal behaviour strangely paralleled the

*The large decreases, over much of the water column, in 1979 are impossible to explain other than as a shift in thermistor calibration. However, the much smaller temperature drops observed on the other occasions are real events, measured with the same reliable mercury thermometer.

cover which persisted for most of the Wet. The lily population was accompanied by dense stands of submerged macrophytes such as Najas.

The lily pads seriously retarded wind-induced water movements,and they and the other macrophytes produced a steady rain of oxygen-demanding organic debris. Not surprisingly, isothermy, accompanied by abundant oxygen uniformly distributed, was restricted to the lily-free period (mid Dry) (Fig A3.7). Ventilation of deeper water was then thorough, as indicated by oxygen concentrations of 60% saturation at depth on 6/8/80 (Fig A3.8). For all of the latter part of the Dry, as the macrophyte population increased, gentle thermal gradients were present (Figs. A3.1,2,9,10) and oxygen was virtually absent in deeper water, or even throughout the water column (Fig. A3.2), and H_2S could be present. Because of the lily cover, it is considered unlikely that holomixis occurred during this period, though partial circulation was indicated by changing thermal gradients.

During the Wet, Red Lily differed from all other billabongs in that, first, it was not flushed by through-flow. Second, strong thermal gradients developed and in most cases they were accompanied by equally pronounced oxyclines (Figs. A3.3,5,12). The bottom waters were anoxic and sulphurous so that the billabong probably remained stratified throughout the Wet. However, with floodwaters entering, it was unlikely that some intrusion and partial circulation did not take place.

8.5 Leichhardt (refer to Appendix 4)

It seems likely that Leichhardt, the most protected of the Magela floodplain billabongs, experienced de-facto stratification for much of the Dry. Morning temperature profiles (Appendix 4) often indicated that some degree of thermal stratification had persisted overnight. This opinion is based on obvious thermal discontinuities (e.g. Fig. A4.14,22,24).

The shape of the morning profiles of the uppermost 1.5 m water column varied with season, sampling time relative to the onset of daily heating, and weather conditions. Often slight inverse temperature gradients were present during the cool season (Fig. A4.14,15,22,23), apparently a common event in the tropics (e.g. Green et al. 1978; Lewis 1973; Schmidt 1973; Viner

1970). Presumably, this was a transient state when rate of heat loss at the surface exceeded the rate of convective mixing (cf. Lewis 1973), and as such has no obvious ecological implication. The profile of 2/5/79 (Fig. A4.12), repeatable at several points in the billabong, was anomalous and without ready explanation.

The afternoon profiles showed pronounced effects of daytime heating. Under calm conditions an exponential profile was produced (e.g. Fig. A4.16,27), whereas wind induced mixing of surface water produced a classical tripartite profile (e.g. Fig. A4.13,21,26).

The prevalence of deepwater anoxia during the Dry season, despite the absence of persistent stable thermoclines, suggests that partial mixing was prevalent, but overturn uncommon. In some years, bottom anoxia appeared to persist for several months (e.g. May-August inclusive 1980). However, on other occasions, increases in bottom oxygen values between 2 periods of anoxia (e.g. 14/10/78, 5/9/80) indicate an intervening mixing, and it cannot be assumed that the former case indicates unequivocally that stratification persisted over the entire 4 month period. It appears that vertical entrainment in Leichhardt was sufficient to preclude lasting thermoclines but insufficient to effect wholesale ventilation. Undoubtedly, this state of affairs owed much, as in Kulukuluku, to the continuous rain of organic debris from floating meadows. Most likely, if Leichhardt were deeper and more protected, it would behave more like Kulukuluku than it does.

In Leichhardt there was considerable horizontal heterogeneity of temperature and oxygen at any one time. Figs. 20 and 21 illustrate the variability encountered along a transverse transect just upstream of the main buoy site (see Fig. 11) on one occasion when oxygen was present at depth. Deepwater regions at adjacent sites only 10 metres apart could differ by 0.1^{o}C and by more than 10% saturation of dissolved oxygen. These profiles were noteworthy for the unexplained rise in oxygen status of deepwaters. Longitudinal transects during the late Dry 1980, (Table 11) further emphasized that horizontal heterogeneity was common, suggesting as for Kulukuluku, a dynamic system of water cells. Phytoplankton data (Kessell and

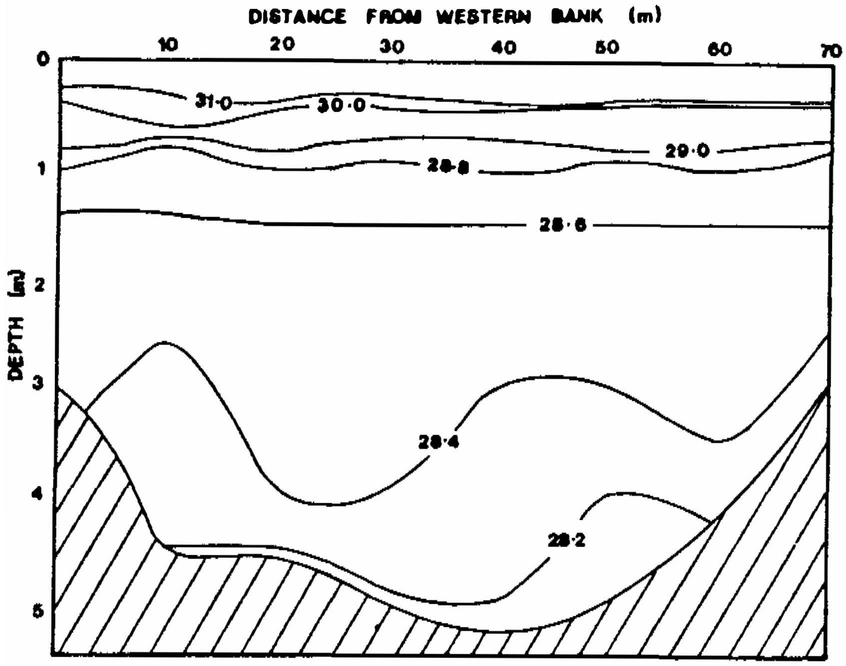


FIG 20. Variation in water temperatures along a transverse transect across Leichhardt billabong on 9/5/79. Location of transect is shown in FIG 18.

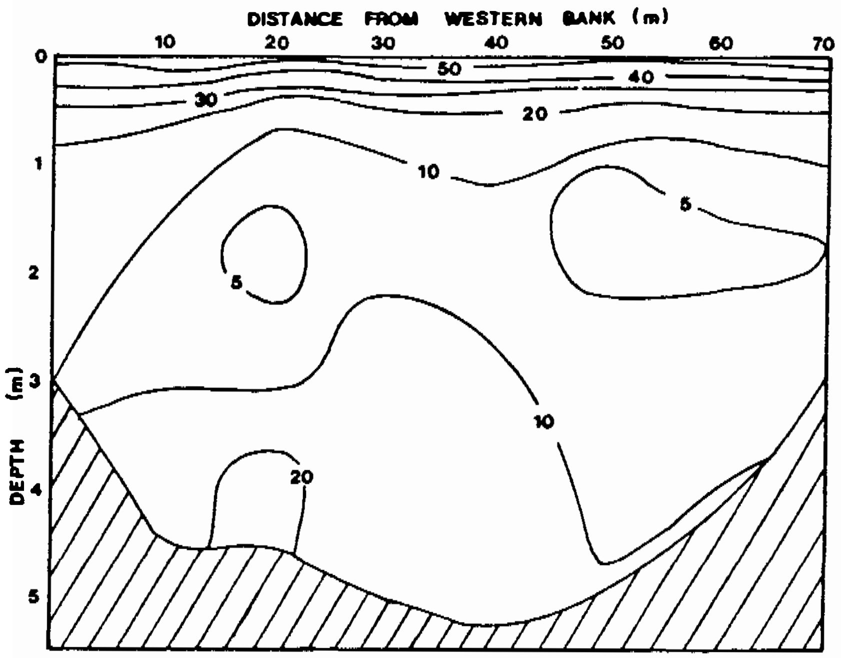


FIG 21. Variation in dissolved oxygen concentrations along a transverse transect across Leichhardt billabong on 9/5/79. Location of transect is shown in FIG 18.

TABLE 11: The distribution of temperature and dissolved oxygen (°C/% sat.) along a longitudinal transect in Leichhardt billabong in October and November, 1980. Location of sites as in Fig 18.

SITE	A	B	C	D
TIME (16/10/80)	10.30	11.00	11.25	12.00
DEPTH (m)				
0.1	31.1/42	31.4/42	31.6/42	32.9/72
0.5	30.4/29	30.5/31	30.6/27	30.9/36
1.0	29.6/24	30.0/20	30.0/15	30.3/20
1.5	29.5/22	29.8/16	29.8/11	30.0/13
2.0	29.5/21	29.7/16	29.8/11	29.8/9
2.5	29.5/19	29.6/15	29.8.9	—
3.0	—	29.6/15	29.8/8	--
3.5	--	—	29.8/7	—
TIME (10/11/80)	13.05	14.20	14.50	
DEPTH (m)				
0.1	33.3/76	33.9/94	33.9/108	
0.5	31.8/44	31.9/84	32.0/44	
1.0	30.7/28	30.9/47	30.9/39	
1.5	30.4/24	30.6/33	30.7/27	
2.0	30.3/21	30.6/27	30.4/16	
2.5	30.3/23	30.4/23	30.3/17	
3.0	—	30.3.17	30.3/12	

Tyler 1985) also indicated that dynamism was the hallmark of Leichhardt. However, horizontal variability was not sufficient to invalidate interpreting billabong behaviour from sampling at a single site, since significant vertical discontinuities in thermal or oxygen characteristics were repeatable around the billabong, although absolute values could differ.

Figures A4.7-8, 31-33 suggest that the incoming floodwaters at the beginning of the Wet did not homogenize the billabong immediately. Rather, deepwater oxygen levels appeared to fall, suggesting that organic debris was washed into the billabong, creating a short-lived peak in oxygen demand before through-flow eliminated isolation of water layers. As the Wet progressed, through-flow increased the oxygen content of deepwater, to level exceeding 70%.

8.6 Noarlanga (refer to Appendix 5)

Because of its considerable depth and comparative protection, this billabong generally showed a thermal gradient in the mornings during the mid-Dry (e.g. Fig. A5.2,4,10-12). Near, or total, isothermy was restricted to just after the cessation of flow (e.g. (Fig. A5.1), on occasions during the late Dry (Fig. A5.6,14-16), and after establishment of through-flow in the Wet (Figs. A5.8,17-19). The strong effects of daytime heating in the Dry were shown in the generally exponential profiles (e.g. Fig. A5.1,4-6). On a number of occasions, temperature rises in deepwater strata were recorded (e.g. A5.2,4,5). A large decrease (1°C) in deepwater regions was recorded during the day on 11/12/79 (Fig. A5.6) with the first influx of cool Wet season floodwater.

Oxygen profiles largely substantiated the stratification behaviour deduced from thermal evidence. Generally, morning thermal gradients and discontinuities were accompanied by distinctly clinograde oxygen profiles, indicating de facto stratification, and near or total isothermy coincident with near iso-oxy. Deepwater oxygen concentrations below 10-20% of saturation were rare, but that Noarlanga does not become anoxic does not deny the existence of periods of stratification. Instead, this was attributable to its oligotrophic nature (see Walker & Tyler 1985a Fig. A2.2). The coincidence of isothermy and a distinctly clinograde oxygen curve, with deepwater anoxia, on 16/12/80 (Fig. A5.16) was anomalous, and probably resulted from the high oxygen demand of debris brought in by runoff at the Wet/Dry interchange.

8.7 Jabiluka (refer to Appendix 6)

Inspection of early morning thermal profiles alone suggests,

(1) that the billabong was thermally stratified on some occasions but not on others

(2) that isothermy, or near isothermy, was commoner in the cool part of the Dry (June-August), and usual in the Wet,

(3) that short periods of thermal stratification were most frequent during the early weeks of the Dry when the billabong was near its maximum depth, and therefore more likely to retain unmixed strata, and when wind strength was at a minimum and transverse to Jabiluka's north-south orientation (Figs 2,3). Later in the Dry, winds veered northerly, increasing the fetch and maximising turbulence.

The corresponding afternoon profiles usually showed either the classical tripartite structure (e.g. Fig. A6.14) indicative of wind mixing, or a strong, exponential form (e.g. Figs. A6.27,28) indicative of heating under calm conditions.

Taking morning and afternoon profiles together, it appears that there was no persistent stratification of the Kulukuluku type, but periods of days of de facto stratification interspersed with considerable mixing if not holomixis. There were some small temperature anomalies, principally a cooling of bottom waters during the day (e.g. Figs. A6.5,7,11,22,24) (cf. Kulukuluku and Leichhardt).

The thermal picture was confirmed by the data for dissolved oxygen. Iso-oxic or near iso-oxic conditions could occur at most times of the year, and rarely did oxygen values fall below 20% of saturation, indicating that persistent deepwater stagnation was rare. The exception was at the beginning of the Dry when, with distinct seasonality, deepwater values fell to zero or near zero as, with the billabong most likely to experience thermal stratification, rotting macrophytes in littoral regions and on the adjacent floodplain supplied oxygen-demanding organic debris.

One short period of persistent stratification was demonstrated by a 5 day sampling in May 1981, just after the annual oxygen minimum. Figures A6.35-37 show that mixing was limited to about 3 m. Below that level, oxygen concentrations fell sharply both in the morning and afternoon. Though the winds at this time were strong, they came from the east and had little effect on the northerly orientated billabong.

Short-lived, deepwater, anoxic conditions could also be experienced as the first floodwaters of the Wet reached the billabong (Fig. A6.10; Hart and McGregor 1980 - data for 5/1/78), as in Leichhardt. Pancontinental Mining Ltd. (1981) found that during the initial filling phase, inflowing water did not induce significant mixing until the billabong had risen sufficiently to flow out of the northern end. Thus, initially, whilst the floodwaters are washing organic material into the billabong, they were not yet promoting significant mixing, so that the oxygen demand produced by the sedimenting organics could lead to deepwater anoxia.

8.8 Jingalla (refer to Appendix 7)

Isothermy was generally restricted to the height of the Wet and to the cool Dry season months (e.g. Figs. A7.7,10.11.13). On these occasions it was generally accompanied by iso-oxy. For the rest of the time, thermal gradients were present and, though generally slight, were usually accompanied by some diminution of oxygen. It might be tempting to suggest that stratification persisted for at least a month between 24/4/80 and 30/5/80, because deepwaters were anoxic on both occasions (Figs. A7.5,6). However, some interaction between surface and deepwater strata must have occurred because bottom water temperatures declined 2.5^{o}C over this, the cooling period (see section 3.2). At best, stratification was a transitory event in this billabong.

8.9 Nimbawah (refer to Appendix 8)

The limited data for this billabong suggested that some degree of thermal gradient at dawn was common for much of the year. Periods of complete isothermy and iso-oxy did occur however (e.g. Fig. A8.9). The thermal gradients were generally accompanied by some diminution of oxygen in deepwater regions, but deepwater anoxia occured only in the early Wet (Fig. A8.5) and early Dry (Fig. A8.8), in common with many deeper billabongs in the region (see Jabiluka). The two afternoon profiles (Fig. A8.1,2) indicated that the effects of daytime heating and photosynthesis could extend right through the water column. During the Wet, Nimbawah could display gentle thermal gradients, sometimes accompanied by significant diminution in oxygen, suggesting that flow in the channel could be sluggish.

8.10 Nankeen (refer to Appendix 9)

The exposed position of this billabong appeared to be a cardinal factor in its circulation pattern, for near or complete isothermy in the early morning during the Dry was frequent (e.g. Figs. A9.3,4,7,12,14). That mixing normally occurred right to the bottom (approx. 4 m) was indicated both by the transfer of daytime heat and oxygen to those levels (e.g. Figs. A9.3-5), and the frequency of near iso-oxic morning profiles (e.g. Figs. A9.3,7,12,17). Nonetheless, on many occasions there were small vertical discontinuities in the morning thermal profiles, accompanied by some diminution of oxygen (e.g. Figs.. A9.5,13,15,16,22). During calm days, strongly exponential thermal profiles could develop (e.g. Fig. A9.6). Only twice did oxygen fall to zero in bottom strata (4/7/78; 6/4/81). Frequent holomixis was the rule for this billabong.

The profiles for 11/1/80 and 14/1/80 (Figs. A9.9,10) indicate that the first inflows of the Wet (between 11/1/80 and 14/1/80 the water level rose by 1 m) did not always homogenise the water body immediately, a situation noted in many other billabongs.

8.11 Island (refer to Appendix 10)

Although surrounded on all sides by trees, Island, being the biggest of all the study billabongs, has the longest fetch, especially in relation to northerly winds, and so was seldom stratified. Dawn isothermy, or near isothermy, was the rule rather than the exception throughout the first half of the Dry (e.g.. Figs. A10.1,16-19.24), and was usually accompanied by iso-oxy. This was clearly shown by the three day sampling in May 1981 (Figs. A10.39-41). Then, the afternoon exponential thermal profiles, and clinograde/exponential oxygen profiles, were degraded by night-time circulation to the isothermal and iso-oxic condition of the dawn sampling. Only occasionally was fleeting separation of water layers recorded during the early Dry (e.g. Figs. A10.2,42), where a very slight thermal discontinuity (e.g. 0.1-0.2^{o}C) was sufficient to lead to significant oxygen depletion in deepwater strata. Once, a completely isothermal profile was accompanied by a distinctly clinograde oxygen distribution (Fig. A10.18).

During the latter half of the Dry, total isothermy was rare, but so too were large thermal gradients. The five day sampling in November 1978 (Figs. A10.7-10) showed that thermal gradients were slight and transient. Using oxygen profiles as a guide, this data also suggested that from the 6-8/11/78 the thermal and oxygen gradients were strengthened, but some circulation on the nights of the 9-10/11/78 partially ventilated deepwater zones, causing not only some reoxygenation, but slight modification of the thermal profile.

As in Leichhardt, considerable horizontal heterogeneity was demonstrated in Island. Whilst the early morning sampling at the regular buoy site on 29/10/80 revealed isothermy and iso-oxy (Fig. A10.29), the mid-morning survey of four sites along the billabong (see Fig. 12 for location of sites) revealed considerable differences in both thermal and oxygen profiles (Table 12). On 7/5/81 morning measurements at the same four sites revealed that near or total isothermy was the rule, but that the isothermal temperature differed along the billabong (Table 13). These differences were compounded by the daytime surface heating but, by the following morning, all four sites were isothermal at 28.1°C (Table 13) (allowing for the time lag between sampling sites C and A, and its effect on surface heating).

As noted for many billabongs, Wet season inflows did not necessarily homogenise the water column immediately (e.g. Figs. A10 13,34) (cf. Pancontinental Mining Ltd. 1981). During periods of through-flow, however, temperature and oxygen profiles indicated a generally homogeneous distribution (e.g. Figs. A10. 14,15,36), although transient gradients could develop between floodpeaks (e.g. Fig. A10.35) and at the end of the Wet (e.g. Fig. A10.37).

It appears that thermal stratification if it occured in this billabong, was ephemeral and infrequent, but that clinograde oxygen distributions could occur under these conditions. Mixing during the first half of the Dry appeared to be effected by nocturnal overturn and steady circulation, whereas partial mixing, promoting some degree of thermal and oxygen gradients, appeared to be dominant during the late Dry.

8.12 Ja Ja (refer to Appendix 11)

During the Dry the billabong was usually isothermal, or nearly so, at the morning sampling (Figs. A11.1-3,11-14). Oxygen concentrations were fairly uniform and usually less than 30%. These conditions indicated a lack of any lasting stratification. The effects of heating and of photosynthesis during the day were visible in the exponential temperature distribution and clinograde oxygen profiles at the afternoon sampling. Exceptions were on 18/3/81 when a distinct thermal gradient at about 2 m

TABLE 12: The distribution of temperature and dissolved oxygen (°C/% sat.) along a longitudinal transect in Island billabong in November, 1980. Location of sites as in Fig 19.

SITE	A	B	C	D
TIME	10.00	10.40	11.20	12.05
DEPTH (m)				
0.1	33.2/82	33.3/76	33.1/75	32.3/78
0.5	32.9/78	32.6/77	32.5/76	32.3/81
1.0	32.5/72	32.3/70	31.9/75	31.9/74
1.5	32.4/66	32.1/56	31.6/69	31.6/70
2.0	32.3/60	32.0/46	31.4/62	31.4/59
2.5	32.2/58	32.0/41	31.4/57	31.4/55
3.0	—	—	31.4/53	—
3.5	—	—	31.4/49	—

TABLE 13: Temperatures (°C) along a longitudinal transect in Island billabong on consecutive days in May, 1981. Location of sites as in Fig. 19.

SITE	A	B	C	D	A	B	C	D
TIME (7/5/81)	09.30	09.00	08.00	08.35	16.35	16.05	15.15	15.00
DEPTH (m)								
0.1	28.6	28.5	28.2	28.3	30.0	30.4	30.6	30.3
0.5	28.5	28.5	28.2	28.3	29.4	29.8	29.8	29.7
1.0	28.4	28.3	28.2	28.3	28.7	28.9	28.8	28.8
2.0	28.4	28.3	28.2	28.3	28.5	28.5	28.6	28.6
3.0	28.4	28.3	28.1	28.3	28.3	28.4	28.4	28.5
4.0	28.3	28.3	28.1	28.3	28.2	28.3	28.3	28.5
4.5	28.3	28.2	28.1	28.3	28.1	28.3	28.3	28.5
TIME (8/5/81)	09.15	09.00	08.00	08.30	16.20	15.15	15.10	14.40
DEPTH (m)								
0.1	28.3	28.3	28.1	28.1	30.3	30.2	30.9	30.3
0.5	28.2	28.2	28.0	28.1	29.0	29.2	29.1	29.7
1.0	28.2	28.2	28.0	28.1	28.5	28.5	28.5	29.2
2.0	28.2	28.1	28.1	28.1	28.3	28.3	28.2	28.4
3.0	28.2	28.1	28.1	28.1	28.2	28.1	28.2	28.3
4.0	28.1	28.1	28.1	28.1	28.0	28.1	28.1	28.3
4.5	28.1	28.1	28.1	28.1	28.0	28.1	28.1	28.2

was accompanied by a drop of 30% in oxygen concentrations (Fig. A11.16), and on 6/4/81 when a slight thermal gradient at about 4 m coincided with a drop of 15% in oxygen saturation values. On 28/12/78 the lowest oxygen concentration (5%) was recorded in bottom strata (Fig. A11.8). None of these events suggested anything other than fleeting episodes of stratification.

8.13 Mudginberri (refer to Appendix 12)

With respect to morphometry, Mudginberri is similar to Island. This similarity extends to its thermal behaviour as isothermy, or near isothermy, was the dominant condition throughout the Dry.

This picture of complete lack of thermal stratification was substantiated by oxygen profiles which indicated a pronounced tendency to iso-oxy. Rarely was there deepwater depletion (e.g. Figs. A12.6,17). The oxycline evident on 19/10/78 (Fig. A12.6) accompanied by a gentle thermal gradient, possibly resulted from an increased oxygen demand in deepwater strata caused by an algal bloom occurring at the time.

As discussed by Pancontinental Mining Ltd. (1981), the first flows of the Wet exaggerated thermal gradients, as the cool influent waters underlay billabong water (e.g. Figs. A 12.10,24). Strong throughflow then led to well-mixed conditions (e.g. Figs. A12.27-29).

8.14 Buffalo (refer to Appendix 13)

Buffalo, a small, sheltered billabong adjacent to Mudginberri was sampled for one year (1978) only. With one exception, it was isothermal or nearly so at the morning sampling, and oxygen was uniformly distributed at relatively high (40-60%) concentrations. In this regard, it resembles Mudginberri closely.

The one exception was the morning of 29/12/78 when between 4 m and 4.7 m the oxygen dropped from 65% to 12%, concurrent with a slight increase in temperature. Since the floodwaters of the Wet had already entered the billabong by this date, it was likely that the distinct bottom stratum resulted from a denser, oxygen-demanding, inflow rather than the thermal behaviour of the billabong itself.

8.15 The backflow billabongs - Georgetown, Coonjimba, Gulungul, Corndorl, Umbungbung, Goanna (channel/backflow). (refer to Appendix 14)

The backflow billabongs were all too shallow to exhibit more than occasional, short-lived periods of stratification. During the Wet they often displayed a thermal gradient consequent on inflow of cooler, creek water. Since the stratification behaviour of all backflow billabongs was very similar, one, Gulungul, will be discussed and any exceptions mentioned subsequently.

In Gulungul, at no time during the Dry was there any evidence of thermal stratification at the morning sampling. The phenomenon of inverse temperature stratification was detected on a few occasions, notably 9.7.79 and 21/5/80 (Figs. A14.11,19). As discussed previously (section 8.5), this presumably resulted when the rate of surface cooling exceeded the rate of convective mixing, and was characteristic of calm, sheltered conditions. This same calmness could lead to impressive exponential temperature gradients by afternoon, with a temperature decline of over 10^{o}C possible in the first 0.7 m (e.g. Fig. A14.7). At other times, mixing brought about by light winds resulted in classical tripartite thermal profiles by afternoon (e.g. Fig. A14.10,18), and often led to daytime heat penetrating to the bottom (e.g. Fig. A14.1,26).

In the mornings, oxygen was usually homogeniously distributed indicating nocturnal mixing. Values were usually relatively high (50%), except at times in the early Dry (e.g. Figs. A14.10,20) (35%) when macrophyte decomposition was in progress. The usual effect of daytime photosynthesis was a pronounced gradient of oxygen from surface to bottom (e.g. Figs. A14.3,5,20). On some occasions (e.g. Fig. A14.27) there was a uniform increase throughout most of the profile.

Isothermy, or near isothermy, was rare during the Wet. Rather, thermal gradients were usually evident in the morning (e.g. Figs. A14.15,16,26,27), resulting from cool influent water, from either Gulungul Creek or the Magela, underlying billabong water. For example, on the 17/2/81, Magela water just upstream of the confluence with Gulungul Creek (gauging station

821009) was homothermal at 28.4°C, whereas surface water in Gulungul at dawn 17/2/81 was 29.3°C, and bottom water was 28.7°C. Being a backflow billabong, Gulungul experienced periods of relative stagnancy during the Wet, depending on water level in the Magela and its own small tributary, so that the heat content of the billabong could rise appreciably relative to the creeks. This was illustrated by the temperatures in May 1981, after backflow had ceased for the season, but while the Magela was still flowing. At G.S. 812009, surface water in the Magela was 28.9°C, whereas the billabong was virtually isothermal at 30.4°C. Thus influent water during the Wet would generally have been cooler than the existing billabong water, creating or exaggerating a thermal gradient, providing the turbulence of inflow was insufficient to mix new and old water.

Somewhat contrary to the situation in Gulungul, Georgetown and Goanna could experience fleeting episodes of Dry season stratification. During the September and October 1978 samplings (Figs. A14.31,32) on four occasions during 1980 (Figs. A14.33-36), and in May 1981 (Fig. A14.38), some degree of thermal stratification, mirrored by some oxygen depletion in bottom water, was detected in Georgetown. However, deepwater oxygen values never dropped below 30%, suggesting that bottom waters were not out of contact with the atmosphere for long. On other occasions (e.g. Fig. A14.37) a clinograde oxygen curve accompanied an isothermal profile, and on 4/7/80 (Fig. A14.34) iso-oxy was coincident with a thermal gradient.

The short-term stratification noted in Goanna was more pronounced than in Georgetown, which was perhaps not surprising given its more abrupt morphometry. On 10/7/78 (Fig. A14.39) there was a 0.9°C drop between 0.5 m and 1.9 m accompanied by a drop from 70% to 20% in dissolved oxygen. On the morning of the 16/7/81 (Fig A14.40) the thermal gradient involved a drop of 0.5°C, whilst the oxycline involved a decline from 43% to 8%.

8.16 Mine Valley (refer to Appendix 15)

As noted for the backflow billabongs, Mine Valley displayed a marked tendency to isothermy and iso-oxy in the morning profiles. Daytime heating and photosynthesis generally produced strongly exponential profiles in the Dry, and the effects of these daily events often extended to the bottom of this shallow billabong.

Unfortunately, dawn data for the Wet is lacking, but the available evidence suggests that isothermy and iso-oxy could have been a frequent event during this period. This would not be surprising given that this billabong was really nothing more than a shallow depression on the edge of the floodplain, and thus subject to sheet flow.

8.17 Bowerbird (refer to Appendix 16).

Bowerbird was something of a special case, being a billabong which flowed throughout the year. Accordingly, morning temperature profiles were always isothermal. The effects of daytime heating were evident at the afternoon sampling. On most occasions oxygen was uniformly distributed. On two occasions slight diminution in bottom waters occurred (Fig. A16.5,8), possibly caused by oxygen-demanding inflows after the first storms of the Wet. The lack of appreciable oxygenation during the day emphasized the oligotrophic nature (see Walker & Tyler 1985a; Fig A1.2) of this billabong.

9.0 DISCUSSION

In the Alligator Rivers Region, stratification can only be expected during the Dry, when the billabongs have no flow. During this study, clear evidence of persistent thermal stratification of the temperate type, in which the bottom waters are isolated from surface waters and atmospheric contact for long periods, has not been found. Rather, a partial but considerable isolation of water masses appears to be prevalent in some billabongs at various times of the year, with attendant phenomena such as anoxia and production of H_2S. In most, anoxia is a rare event. The billabong which approximates most closely to the temperate model of stratification is Kulukuluku.

Because, at tropical temperatures, small temperature differences produce considerable density gradients (pycnoclines sensu Denny (1972)), slight thermal discontinuities confer a stability of stratification which would require a considerably greater temperature range in temperate regions. However, the actual density change across thermoclines in temperate lakes is greater than in tropical regions (Lewis 1973; 1982) because there are much larger temperature gradients involved. A comparison of small, shallow tropical lakes with comparable temperate lakes (Table 14) emphasizes this point, due in large measure to the greater seasonal range of air temperature in temperate latitudes.

As a corollary of the considerable density changes brought about by small temperature changes in tropical lakes, convection currents triggered by nocturnal cooling are often sufficient to intrude into deepwater regions and perhaps precipitate overturn (Ruttner 1963). Even for highly stratified temperate lakes a downward flux of heat across thermoclines has long been recognized (Hutchinson 1957). Molecular diffusion alone is usually insufficient to account for observed rates of transfer, and entrainment of warmer water into the hypolimnion by turbulent transport (vertical eddy diffusivity or eddy conductivity) is implicated (Imberger and Hebbert 1980). This turbulent exchange between surface and deepwater zones, whilst a thermal gradient is maintained, is prevalent in tropical waterbodies, with their relatively slight pycnoclines (Table 14) and consequent lesser stability. In Lake Brokopondo, Surinam, van der Heide (1978) found frequent indications of interchange with deepwater regions, although isothermal conditions were rare. In Africa, Imevbore (1967) and Viner (1970) found that slight oxygenation (<2%) of usually anoxic hypolimnia occurred despite persistent thermoclines. In the Guatemalan lakes Yaxha and Sacnab, Deevey et al. (1980) found similar evidence for downward migration of oxygen despite maintenance of a thermocline. The point is emphasized by Beadle (1974) who suggests that the hypolimnia of both temporarily and permanently stratified tropical lakes are only 'relatively stagnant'. The billabongs of the Region present a continuum of increasing frequency of this turbulent exchange, manifested by decreasing permanence of thermal structure and attendant oxygen depletion - de facto stratification.

TABLE 14: Comparison of density differences between top and bottom waters for selected tropical and comparable temperate lakes.

WATERBODY	LOCATION	ZONE	MAX. DEPTH (m)	DATE	TEMP. RANGE (°C)	TEMP. CHANGE (°C)	DENSITY CHANGE ($\times 10^{-4}$)	SOURCE
Kulukuluku billabong	N.T., Aust.	Tropical	7.5	18/9/81	28.3-25.5	2.8	7.7	This report.
Darwin River Dam	N.T., Aust.	Tropical	18.0	Dry season	28.4-25.8	2.6	7.2	Boland and Allen (unpubl.)
Manton Dam	N.T., Aust.	Tropical	12.0	Dry season	31.1-25.9	5.2	15.0	Boland and Allen (unpubl.)
Lago do Casthano	Amazon, Brazil	Tropical	11.0	29/5/69	29.9-27.3	2.6	7.5	Schmidt (1973)
Americana Res.	Sao Paulo, Brazil	Tropical	9.0	28/8/74	21.5-20.0	1.5	3.2	Froehlich *et al*. (1978)
Barra Bonita Res.	Sao Paulo, Brazil	Tropical	17.0	Nov. 1979	26.7-22.5	4.2	10.6	Matsumura-Tundisi et al. (1981)
L. Juleque	Peten, Gautemala	Tropical	23.0	July 1969	26.0-22.9	3.1	7.8	Brezonik and Fox (1974)
Asejire L.	Nigeria	Tropical	13.0	11/4/75	30.3-25.5	4.8	13.6	Egbore (1978)
L. Ekeiyele	Nigeria	Tropical	10.0	March	29.4-25.8	3.6	10.1	Imevbore (1967)
Perched L.	Tasmania, Aust	Temperate	12.0	23/2/77	22.0-8.0	14.0	20.8	King and Tyler (1980)
L. Elusive	Victoria, Aust	Temperate	21.0	Summer	21.5-10.5	11.5	17.7	Timms (1973)
L. Aroarotamahine	New Zealand	Temperate	22.5	15-20/1/58	23.5-12.0	11.5	20.8	Bayly (1962)
Tom Wallace L.	Kentuchy, U.S.A.	Temperate	8.0	3/8/51	28.0-8.9	19.1	35.5	Idso and Cole (1973)
Litle Crooked L.	Indiana, U.S.A.	Temperate	13.0	18/7/64	28.0-6.5	21.5	36.9	Wetzel (1975)
Little Round L.	Ontario, Canada	Temperate	16.0		22.5-4.0	18.5	23.2	Wetzel (1975)
L. 227	ELA, Canada	Temperate	10.0	8/7/75	23.1-4.5	18.6	24.5	Quay *et al*. (1980)
L. 224	ELA, Canada	Temperate	24.0	27/6/76	19.0-6.0	13.0	15.4	Quay *et al*. (1980)

At one end of the continuum is Kulukuluku where a strong thermocline apparently persisted over the latter half of the Dry, with anoxia and H_2S then a permanent feature of the deepwater. However, during this period considerable temperature rises took place in the hypolimnion. It is considered the only explanation for these contradictory phenomena is limited turbulent entrainment of surface water into deeper strata, incursions sufficient to cause incremental rise in temperature but insufficient to cause complete disruption of the thermocline, and insufficient to alleviate the anoxic condition.

Though other billabongs do not stratify like Kulukuluku, the same hydrodynamic processes operate. Most at some time or other show evidence of greater or lesser periods of de facto stratification. Most show horizontal and temporal variation in thermal structure, indicating a dynamic mosaic of water cells resulting from localized turbulence. Eckhart (quoted by Mortimer 1974)made the distinction between stirring and mixing, the former caused by large scale influences, the latter by patches of turbulence. Mortimer (1974) suggested that the aftermath of the latter would be a very complex density structure, or 'microstructure'. This appears to be common in the small lakes of the tropics (Rai and Hill 1981; Schmidt 1973); Thomas and Ratcliffe 1973), and is similar in many respects to the thermal behaviour of epilimnetic regions of large tropical lakes, such as Lake Lanao (Lewis 1973). In the Alligator Rivers Region, Leichhardt is particularly heterogeneous, both in temperature and in plankton distribution (Kessell and Tyler 1985).

It is clear that neither temperature nor oxygen on their own give clear indication of the degree of permanence of stratification in shallow tropical waters. When the two are considered together, paying due regard to diurnal phenomena in each case, a better judgement is possible. Certainly, congruence of thermocline and oxycline at dawn is strong evidence for de facto stratification. In the tropics, even a short period of stratification, a matter of days, has bearing on important ecological events such as oxygen distribution, nutrient availability and the redox state of the waters.

Though most billabongs do not experience the long periods of deepwater anoxia, common in the temperate zone, neither are surface waters saturated with oxygen, as is usual for temperate lakes. Oxygen is frequently reduced to 50% of saturation, or less, at night and seasonally, when macrophytes rot, the entire water column may be anoxic or nearly so, as on the Nourlangie floodplain. The native fauna must be well adapted and from field observations fish survive in the virtual absence of oxygen. However these conditions must be stressful to aerobic organisms, and increase their susceptibility to toxins.

The clear implications for heavy metal availability of the stratification characteristics of Magela Creek billabongs are that since persistent anoxia is rare there is little likelihood of massive mobilisation of metals in soluble form under low redox conditions. This is not true for Kulukuluku and perhaps some other Nourlangie billabongs and even in the Magela system, acount must be taken of intermittent, short periods of anoxia. In this regard, the critical time is the end of the Wet when macrophytes decompose, and the critical billabong is Leichhardt, with its frequent episodes of anoxia. The considerable ecological dynamism of waterbodies of the Region precludes easy prediction of their behaviour. If it is not possible to predict how they will behave during a study, then it will be necessary to find out how they <u>are</u> behaving, by suitable monitoring.

REFERENCES

APHA (1975). Standard Methods for the Examination of Water and Waste-water. 14th Ed. American Public Health Association, Washington, D.C.

Balon, E.K. and Coche A.G. (1974). Lake Kariba, a man-made tropical ecosystem in Central Africa. Monog. Biol. 24.767p. The Hague

Bayly, I.A.E. (1962) Ecological studies on New Zealand lacustrine zooplankton with special reference to Boeckella propinqua (Copepoda : Calanoida). Aust. J. Mar. Freshwat. Res. 13,143-97.

Bayly, I.A.E. and Williams, W.D. (1973) Inland Waters and their Ecology. Longman, Hawthorn.

Beadle, L.C. (1974) The Inland Waters of Tropical Africa. An Introduction to Tropical Limnology. Longman, London.

Birge, E.A. (1897) Plankton studies on Lake Mendota: II The Crustaceae from the plankton from July, 1894 to December 1896. Trans. Wisconxin, Acad. Sci. Arts Lett., 11;274-448.

Christian, C.S. and Aldrick, J.M. (1977). Alligator Rivers Study - A Review Report of the Alligator Rivers Region Environmental Fact-Finding Study. Australian Govt. Publishing Service.

Davy D.R. and Conway, N.F. (1974) Environmental Studies, Northern Territory Uranium Province, 1971-73. In Newton, P.J.F. (Ed.) The Alligator Rivers Area Fact Finding Study. Four AAEC Reports. Australian Atomic Energy Commission, Lucas Heights.

Denny, P. (1972). The significance of the pycnocline in tropical lakes. Afr. J. Trop. Hydrobiol. Fish. 2(2), 85-9.

Egbore, A.B.M. (1978) Seasonal variations in the density of a small West African Lake. Hydrobiologia 61(3), 195-203.

Fox, R.W., Kelleher, G.G. and Kerr, C.B. (1977). Ranger Uranium Environmental Enquiry Second Report. Australian Government Publishing Service, Canberra.

Ganf, G.G. and Horne, A.J. (1975). Diurnal stratification, photosynthesis and nitrogen fixation in a shallow equatorial lake (Lake George, Uganda). Freshwat. Biol. 5, 13-39.

Goldman, C.R. (1968) Aquatic primary production. Am. Zoologist 8;31-42.

Green, J.; Corbet, S.A.; Watts, E. and Lan, O.B. (1978) Ecological studies on Indonesian Lakes. The montane lakes of Bali. J. Zool., Lond. 186:15-38.

Harris, S. (1980). Uranium mining development in the Northern Territory : An overview of the issues. In : S. Harris (Ed) Social and environmental choice : the impact of uranium mining in the Northern Territory, pp 1-11. Centre for Resource and Environmental Studies, Australian National University, Canberra.

Hart, B.T. (1980). Water quality and aquatic biota in Magela Creek. In S. Harris (Ed.) : Social and environmental choice: the impact of uranium mining in the Northern Territory, pp 47-63. Centre for Resource and Environmental Studies, Australian National University, Canberra.

Hart, B.T. and McGregor, R.J. (1980). Limnological survey of eight billabongs in the Magela Creek Catchment, Northern Territory. Aust. J. Mar. Freshwat. Res. 31,611-26.

Heide, J. van der (1978). Stability of diurnal stratification in the forming. Brokopondo Reservoir in Surinam, S. America. Verh. int. Ver. Limnol., 20, 1702-9.

Hutchinson, G.E. (1957). A Treatise on Limnology. Vol. I. John Wiley and Sons, New York.

Idso, S.B. and Cole, G.A. (1973). Studies on a Kentucky Knobs Lake: V. Some aspects of the vertical transport of heat in the hypolimnion. J. Ecol. 61,413-20.

Imberger, J. and Hebbert, R.H.B. (1980). Management of Water Quantity in Reservoirs. Australian Water Resources Council Tech. Pap. No. 99. Australian Government Publishing Service, Canberra.

Imevbore, A.M.A. (1967). Hydrology and plankton of Eleiyele reservoir, Nigeria. Hydrobiologia, 30,154-76.

King, R.D. and Tyler, P.A., (1981). Limnology of Perched Lake, South-west Tasmania. Aust. J. Mar. Freshwater Res., 32, 501-15.

Lewis, W.M. (1973). The thermal regine of Lake Lanao (Phillipines) and its theorectical implications for tropical lakes. Limnol. Oceangr. 18:200-17.

Lewis, W.M. (1982). Vertical eddy diffusitivities in a large tropical lake. Limnol. Oceanogr. 27, 161-2.

Ling, H.U. & Tyler, P.A., 1985: A limnological survey of the Alligator Rivers Region, Northern Territory. 6. Algae (exclusive of diatoms) of the Region. - Supervising Scientist for the Alligator Rivers Region Res. Rept. 3: (in press). Australian Govt. Publishing Service, Canberra.

Magis, M. (1962). Etude Limnologique des lacs artificiets de la Lufira et du Lualaba (Haut Katanga). I. Le regime Hydraulique, Les variations saisonieres de la temperature. Int. Rev. Hydrobiol. 47:33-84.

Matsumura-Tundisi, T; Hino, K. and Claro, S.M. (1981) Limnological studies at 23 reservoirs in southern part of Brazil. Verh. int. Ver. Limnol. 21,1040-7.

Mortimer, C.H. (1974). Lake hydrodynamics. Mitt. Int. Ver. Limnol., 20, 124-97.

Noranda Australia Ltd (1978). Koongarra Project : Draft Environmenal Impact Statement. Appendices - Volume I. Noaranda Australia Ltd., Melbourne.

Pancontinental Mining Limited (1981). A review of Jabiluka Environmental Studies. Pancontinental Mining Ltd., Sydney.

Quay, P.D; Broecker, W.S; Hesslein, R.H. and Schindler, D.W. (1980) Vertical diffusion rates determined by tritium tracer experiments in the thermocline and hypolimnion of two lakes. Limnol. Oceanogr. 25(2), 201-8.

Ruttner, F. (1963) Fundamentals of Limnology. Translated by D.G. Frey and F.E.H. Fry. 3rd. Ed. University of Toronto Press, Toronto.

Schmidt, G.W. (1973). Primary production of phytoplankton in three types of Amazonian waters: II. The limnology of a tropical floodplain lake in central Amazonia, (Lago do Castanho). Amazoniana 4(2), 139-204.

Seaman, M.T; Scott, W.E; Walmsley, R.D; van der Waal, B.C.W. and Toerien, D.F. (1978). A limnological investigation of Lake Liambezi, Caprivi. J. Limnol. Soc. Sth. Afr. 4(2), 129-44.

Talling, J.F. (1969). The incidence of vertical mixing and some biological and chemical consequences, in tropical African Lakes. Verh. int. Ver. Limnol. 17:998-1012.

Thomas, D.P., 1983 : A limnological survey of the Alligators Rivers Region, Northern Territory. 1. Diatoms (Bacillariophyceae) of the region. - Supervising Scientist for the Alligators Rivers Region Res. Rept. 3. Australian Govt. Publishing Service, Canberra.

Timms, B.V. (1973) A limnological survey of the freshwater coastal lakes of east Gippsland, Victoria. Aust J. Mar. Freshwat. Res. 24, 1-20.

Viner, A.B. (1970) Hydrobiology of Lake Volta, Ghana. I. Stratification and circulation of water. Hydrobiologia, 35:209-29.

Walker, T.D. and Tyler, P.A. (1985a). A limnological survey of the Alligator Rivers Region, Northern Territory. 3. The underwater light climate of the billabongs. - Supervising Scientist for the Alligator Rivers Region Res. Rept. 3. (in press) Australian Government Publishing Service, Canberra.

Walker, T.D. and Tyler, P.A. (1985b). A limnological survey of the Alligator Rivers Region, Northern Territory. 4. Chemical characteristics of the billabongs. - Supervising Scientist for the Alligator Rivers Region Res. Rept. 3. (in press) Australian Government Publishing Service, Canberra.

Walker, T.D. and Tyler, P.A. (1985c). A limnological survey of the Alligator Rivers Region, Northern Territory. 8. Nutrient status of the billabongs. - Supervising Scientist for the Alligator Rivers Region Res. Rept. 3. (in press) Australian Government Publishing Service, Canberra.

Walker, T.D. and Tyler, P.A. (1985d). A limnological survey of the Alligator Rivers Region, Northern Territory. 7. Phytoplankton productivity in the billabongs. - Supervising Scientist for the Alligator Rivers Region Res. Rept. 3. (in press) Australian Government Publishing Service, Canberra.

Wetzel, R.G. (1975). Limnology. W.B. Saunders Co., Philadelphia.

Young, P.C. (1980). Mining and the Natural Environment: Systems Analysis and Mathematical Modelling. In Stuart Harris (Ed.) Social and environmental choice: the impact of uranium mining in the Northern Territory. Centre for Resource and Environmental Studies, Australian National University, Canberra.

APPENDIX 1

Temperature and oxygen profiles in Kulukuluku billabong.

FIG. A 1 (cont.)

FIG. A 1

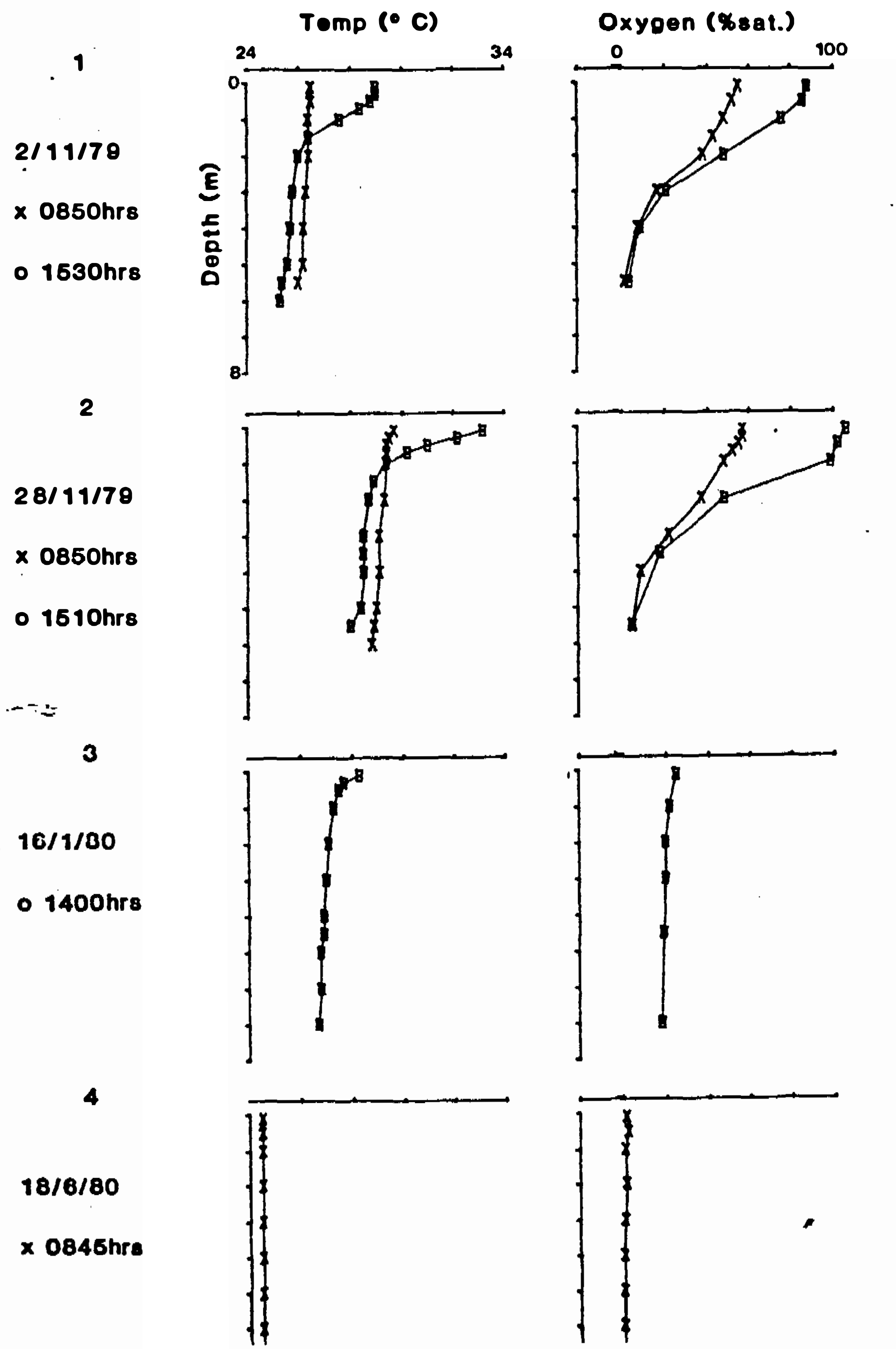
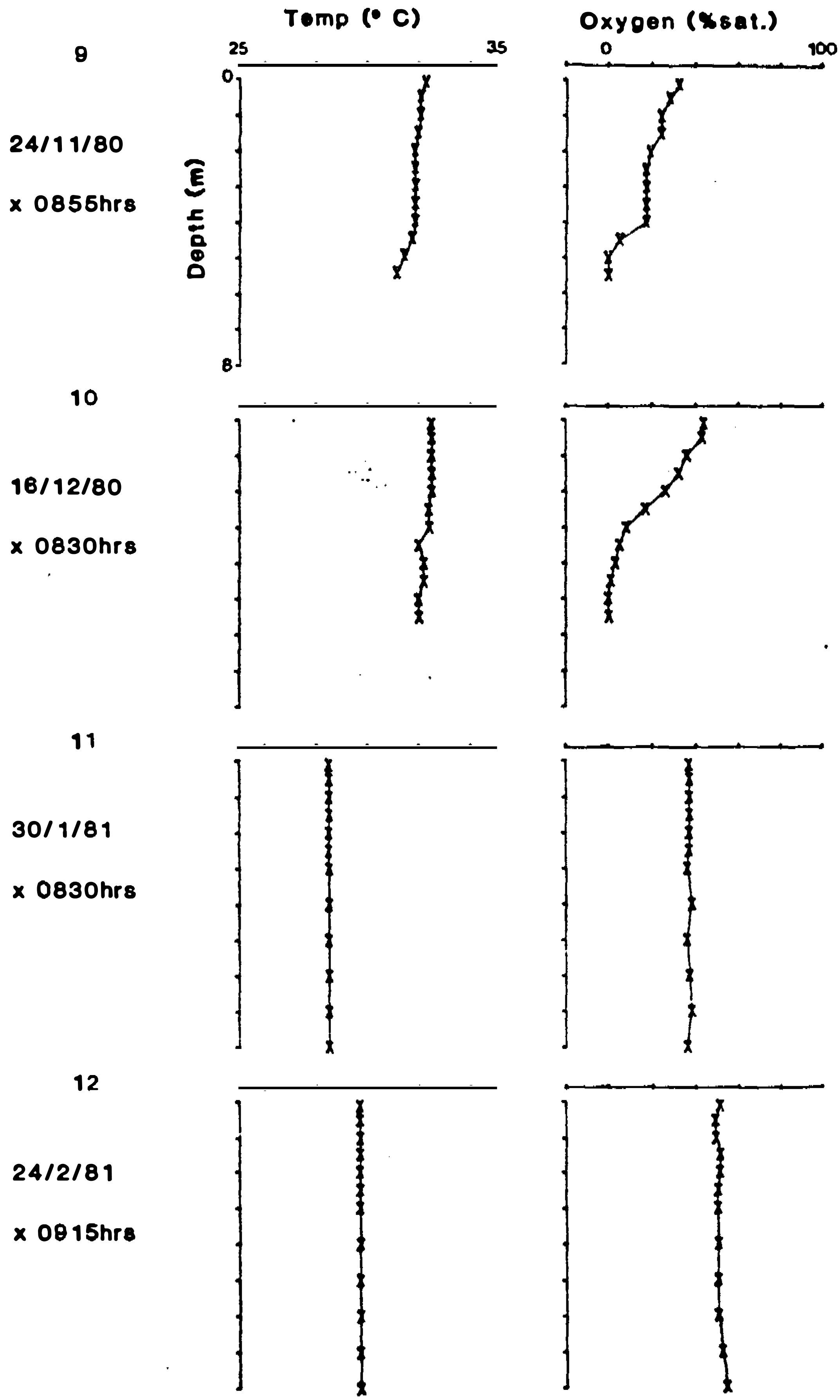
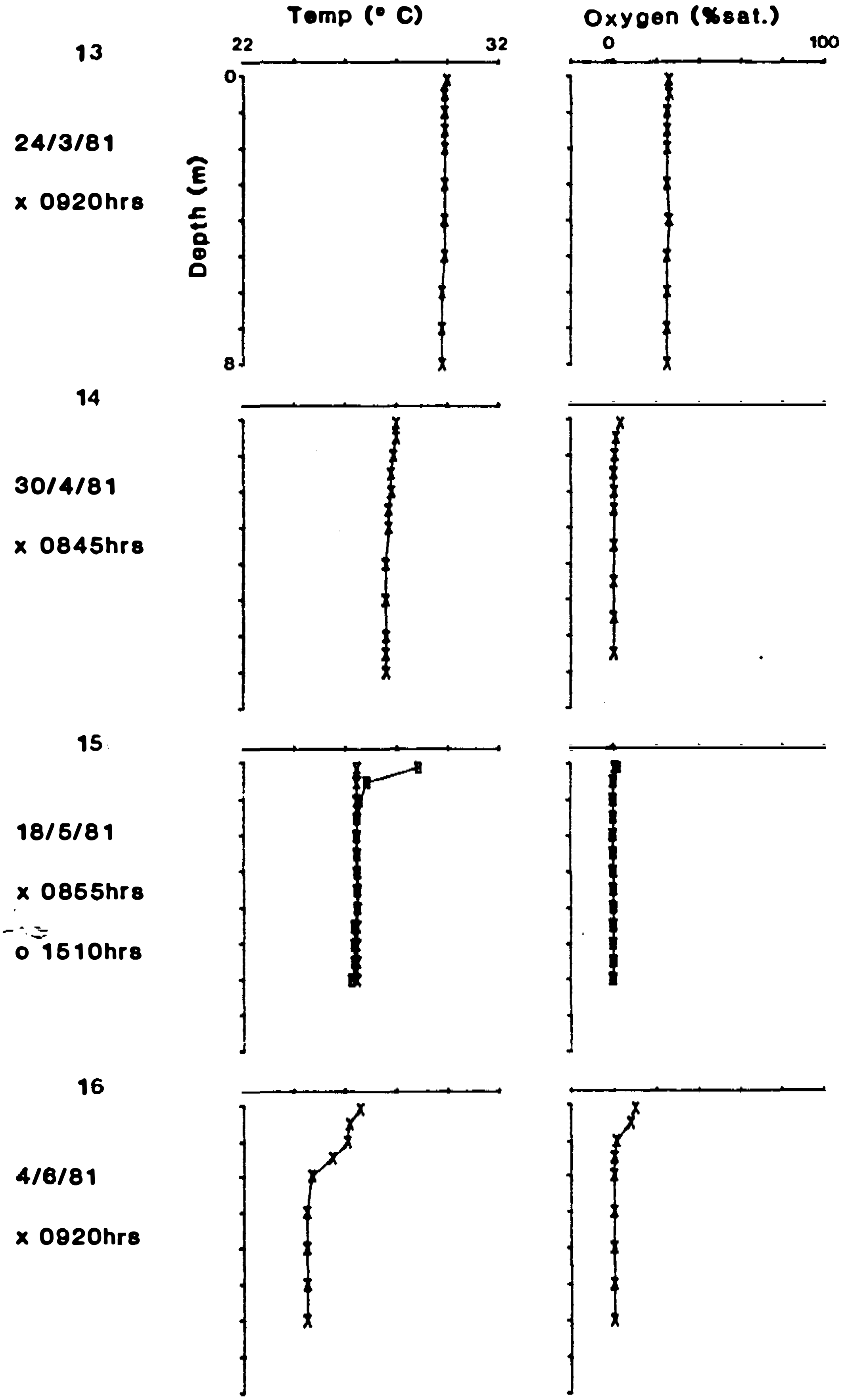


FIG. A1 (cont.)



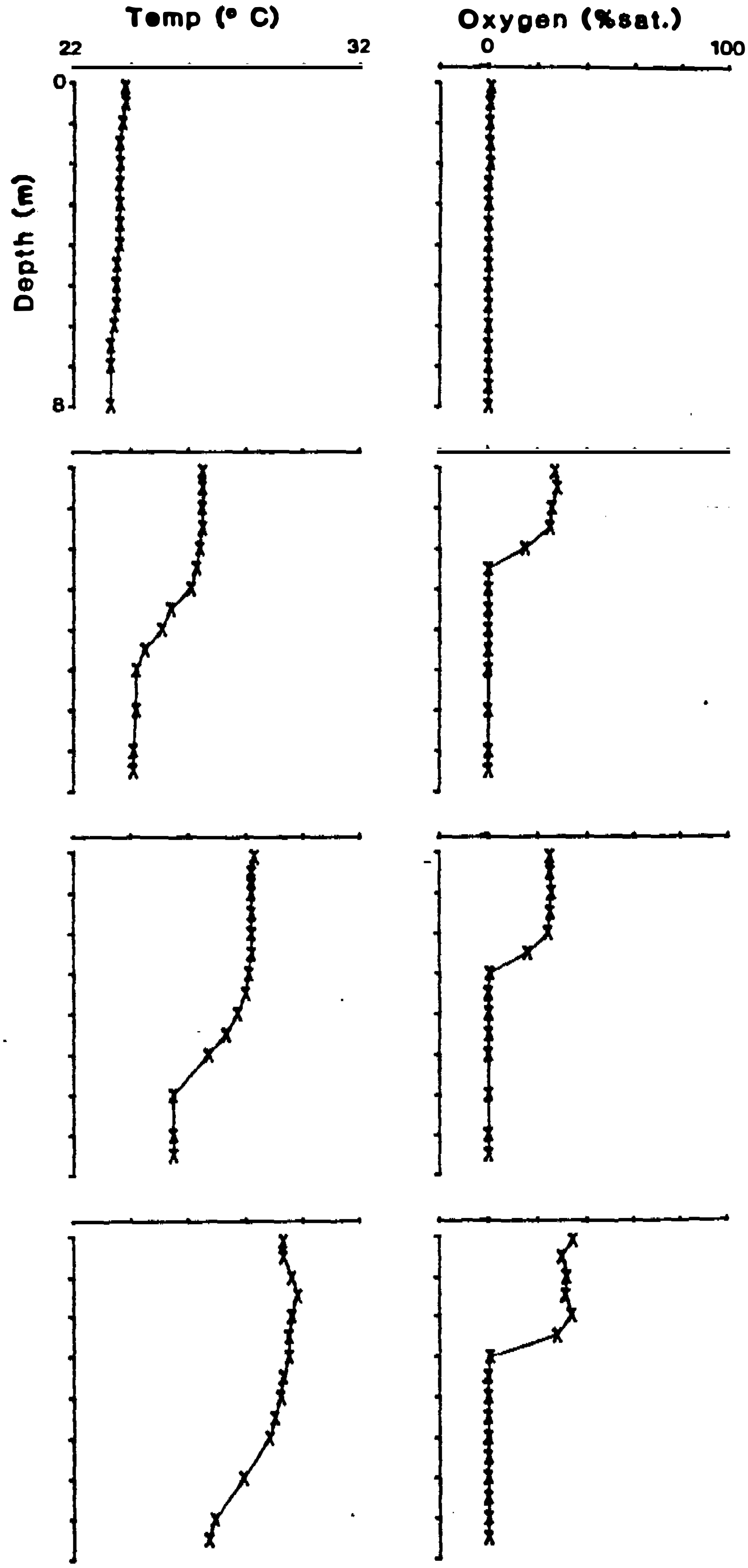
Temp (° C)
Oxygen (%sat.)
25
35
0
100
Depth (m)
0
8
9
24/11/80
x 0855hrs
10
16/12/80
x 0830hrs
11
30/1/81
x 0830hrs
12
24/2/81
x 0915hrs

FIG. A1 (cont.)



Temp (° C)
Oxygen (%sat.)
22
32
0
100
0
8
Depth (m)
13
24/3/81
x 0920hrs
14
30/4/81
x 0845hrs
15
18/5/81
x 0855hrs
o 1510hrs
16
4/6/81
x 0920hrs

FIG. A1 (cont.)



17

17/6/81

x 0935hrs

18

19/8/81

x 0815hrs

19

18/9/81

x 0900hrs

20

19/10/81

x 0605hrs

APPENDIX 2

Temperature and oxygen profiles in Woolwonga billabong.

FIG. A 2

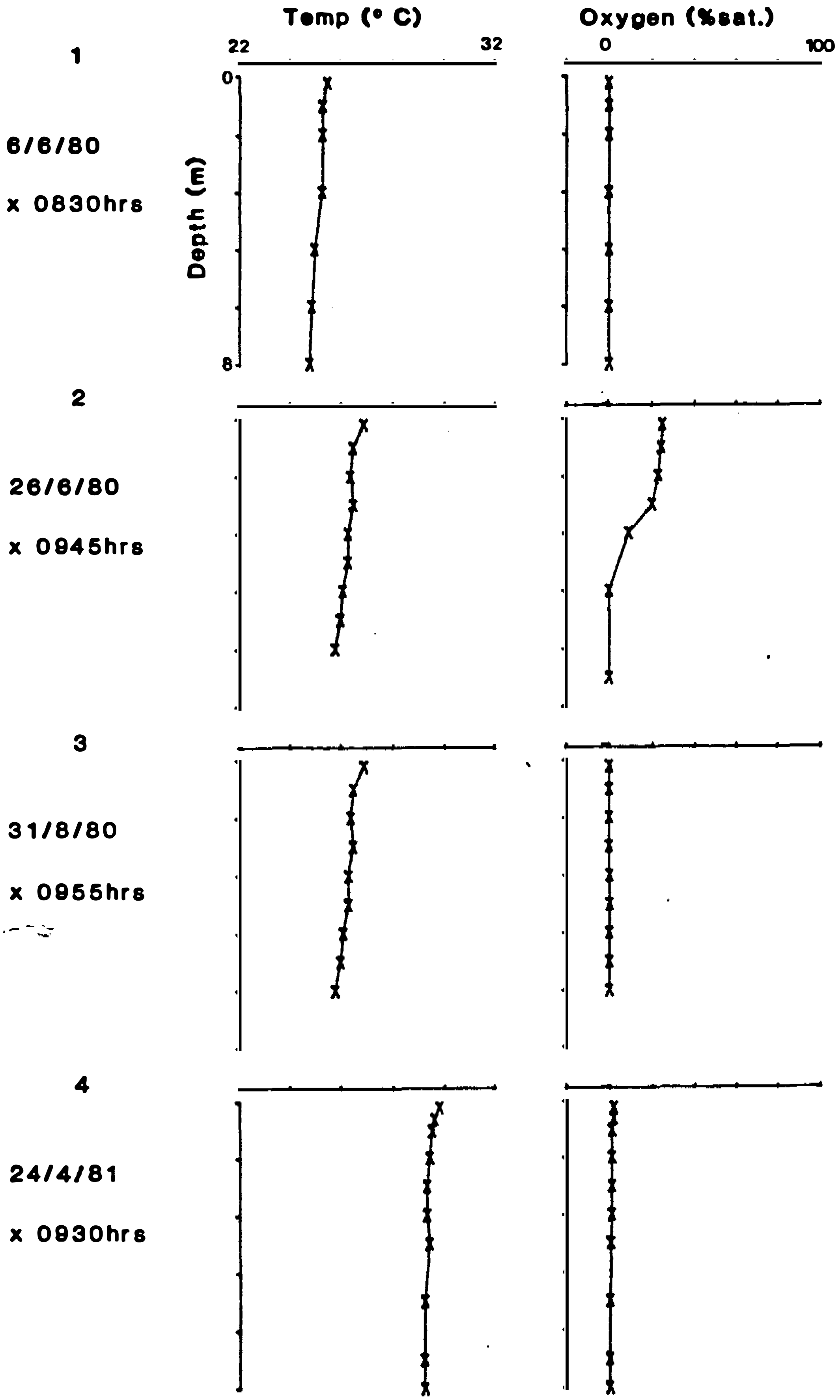
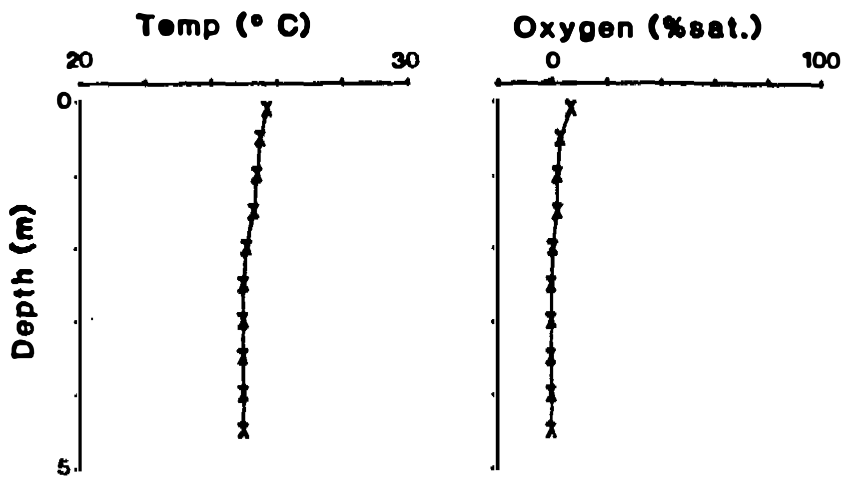

Temp (° C)
22
32
Oxygen (%sat.)
0
100
Depth (m)
0
8
1
6/6/80
x 0830hrs
2
26/6/80
x 0945hrs
3
31/8/80
x 0955hrs
4
24/4/81
x 0930hrs

FIG. A2 (cont.)

5

15/6/81

x 1000hrs



APPENDIX 3

Temperature and oxygen profiles in Red Lily billabong.

FIG. A3

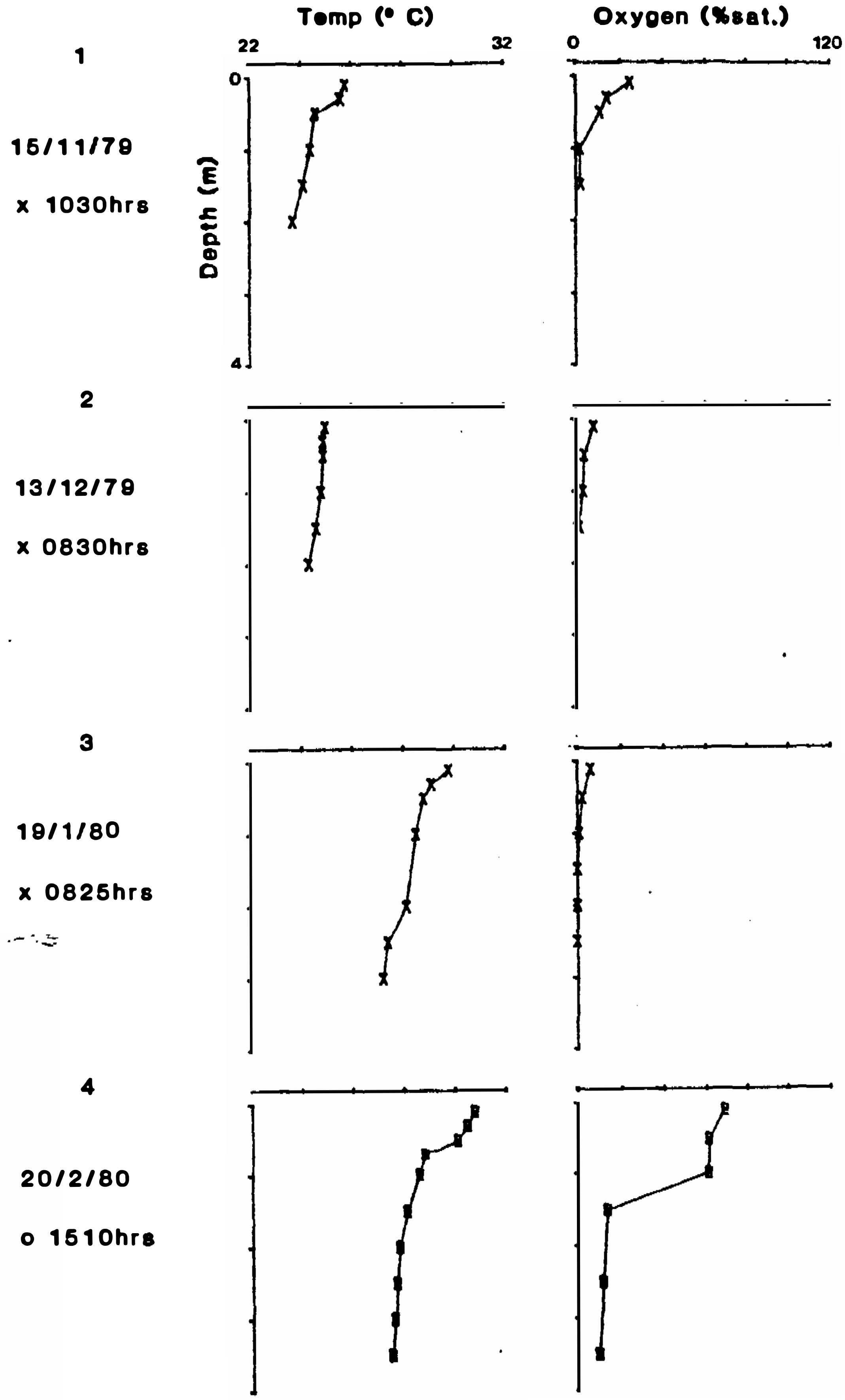
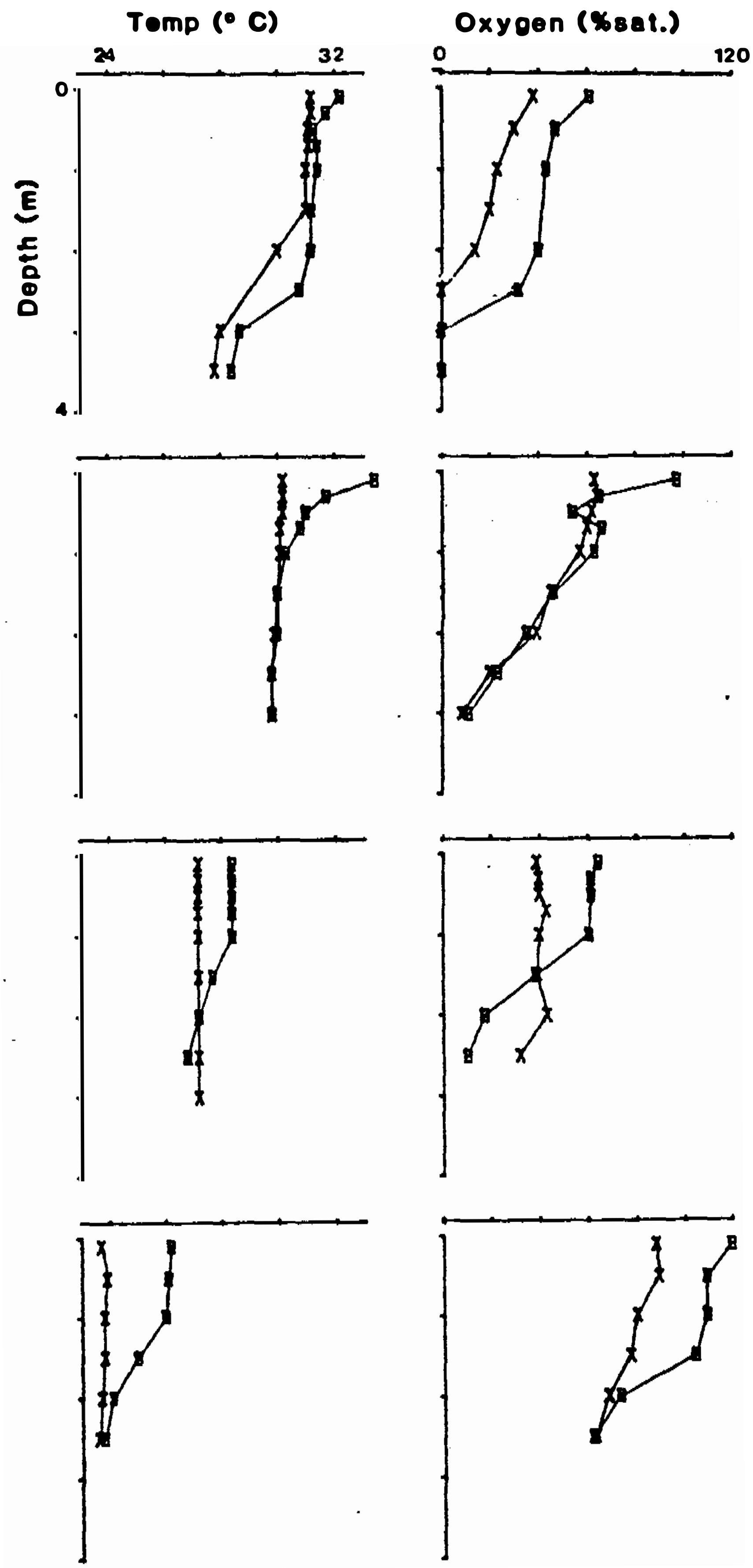

Temp (° C)
22
32
Oxygen (%sat.)
0
120
0
Depth (m)
4
1
15/11/79
x 1030hrs
2
13/12/79
x 0830hrs
3
19/1/80
x 0825hrs
4
20/2/80
o 1510hrs

FIG. A 3 (cont.)



5

28/3/80

x 0930hrs

o 1530hrs

6

22/4/80

x 0915hrs

o 1430hrs

7

29/5/80

x 0930hrs

o 1430hrs

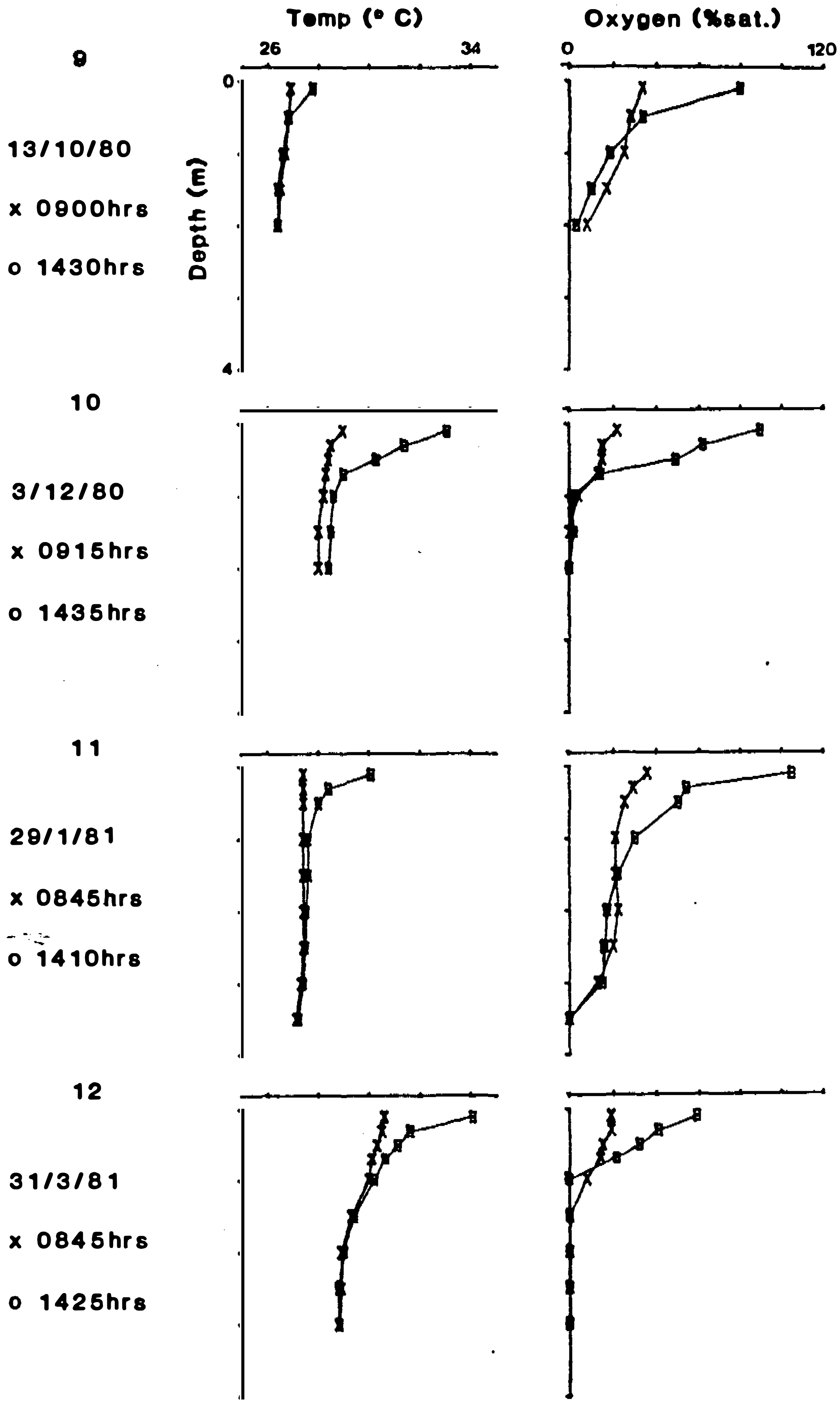
8

6/8/80

x 0900hrs

o 1515hrs

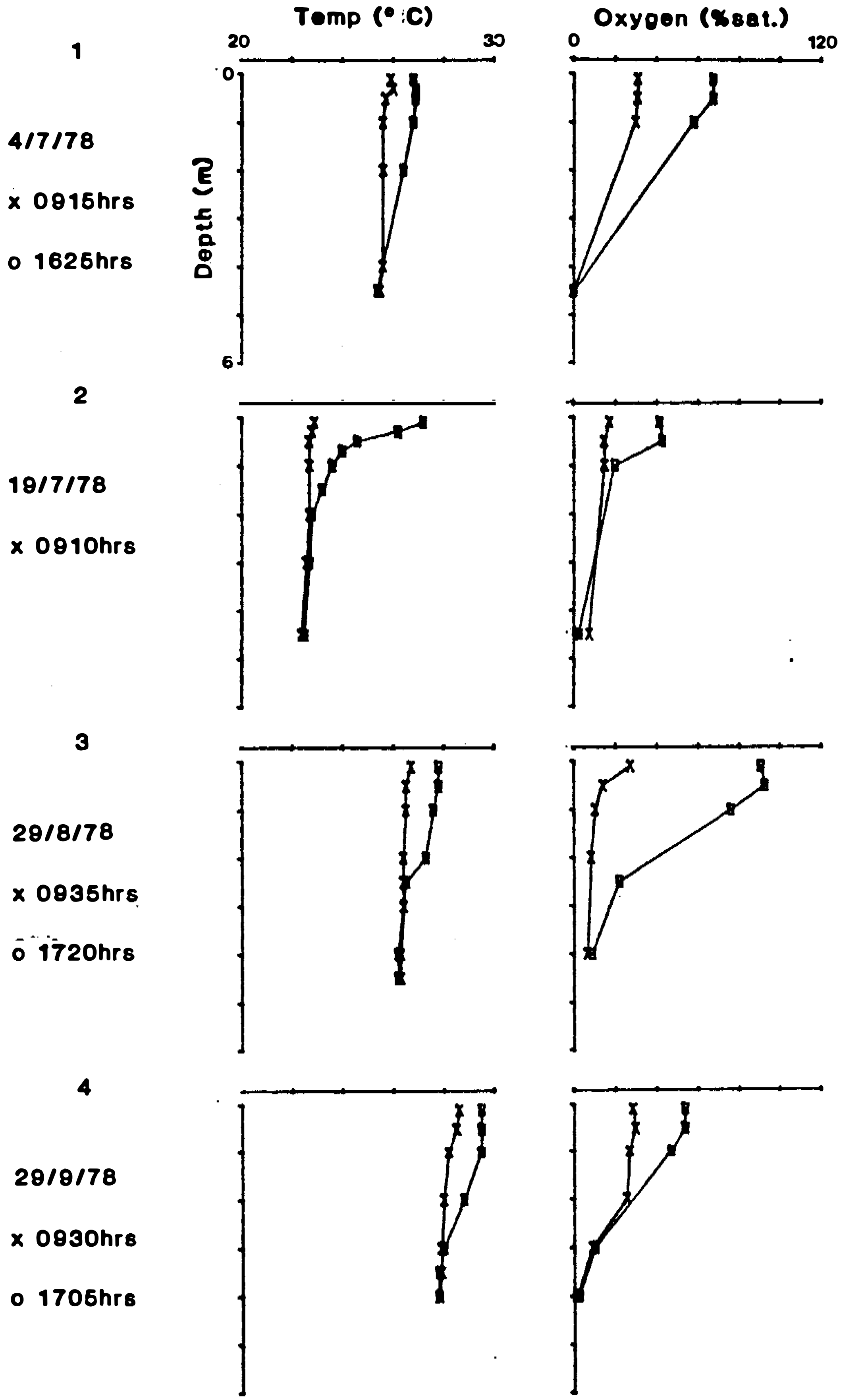
FIG. A 3 (cont.)


Temp (° C)
26
34
Oxygen (%sat.)
0
120
Depth (m)
0
4
9
13/10/80
x 0900hrs
o 1430hrs
10
3/12/80
x 0915hrs
o 1435hrs
11
29/1/81
x 0845hrs
o 1410hrs
12
31/3/81
x 0845hrs
o 1425hrs

APPENDIX 4

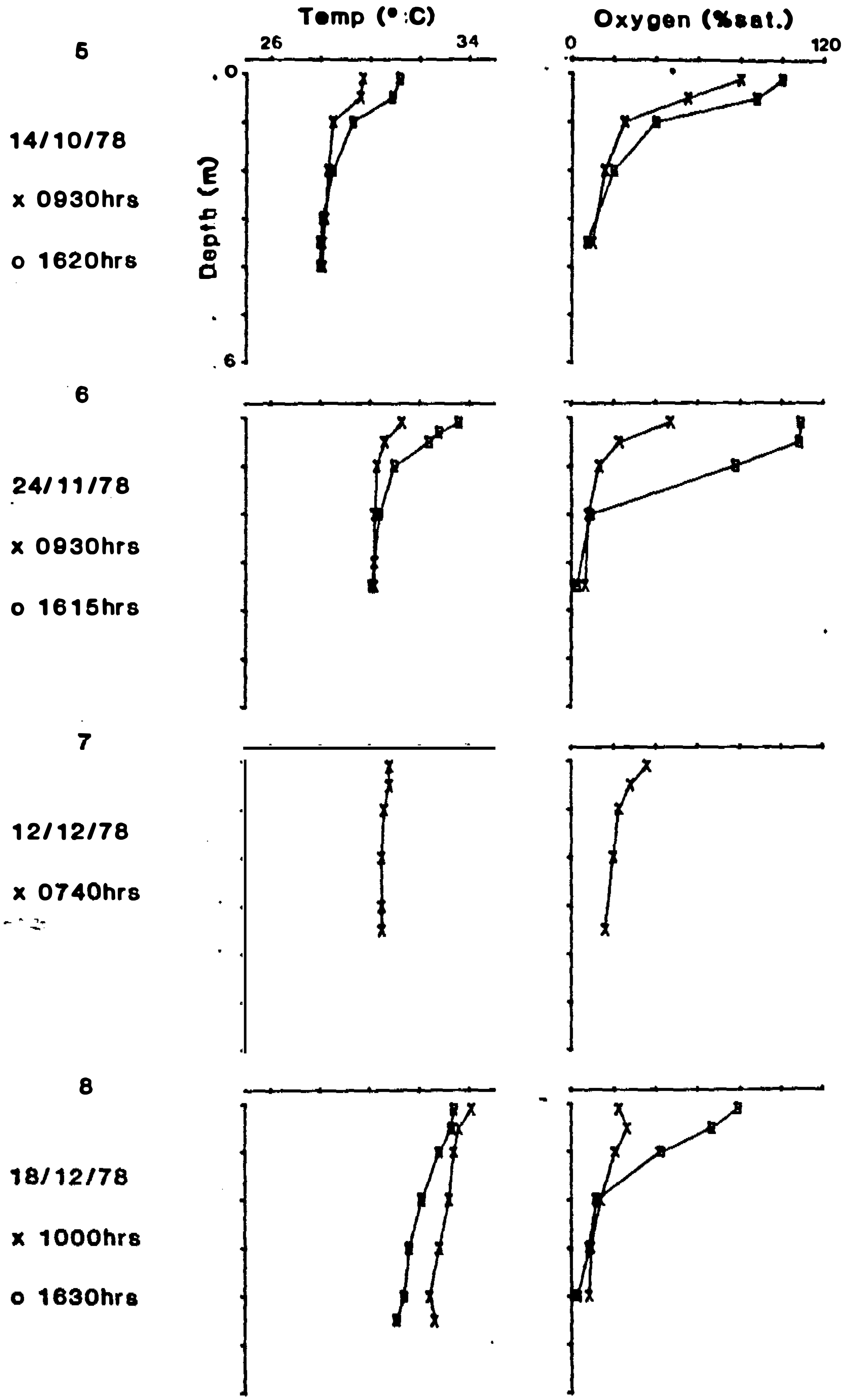
Temperature and oxygen profiles in Leichhardt billabong.

FIG. A 4



Temp (°C)
20
30
Oxygen (%sat.)
0
120
0
6
Depth (m)
1
4/7/78
x 0915hrs
o 1625hrs
2
19/7/78
x 0910hrs
3
29/8/78
x 0935hrs
o 1720hrs
4
29/9/78
x 0930hrs
o 1705hrs

FIG. A 4 (cont.)



Temp (°C)
Oxygen (%sat.)
26
34
0
120
Depth (m)
0
6
5
14/10/78
x 0930hrs
o 1620hrs
6
24/11/78
x 0930hrs
o 1615hrs
7
12/12/78
x 0740hrs
8
18/12/78
x 1000hrs
o 1630hrs

FIG. A 4 (cont.)

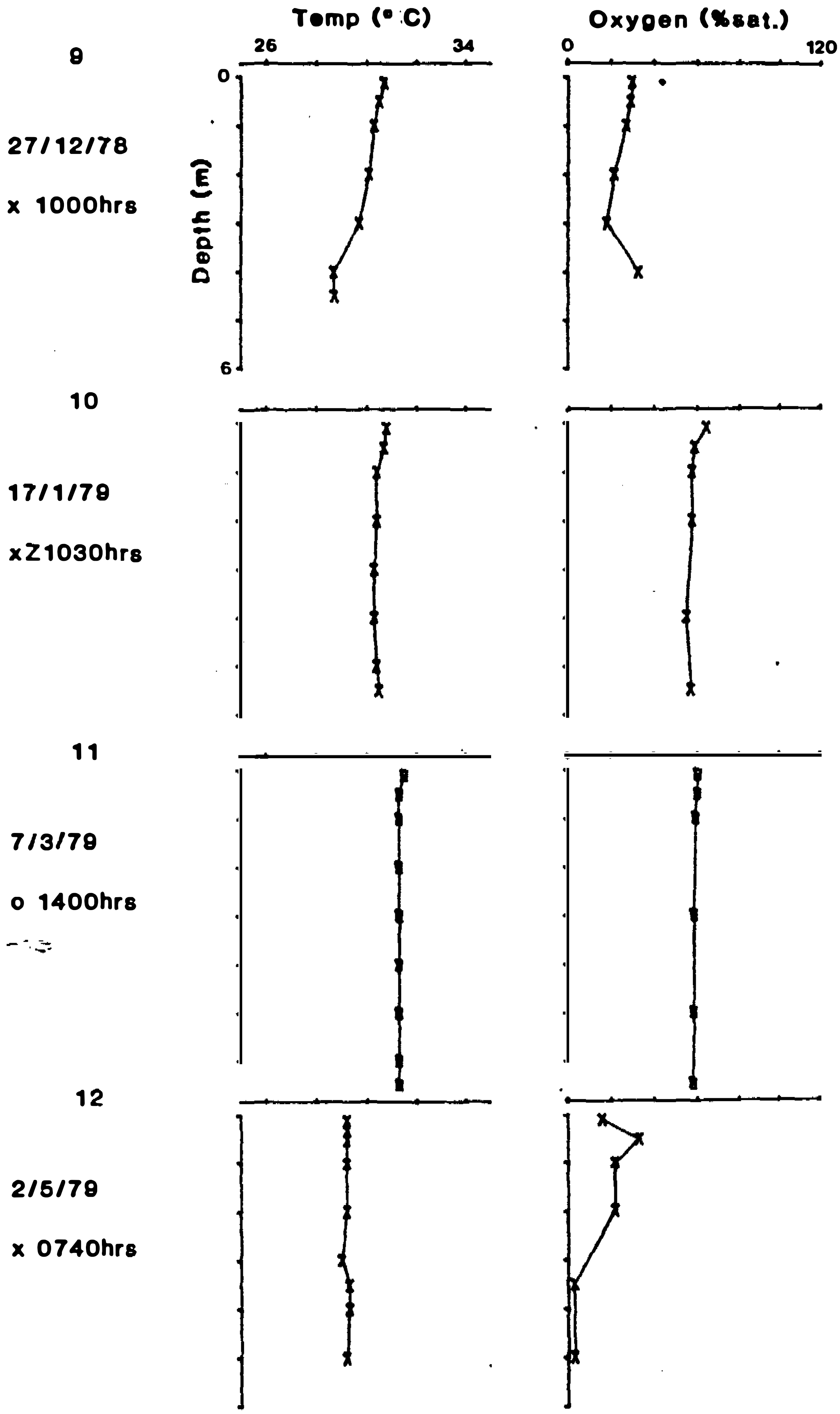

Temp (°C)
Oxygen (%sat.)
26
34
0
120
Depth (m)
0
6
9
27/12/78
x 1000hrs
10
17/1/79
xZ1030hrs
11
7/3/79
o 1400hrs
12
2/5/79
x 0740hrs

FIG. A 4 (cont.)

13

9/5/79

o 1730hrs

-14

8/6/79

x 0745hrs

o 1540hrs

15

10/7/79

x 0740hrs

o 1550hrs

16

1/8/79

x 0815hrs

o 1520hrs

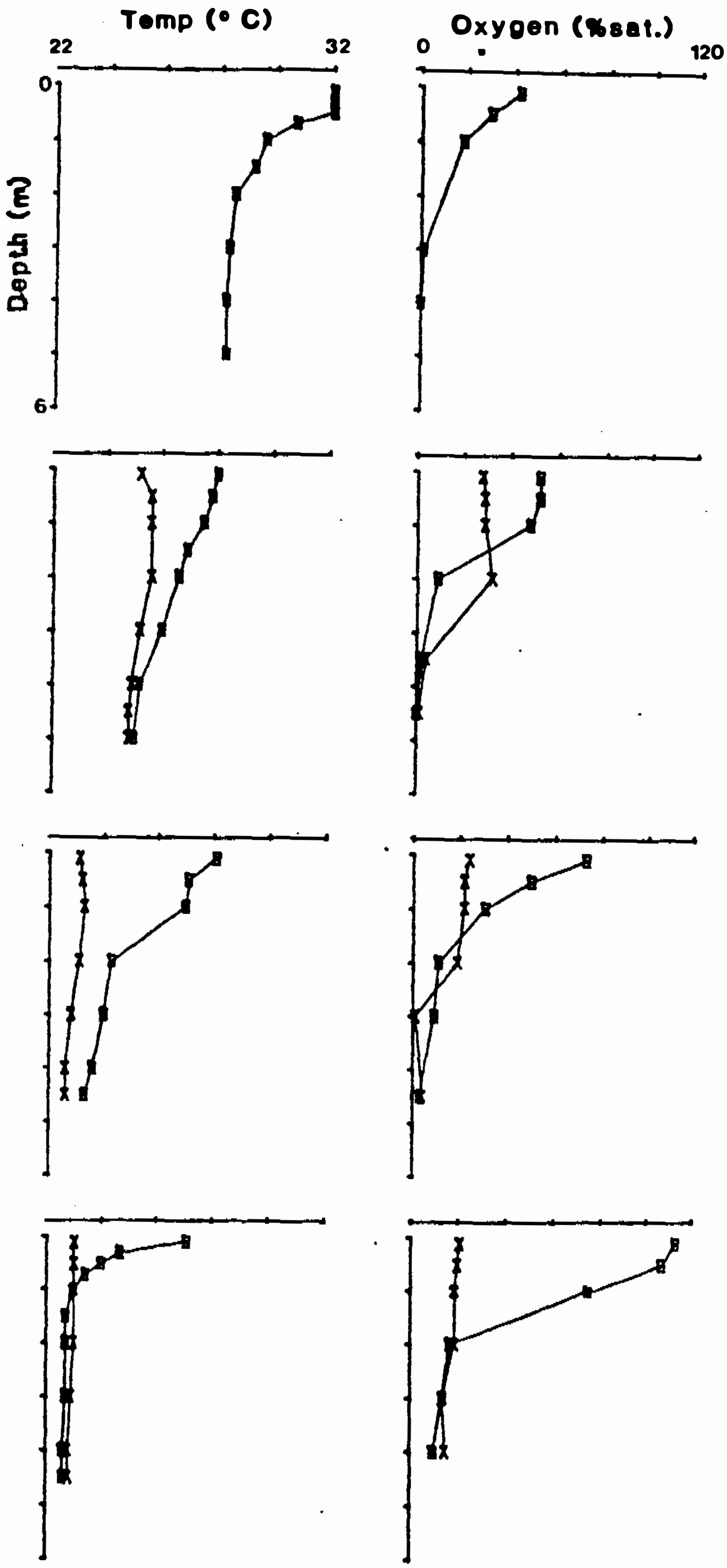


FIG. A 4 (cont.)

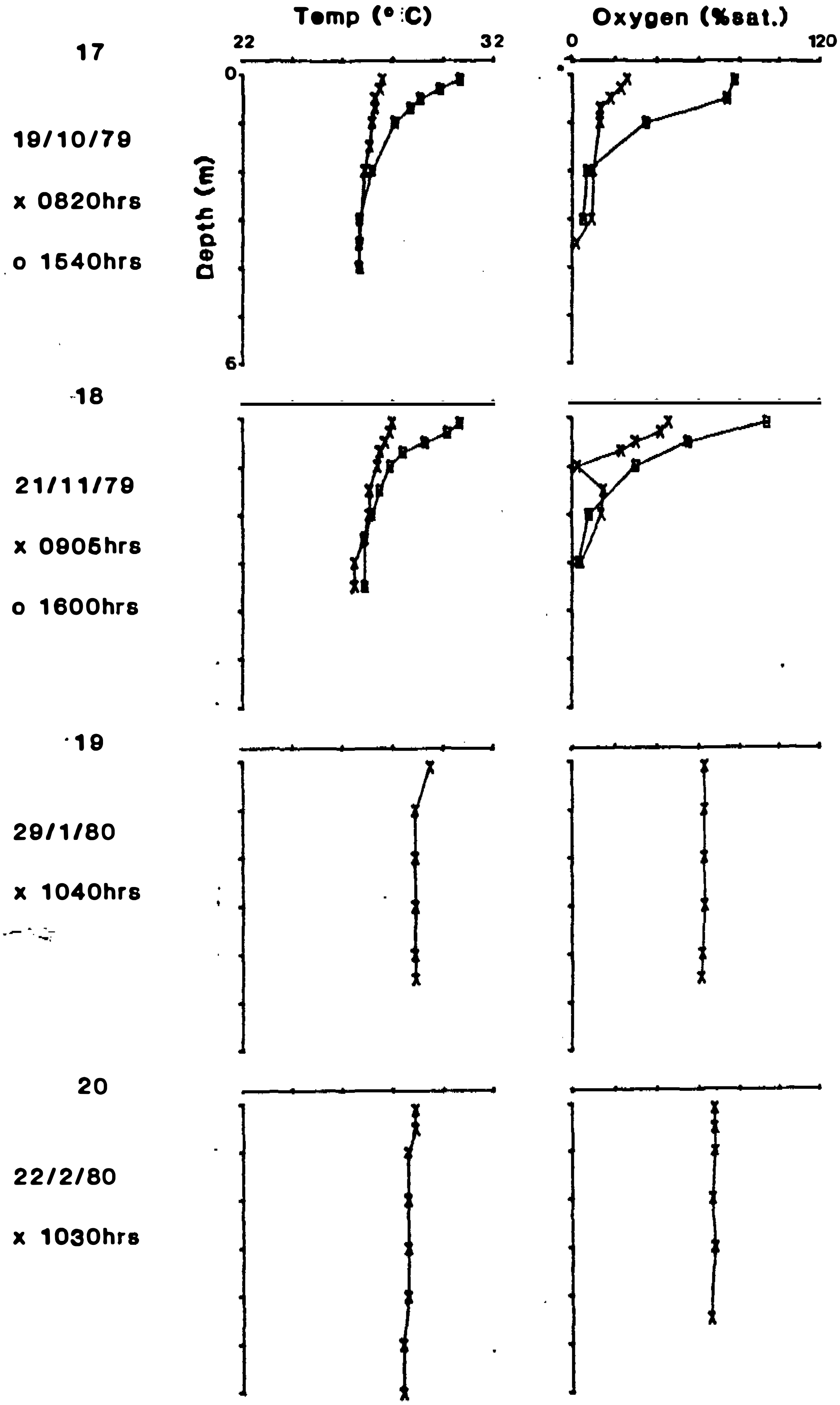
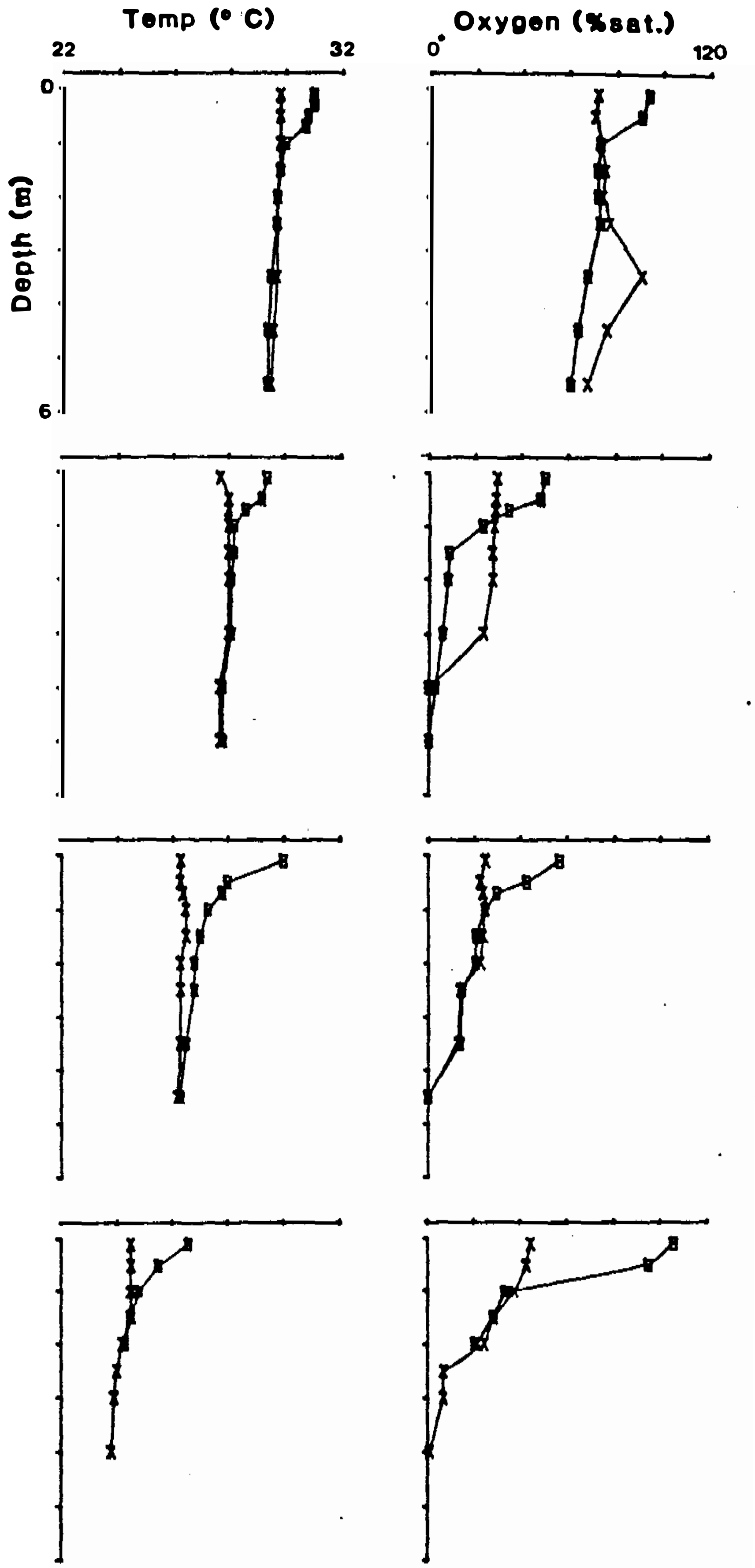

Temp (° C)
Oxygen (%sat.)
22
32
0
120
0
6
Depth (m)
17
19/10/79
x 0820hrs
o 1540hrs
18
21/11/79
x 0905hrs
o 1600hrs
19
29/1/80
x 1040hrs
20
22/2/80
x 1030hrs

FIG. A4' (cont.)



21

1/4/80

x 0820hrs

o 1420hrs

22

13/5/80

x 0805hrs

o 1430hrs

23

4/6/80

x 0820hrs

o 1425hrs

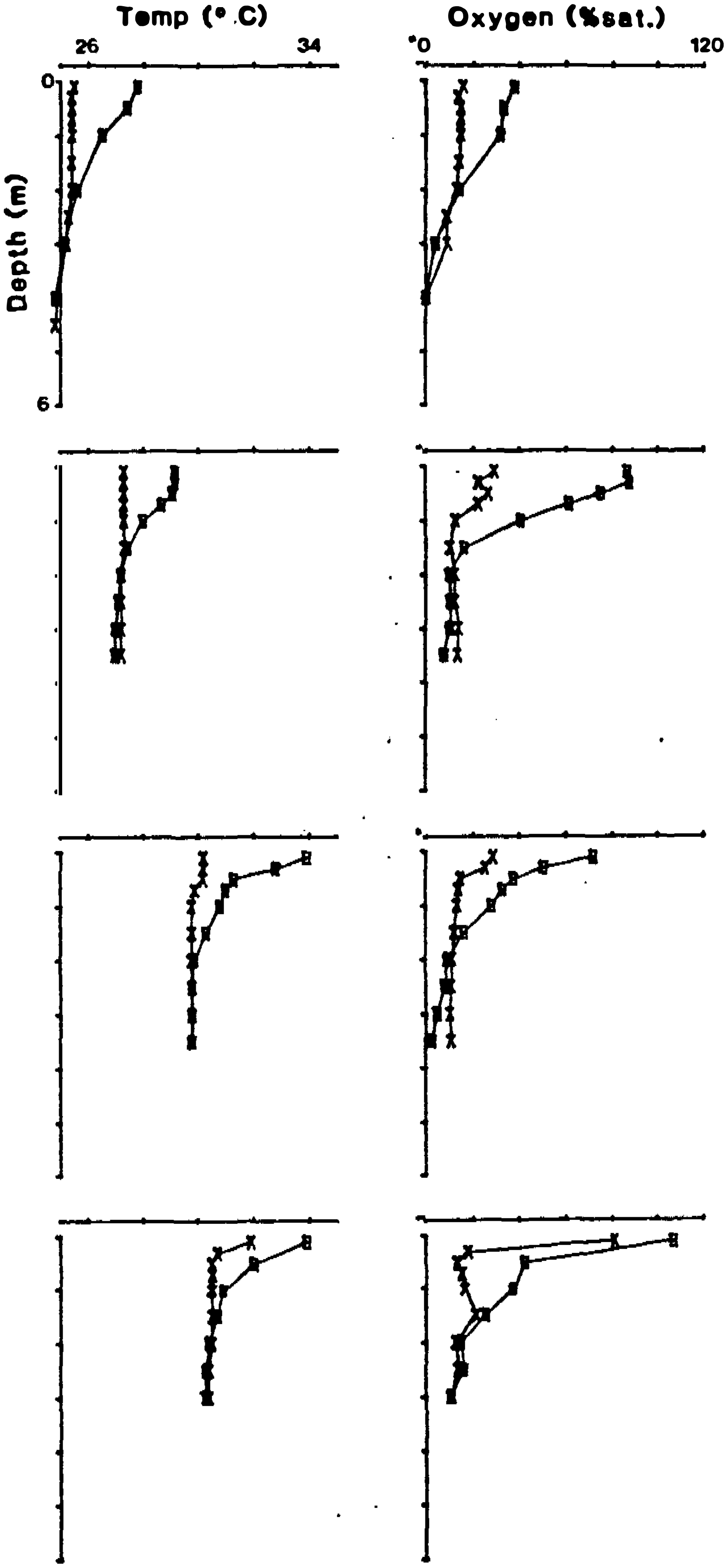
24

13/7/80

x 0830hrs

o 1430hrs

FIG. A 4 (cont.)



25

15/8/80

x 0745hrs

o 1500hrs

26

5/9/80

x 0830hrs

o 1500hrs

27

16/10/80

x 0850hrs

o 1500hrs

28

10/11/80

x 0905hrs

o 1450hrs

FIG. A4 (cont.)

29

12/12/80

x 0910hrs

o 1500hrs

30

18/12/80

x 0830hrs

31

23/12/80

x 1100hrs

32

24/12/80

x 1045hrs

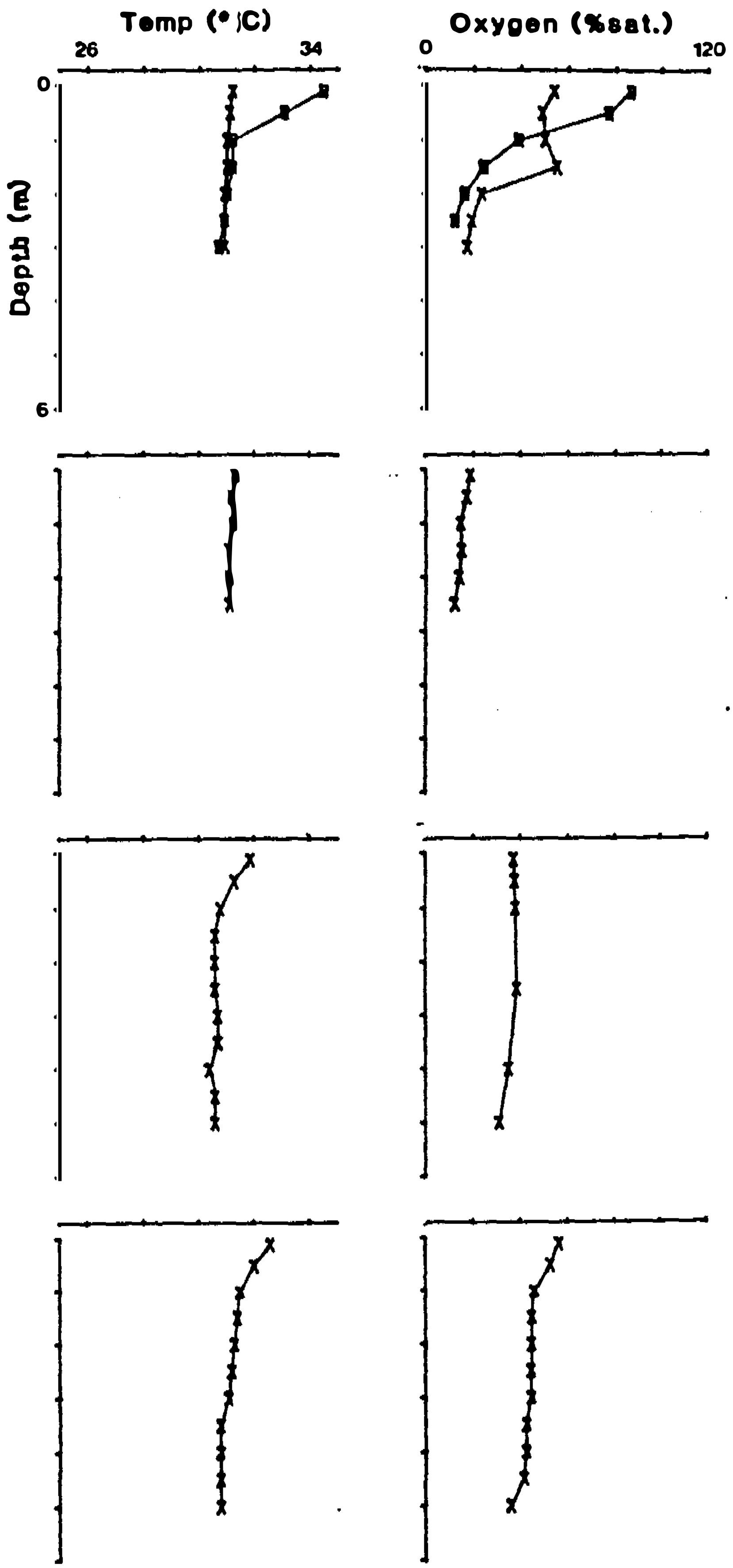


FIG. A4 (cont.)

33

7/1/81

x 1100hrs

34

9/2/81

x 1110hrs

35

18/3/81

x 0940hrs

o 1500hrs

36

7/4/81

x 0700hrs

o 1420hrs

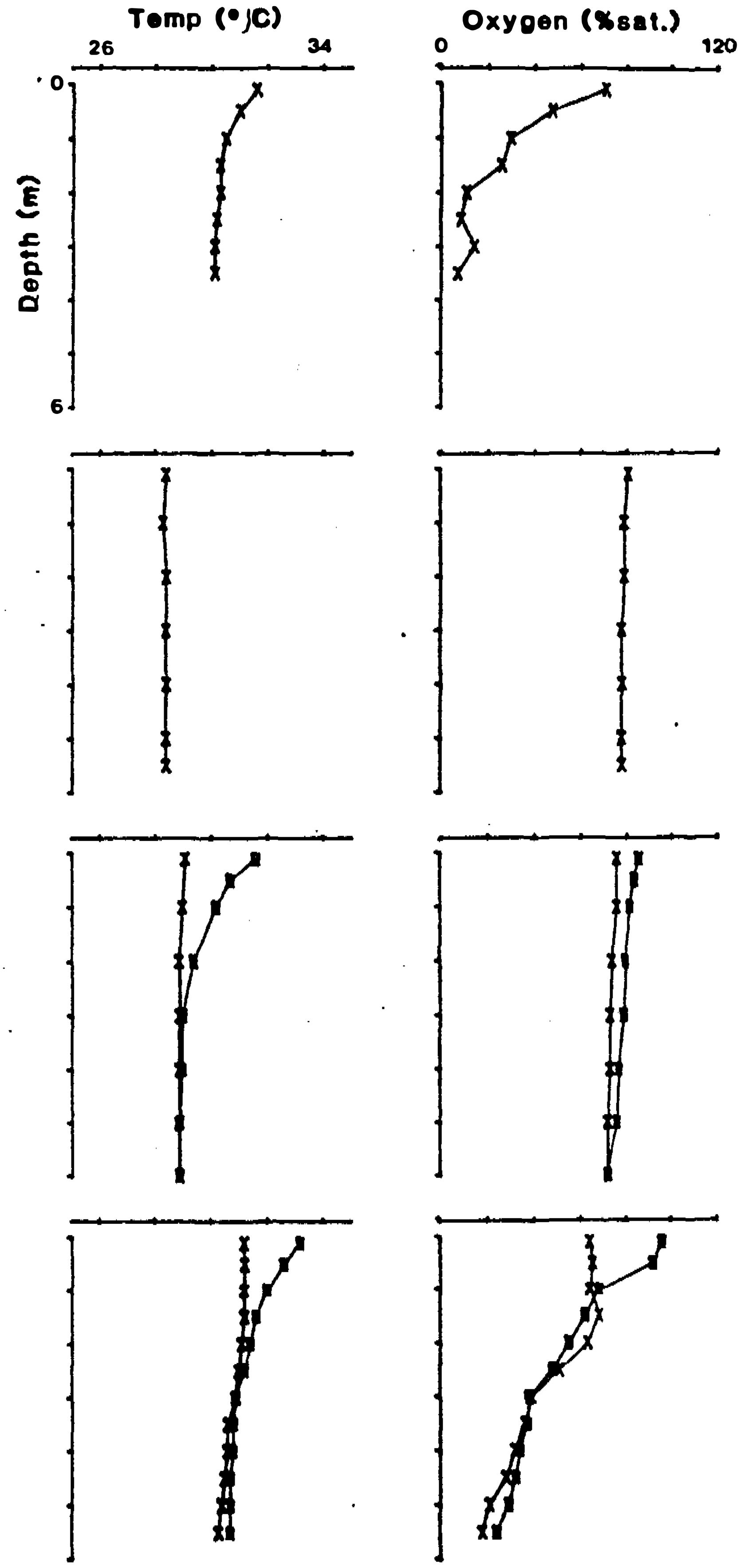
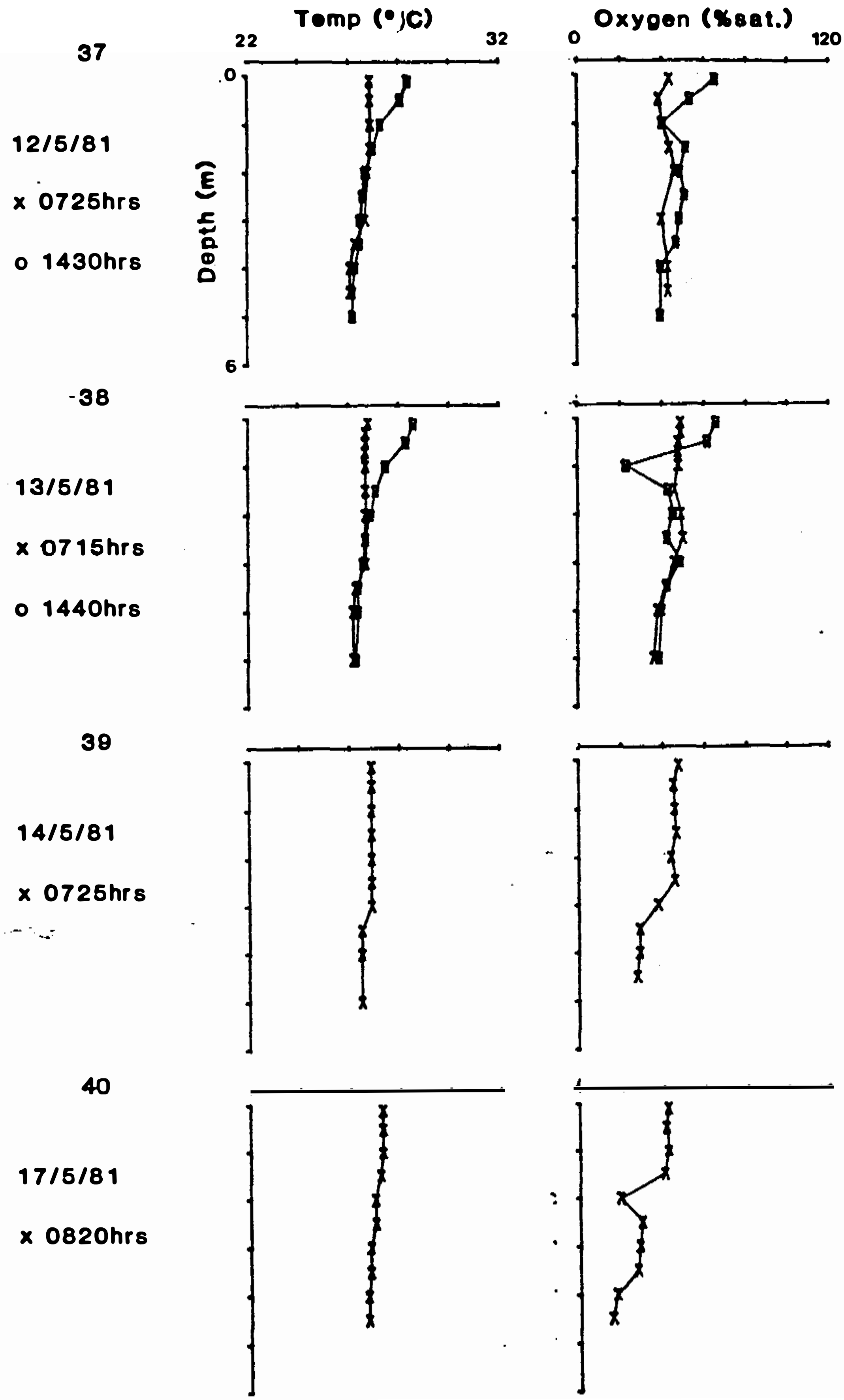


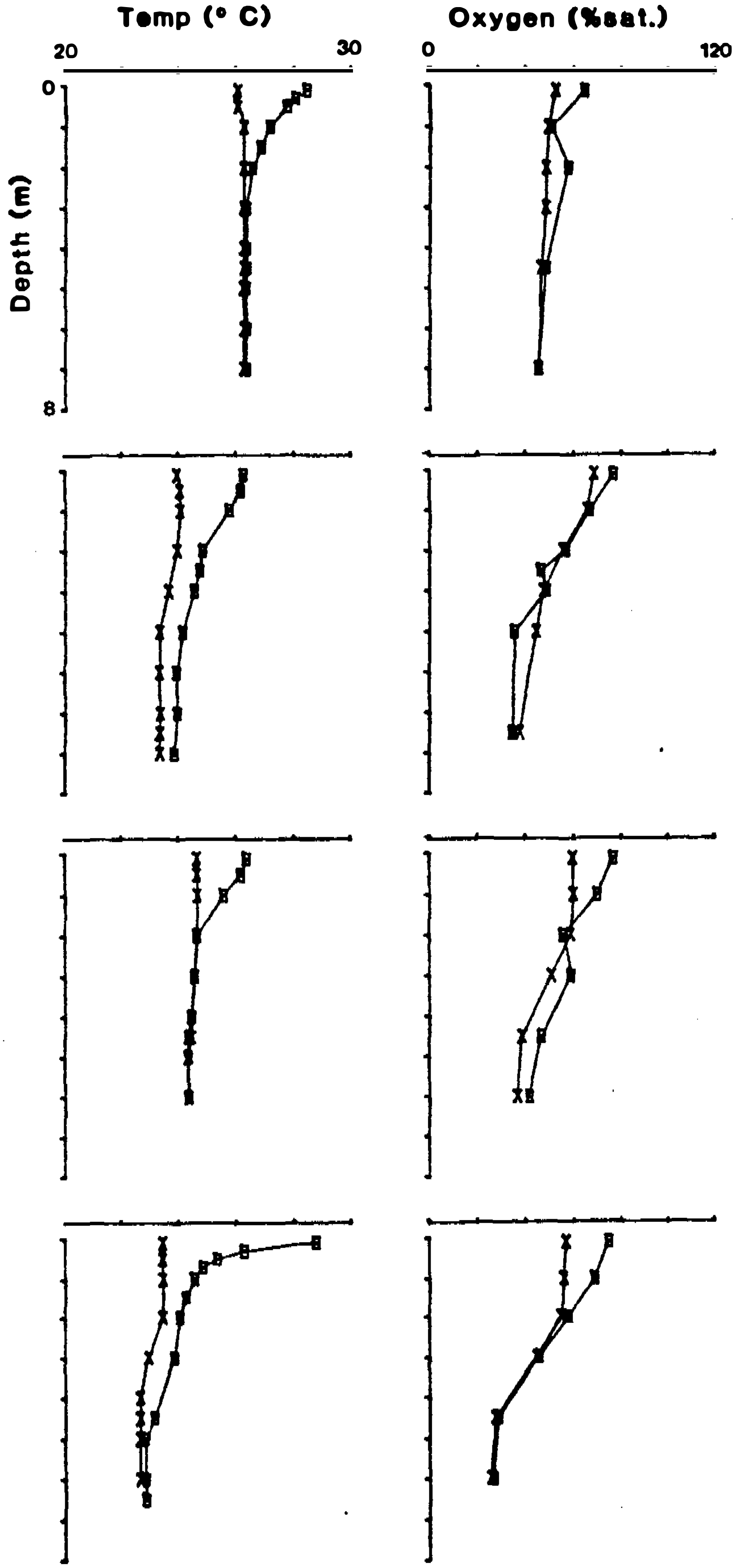
FIG. A4 (cont.)


Temp (°)C)
22
32
Oxygen (%sat.)
0
120
Depth (m)
0
6
37
12/5/81
x 0725hrs
o 1430hrs
38
13/5/81
x 0715hrs
o 1440hrs
39
14/5/81
x 0725hrs
40
17/5/81
x 0820hrs

APPENDIX 5

Temperature and oxygen profiles in Noarlanga billabong.

FIG. A5



1

17/5/79

x 0640hrs

o 1620hrs

2

28/6/79

x 0750hrs

o 1645hrs

3

24/7/79

x 0825hrs

o 1550hrs

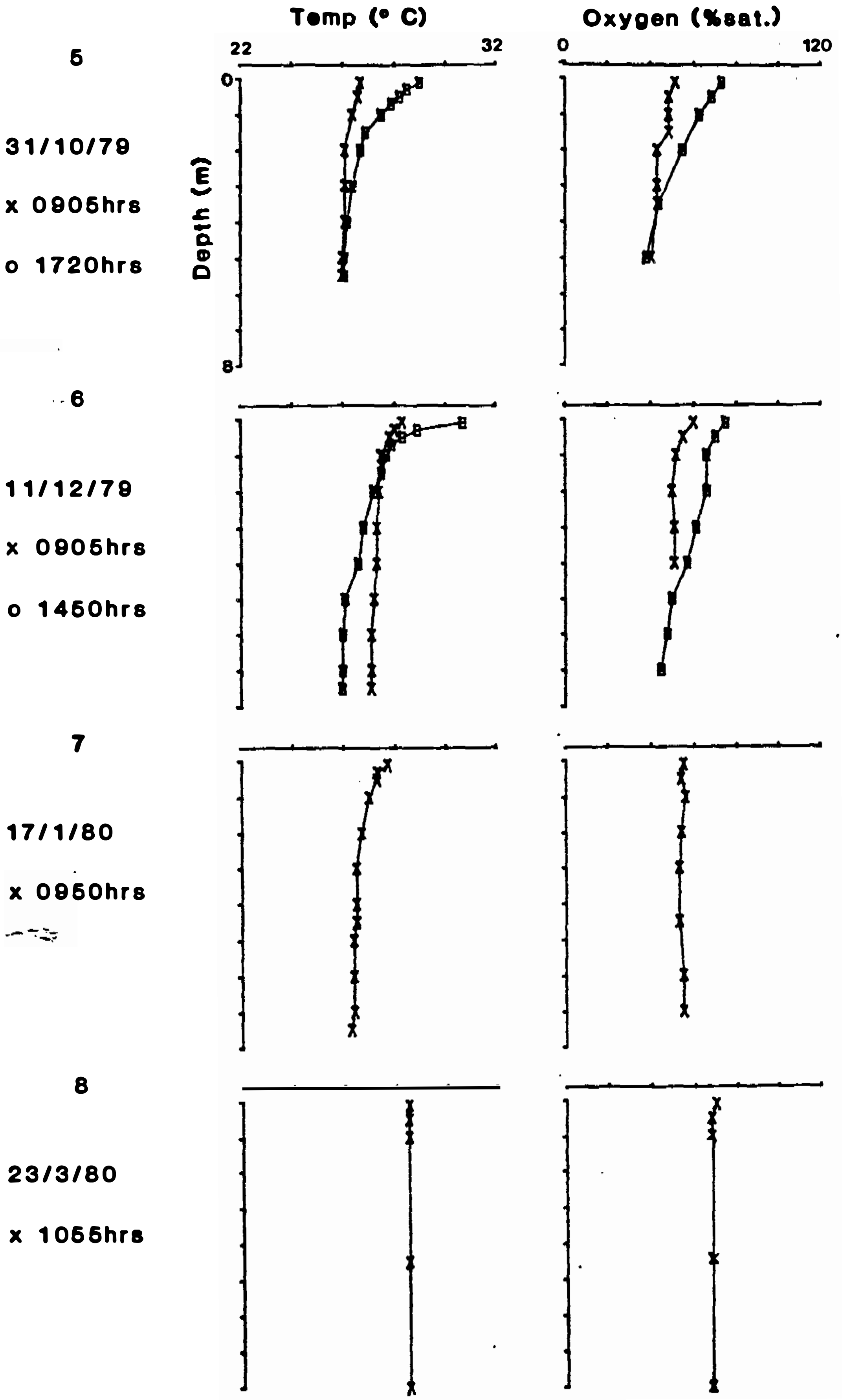
4

22/8/79

x 0805hrs

o 1545hrs

FIG. A5 (cont.)



Temp (° C)
Oxygen (%sat.)
22
32
0
120
0
8
Depth (m)
5
31/10/79
x 0905hrs
o 1720hrs
6
11/12/79
x 0905hrs
o 1450hrs
7
17/1/80
x 0950hrs
8
23/3/80
x 1055hrs

FIG. A5 (cont.)

9

23/5/80

x 0920hrs

o 1520hrs

10

10/6/80

x 0910hrs

o 1600hrs

11

17/7/80

x 0905hrs

o 1530hrs

12

8/8/80

x 0900hrs

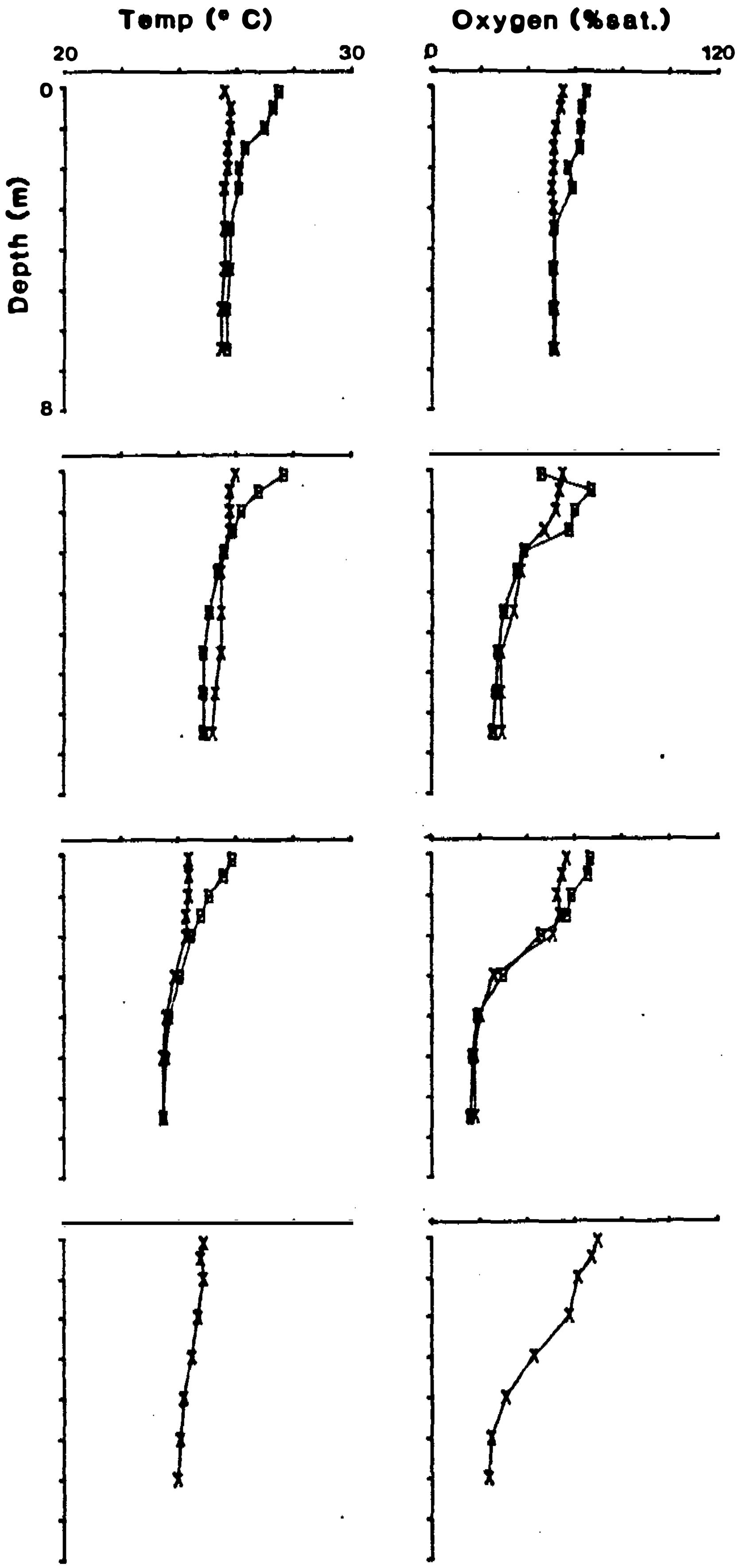
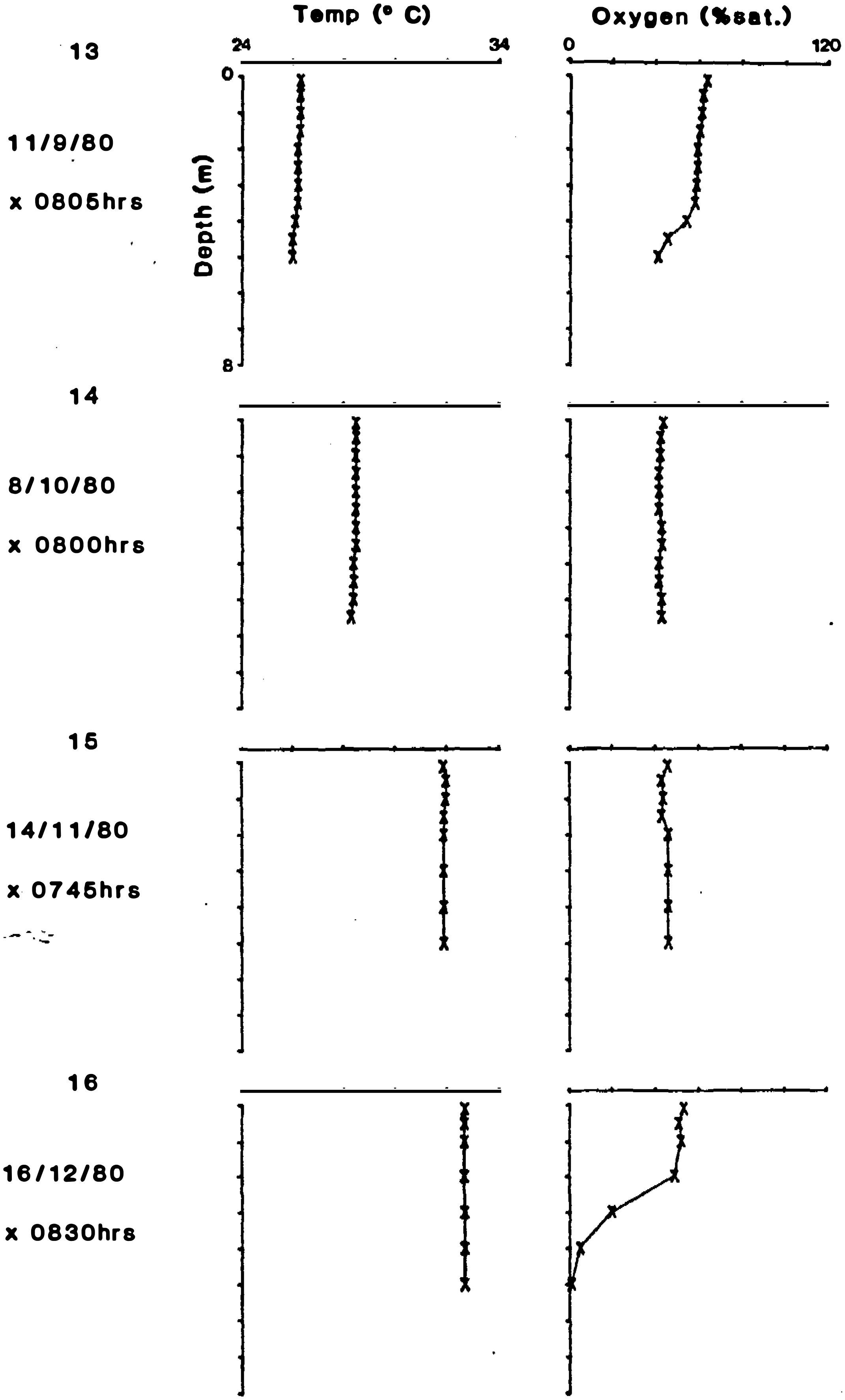
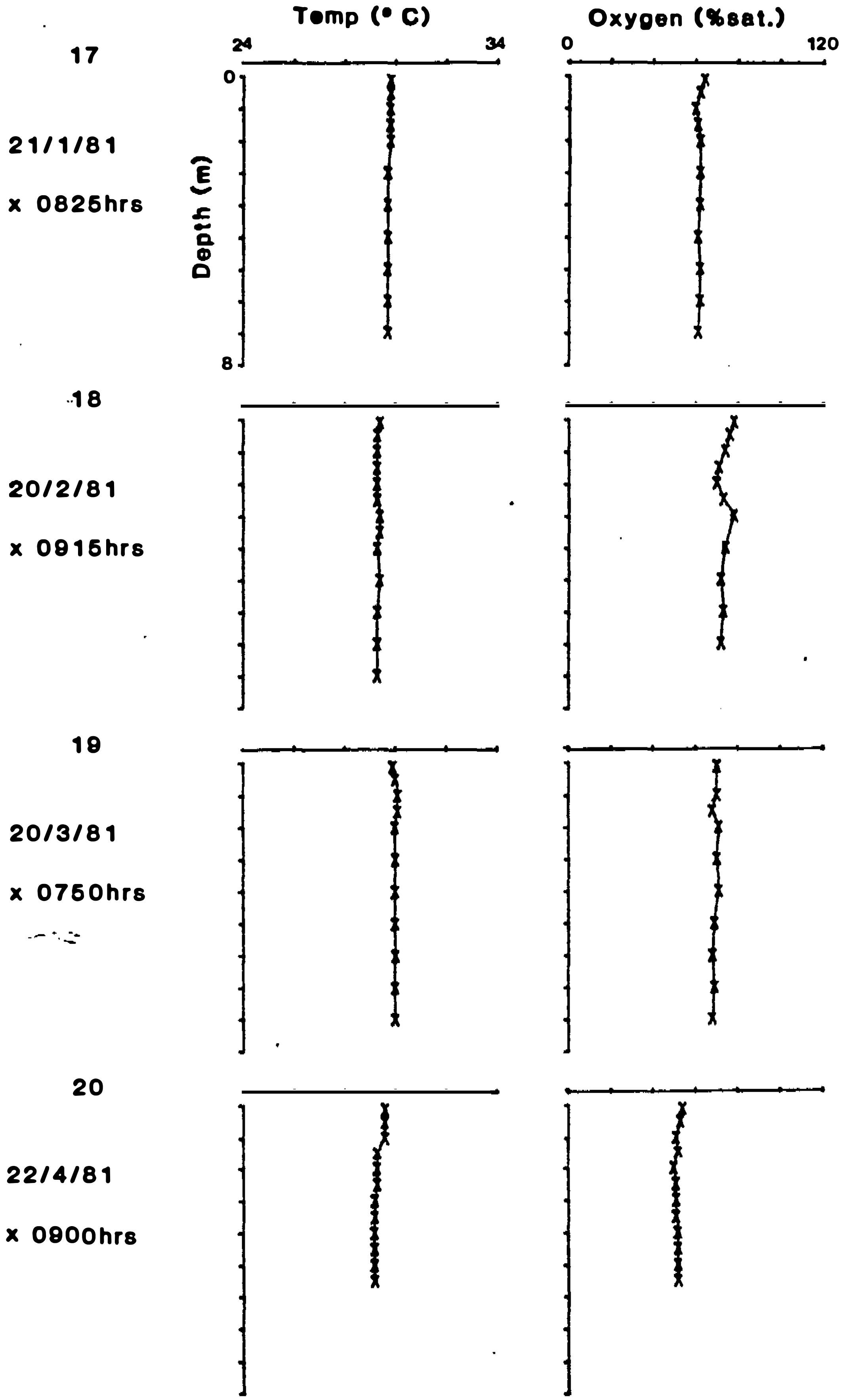


FIG. A5 (cont.)



Temp (° C)
Oxygen (%sat.)
24
34
0
120
0
8
Depth (m)
13
11/9/80
x 0805hrs
14
8/10/80
x 0800hrs
15
14/11/80
x 0745hrs
16
16/12/80
x 0830hrs

FIG. A5 (cont.)

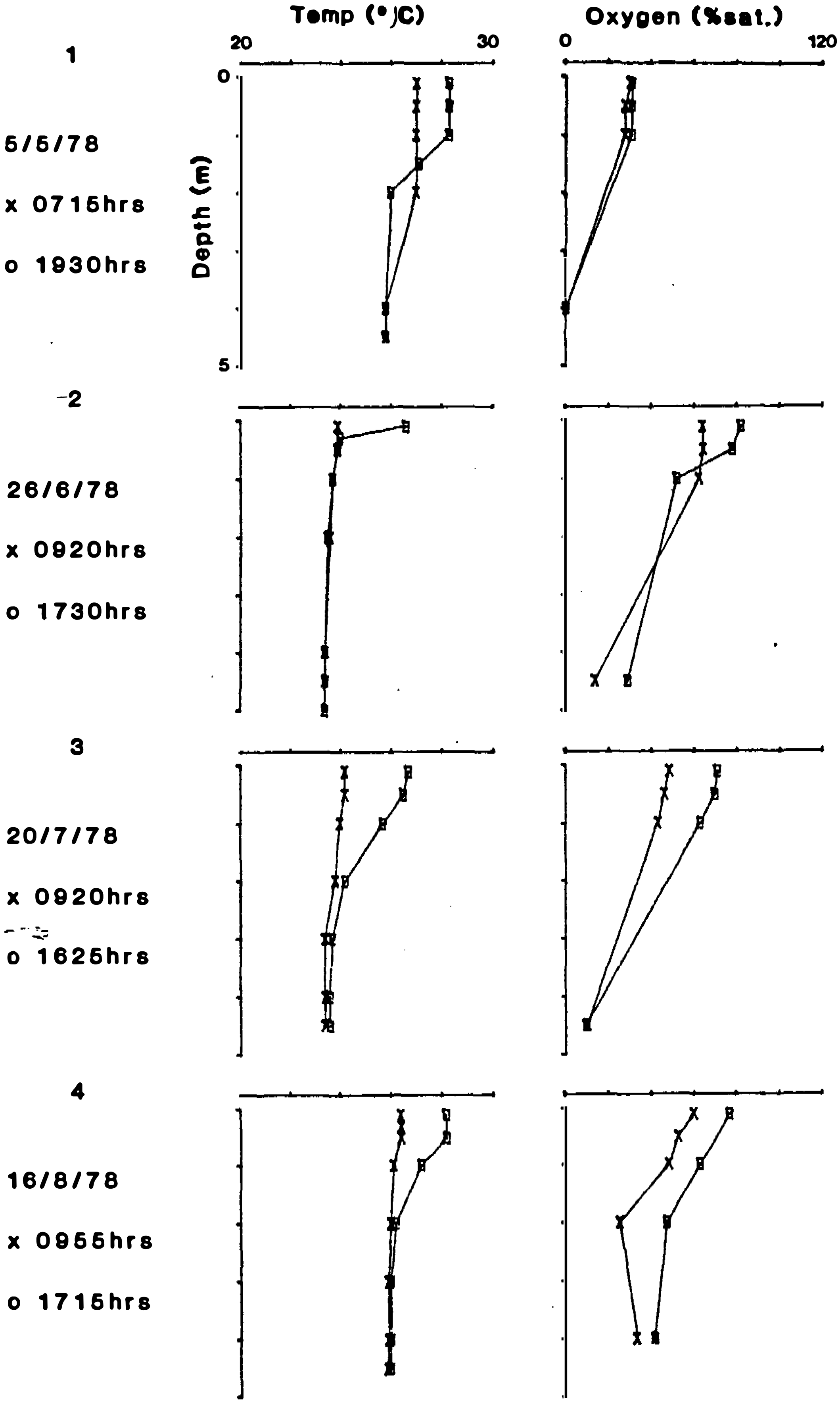


Temp (° C)
Oxygen (%sat.)
24
34
0
120
0
8
Depth (m)
17
21/1/81
x 0825hrs
18
20/2/81
x 0915hrs
19
20/3/81
x 0750hrs
20
22/4/81
x 0900hrs

APPENDIX 6

Temperature and oxygen profiles in Jabiluka billabong.

FIG. A6



Temp (°C)
20
30
Oxygen (%sat.)
0
120
Depth (m)
0
5
1
5/5/78
x 0715hrs
o 1930hrs
2
26/6/78
x 0920hrs
o 1730hrs
3
20/7/78
x 0920hrs
o 1625hrs
4
16/8/78
x 0955hrs
o 1715hrs

FIG. A6 (cont.)

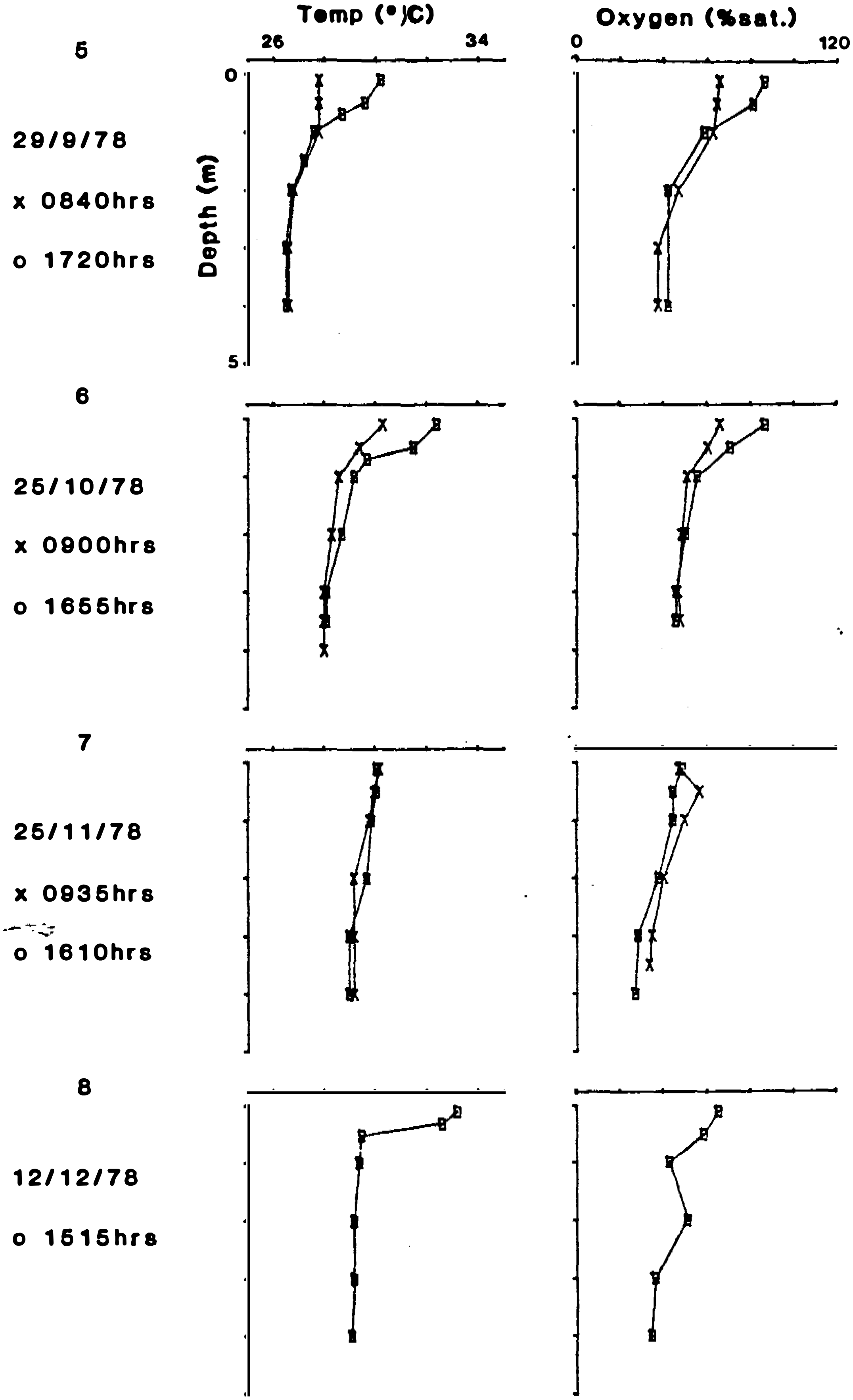

Temp (°)C)
26
34
Oxygen (%sat.)
0
120
0
5
Depth (m)
5
29/9/78
x 0840hrs
o 1720hrs
6
25/10/78
x 0900hrs
o 1655hrs
7
25/11/78
x 0935hrs
o 1610hrs
8
12/12/78
o 1515hrs

FIG. A6 (cont.)

9

19/12/78

o 1530hrs

10

5/1/79

x 1115hrs

11

8/1/79

x 1000hrs

o 1430hrs

12

1/2/79

o 1400hrs

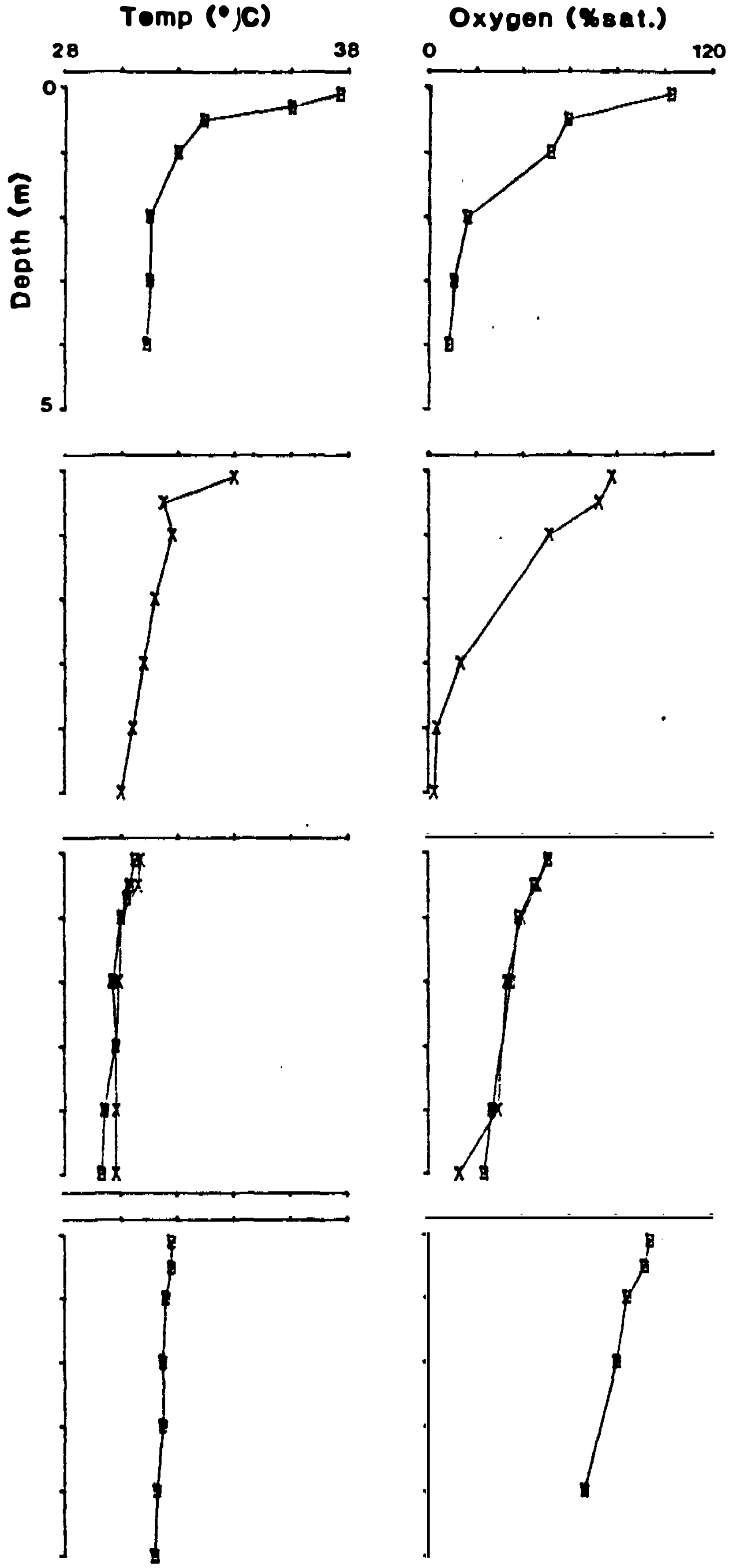


FIG. A6 (cont.)

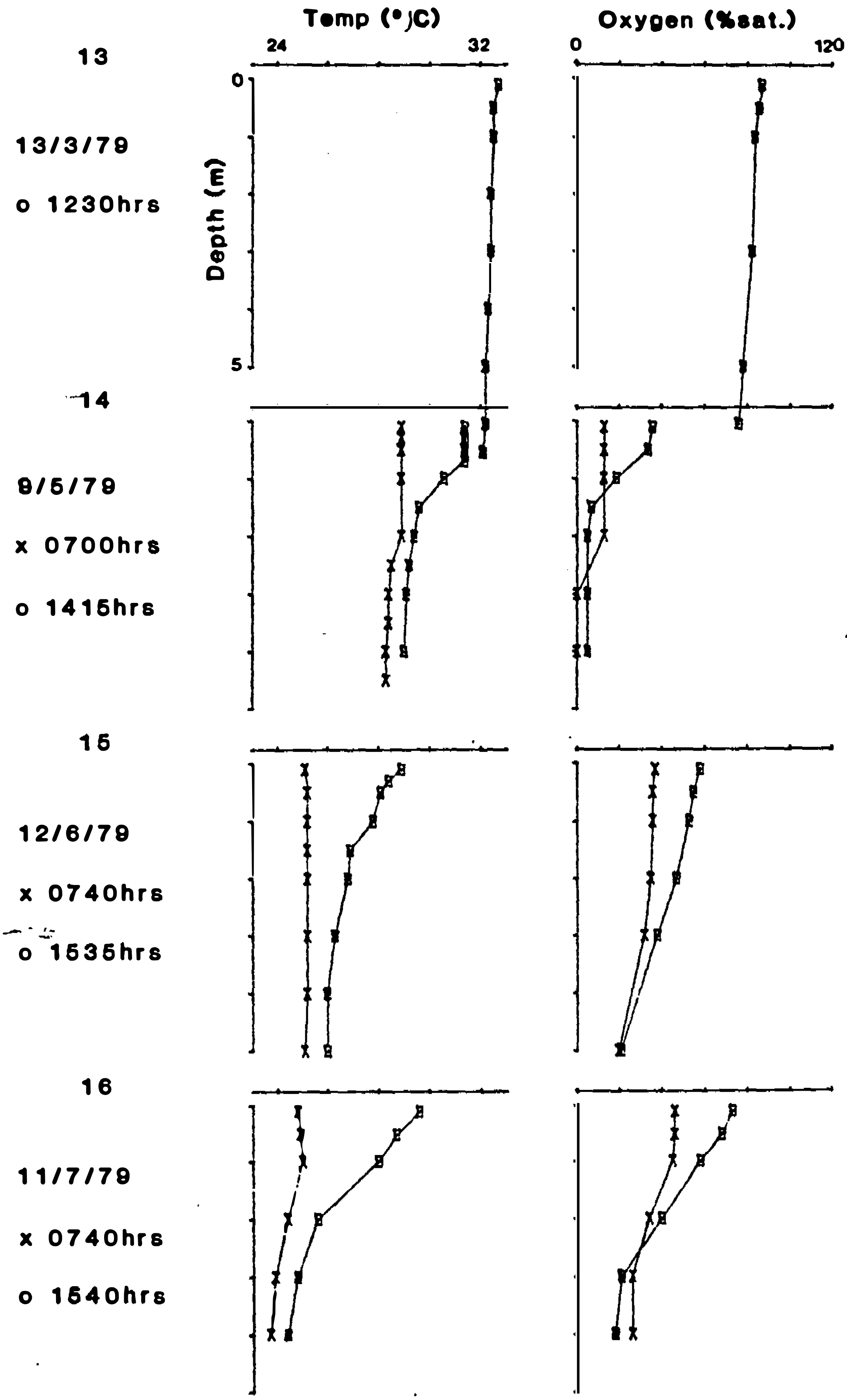
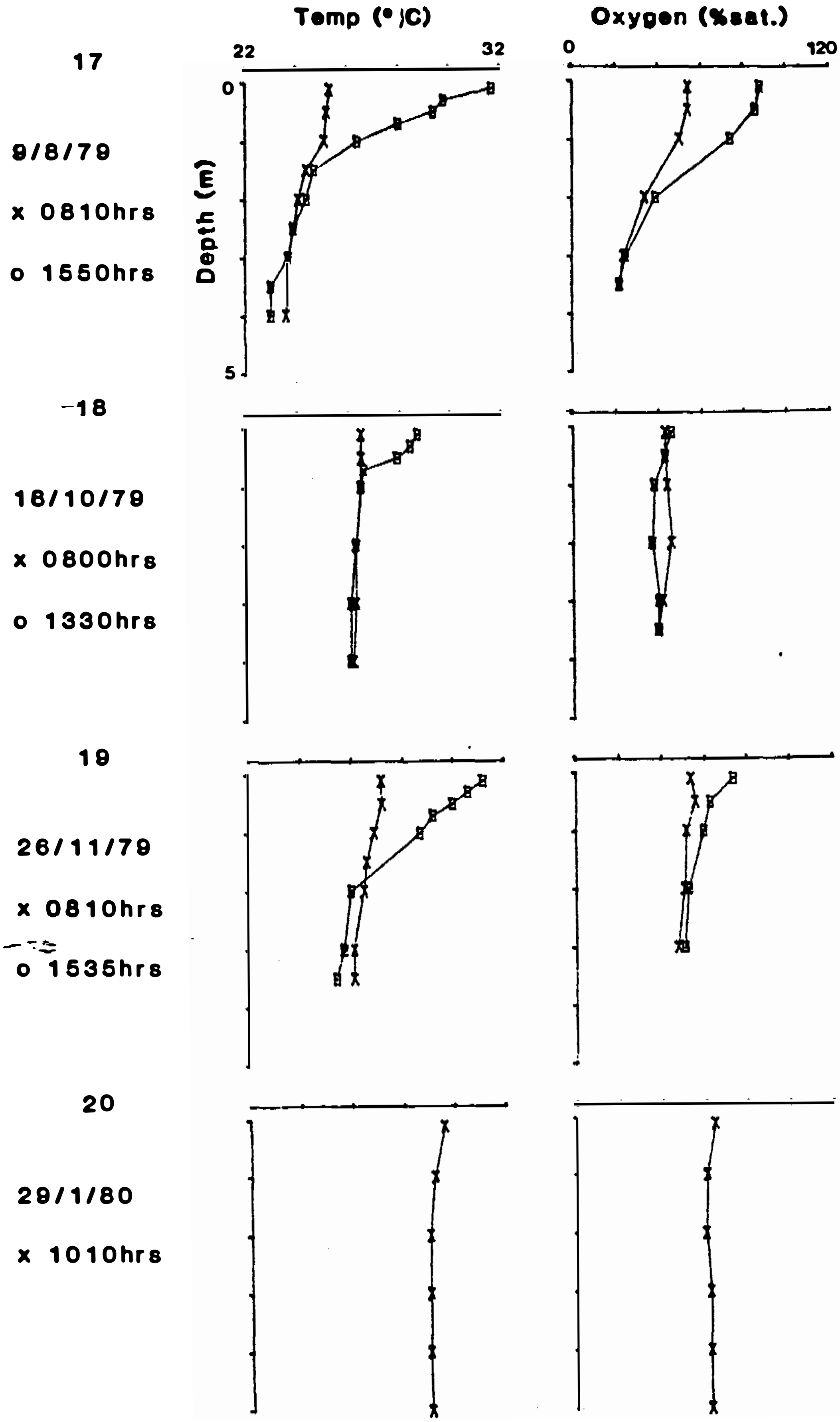

Temp (°C)
Oxygen (%sat.)
24
32
0
120
0
5
Depth (m)
13
13/3/79
o 1230hrs
14
9/5/79
x 0700hrs
o 1415hrs
15
12/6/79
x 0740hrs
o 1535hrs
16
11/7/79
x 0740hrs
o 1540hrs

FIG. A6 (cont.)



Temp (°C)
Oxygen (%sat.)
22
32
0
120
Depth (m)
0
5
17
9/8/79
x 0810hrs
o 1550hrs
18
16/10/79
x 0800hrs
o 1330hrs
19
26/11/79
x 0810hrs
o 1535hrs
20
29/1/80
x 1010hrs

FIG. A6 . (cont.)

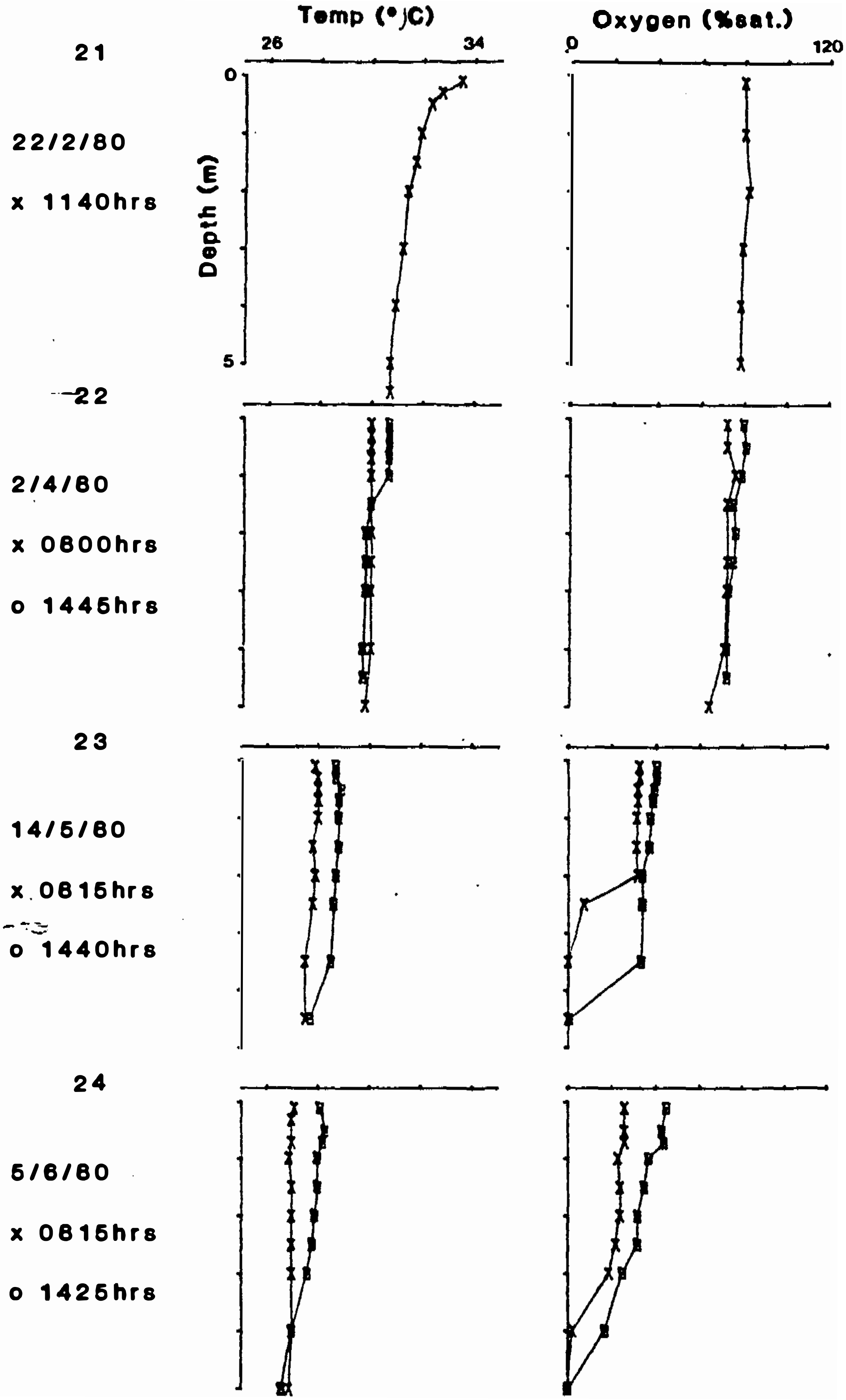
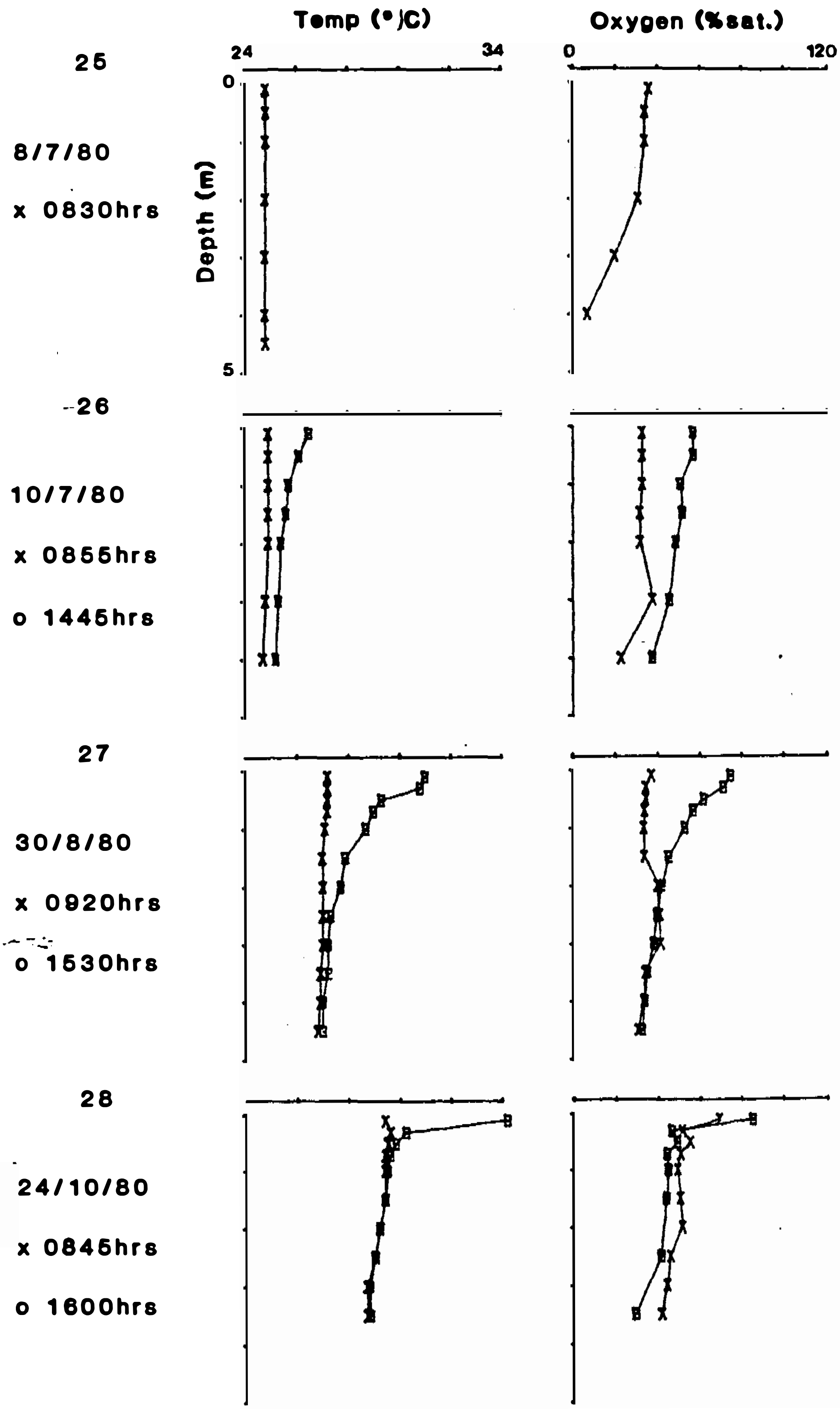

Temp (°)C)
26
34
Oxygen (%sat.)
0
120
Depth (m)
0
5
21
22/2/80
x 1140hrs
22
2/4/80
x 0800hrs
o 1445hrs
23
14/5/80
x 0815hrs
o 1440hrs
24
5/6/80
x 0815hrs
o 1425hrs

FIG. A6 (cont.)



Temp (°C)
Oxygen (%sat.)
24
34
0
120
0
5
Depth (m)
25
8/7/80
x 0830hrs
26
10/7/80
x 0855hrs
o 1445hrs
27
30/8/80
x 0920hrs
o 1530hrs
28
24/10/80
x 0845hrs
o 1600hrs

FIG. A6 (cont.)

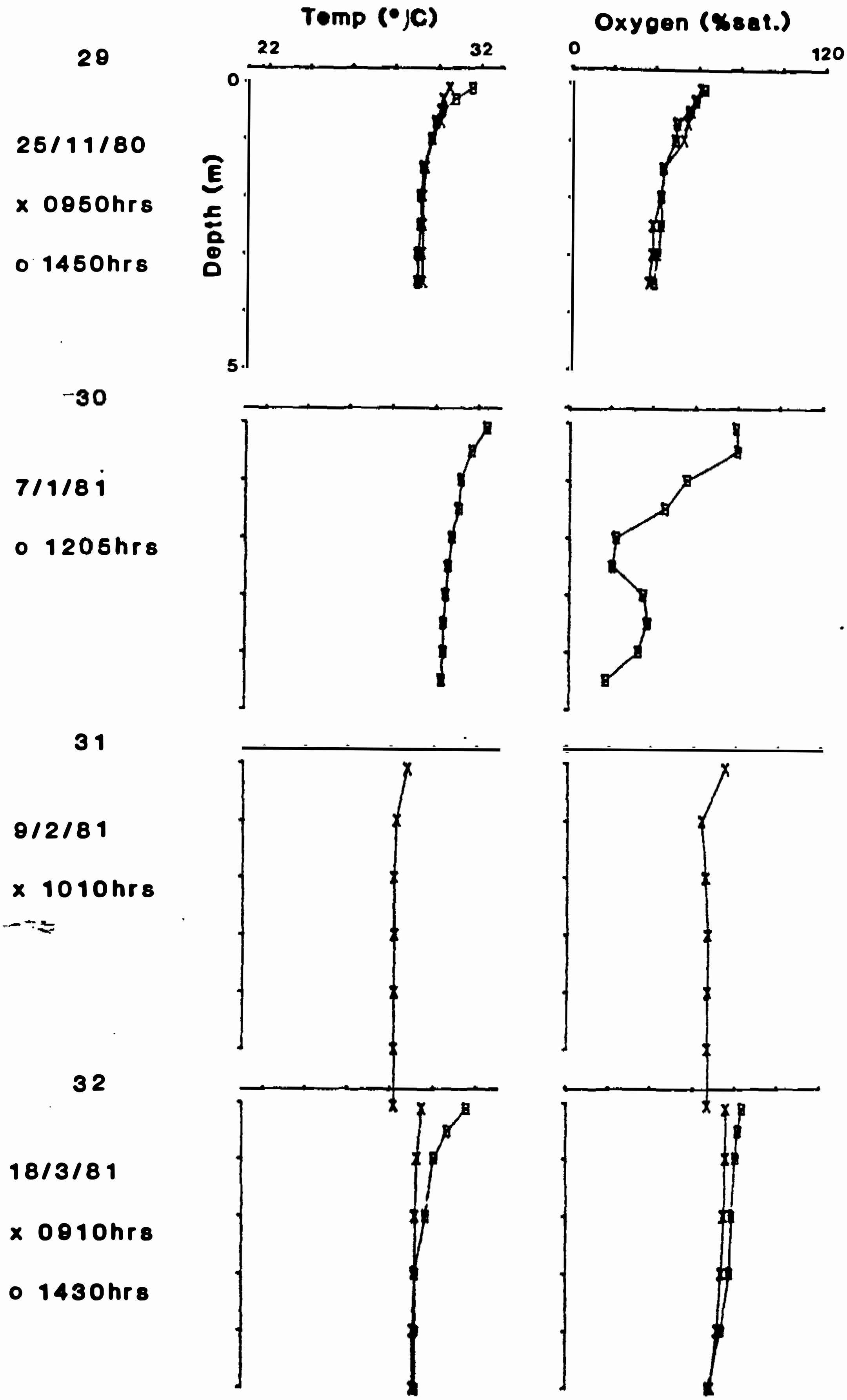
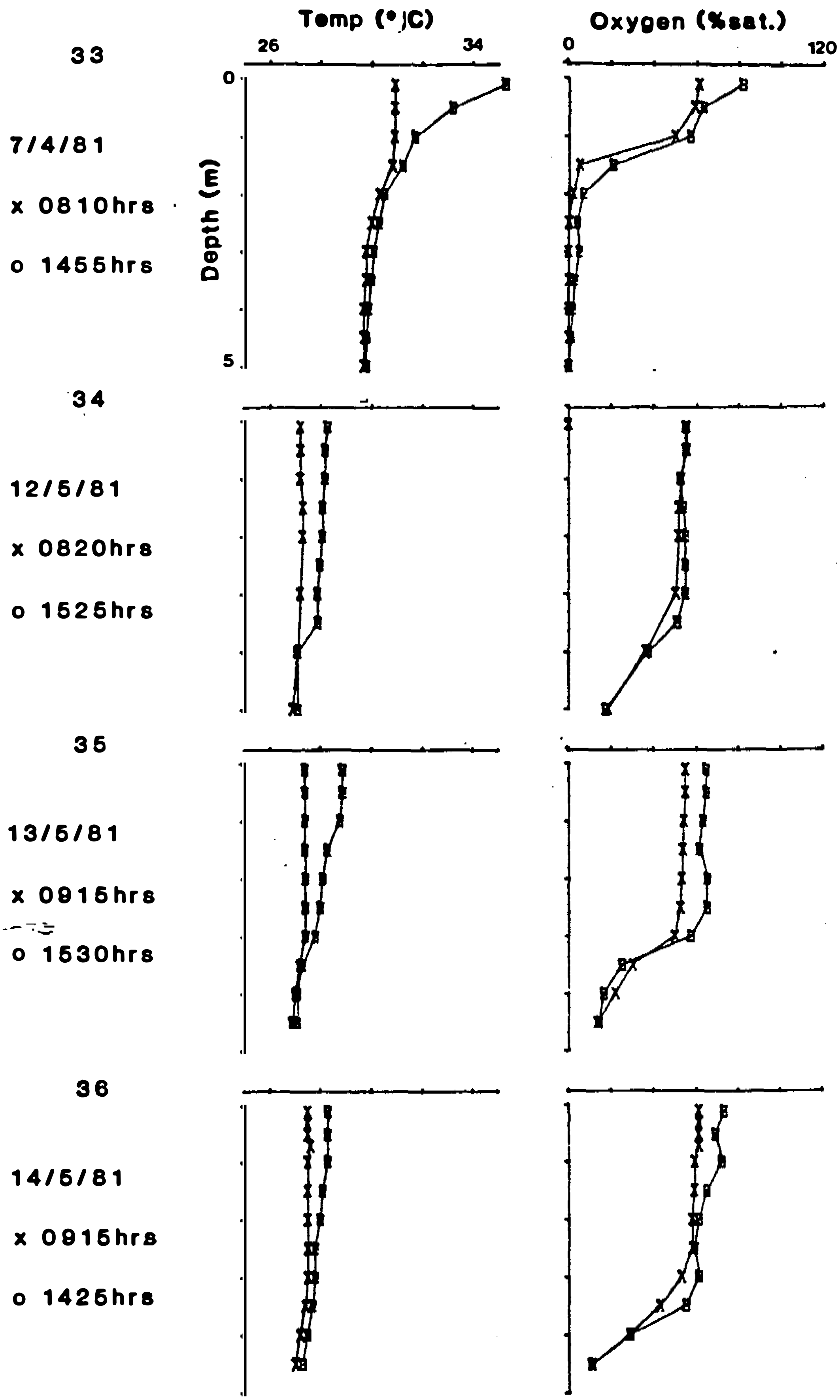
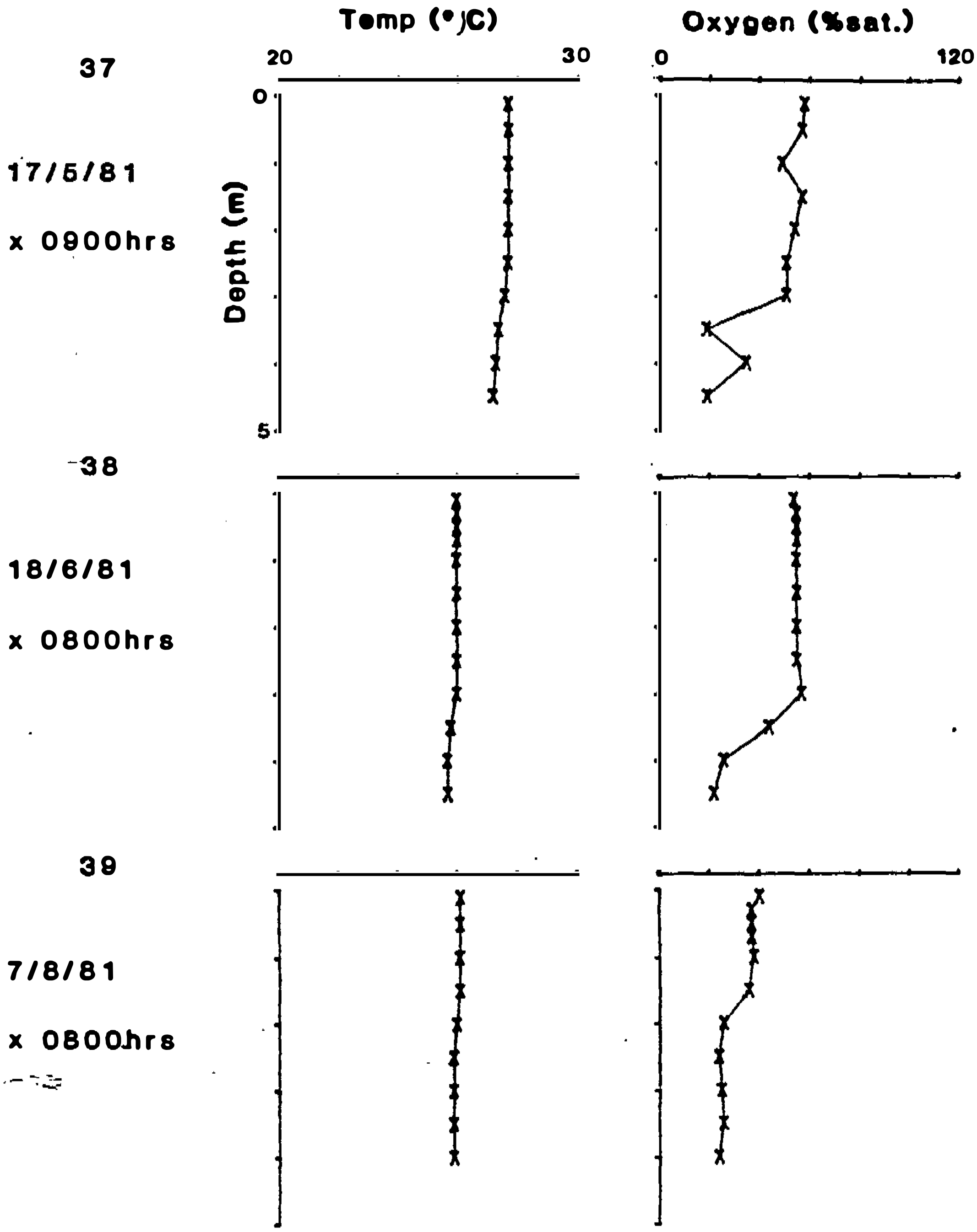

Temp (°)C)
Oxygen (%sat.)
22
32
0
120
0
5
Depth (m)
29
25/11/80
x 0950hrs
o 1450hrs
30
7/1/81
o 1205hrs
31
9/2/81
x 1010hrs
32
18/3/81
x 0910hrs
o 1430hrs

FIG. A6: (cont.)



Temp (°C)
26
34
Oxygen (%sat.)
0
120
Depth (m)
0
5
33
7/4/81
x 0810hrs
o 1455hrs
34
12/5/81
x 0820hrs
o 1525hrs
35
13/5/81
x 0915hrs
o 1530hrs
36
14/5/81
x 0915hrs
o 1425hrs

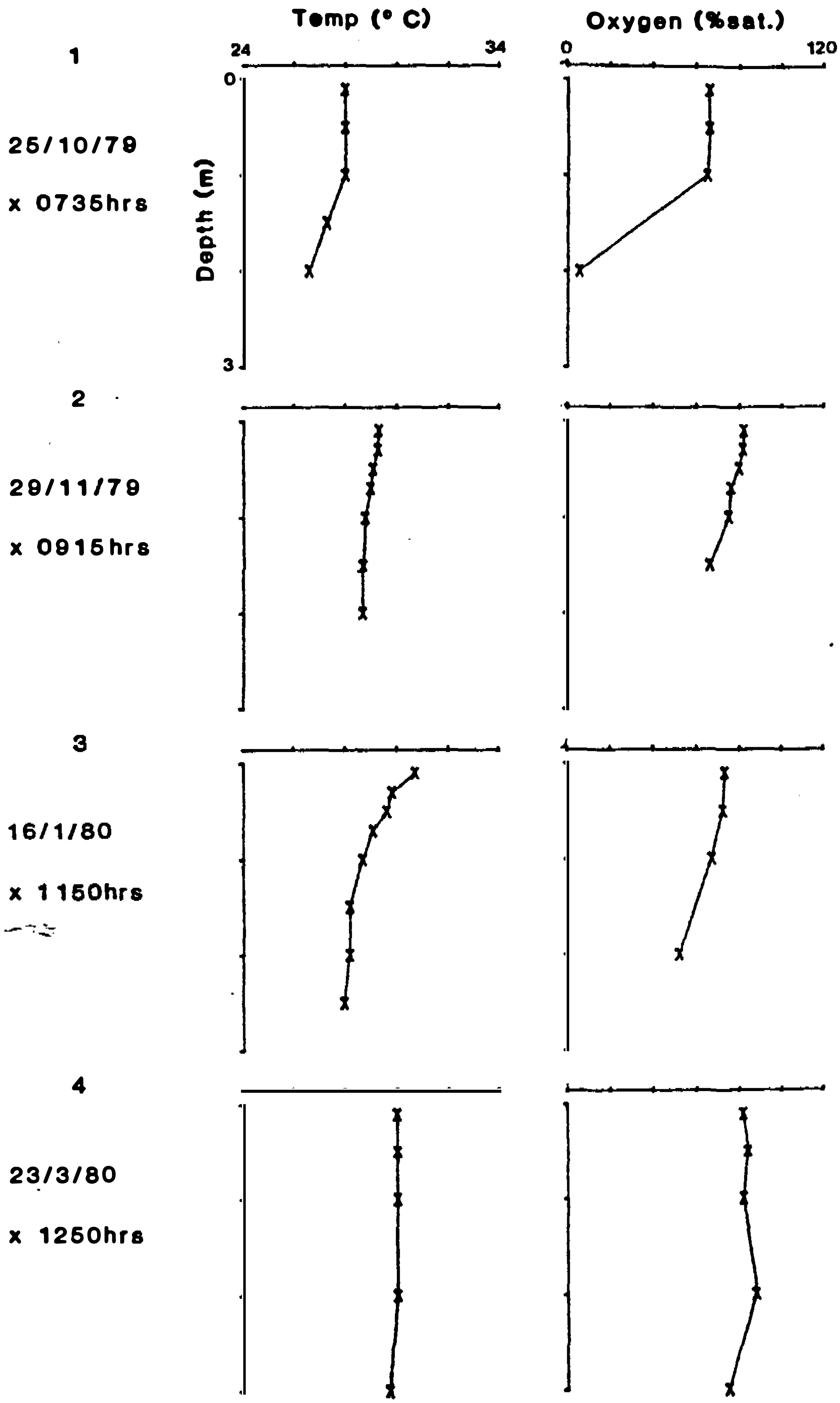
FIG. A6 (cont.)


Temp (°)C)
Oxygen (%sat.)
20
30
0
120
0
5
Depth (m)
37
17/5/81
x 0900hrs
38
18/6/81
x 0800hrs
39
7/8/81
x 0800hrs

APPENDIX 7

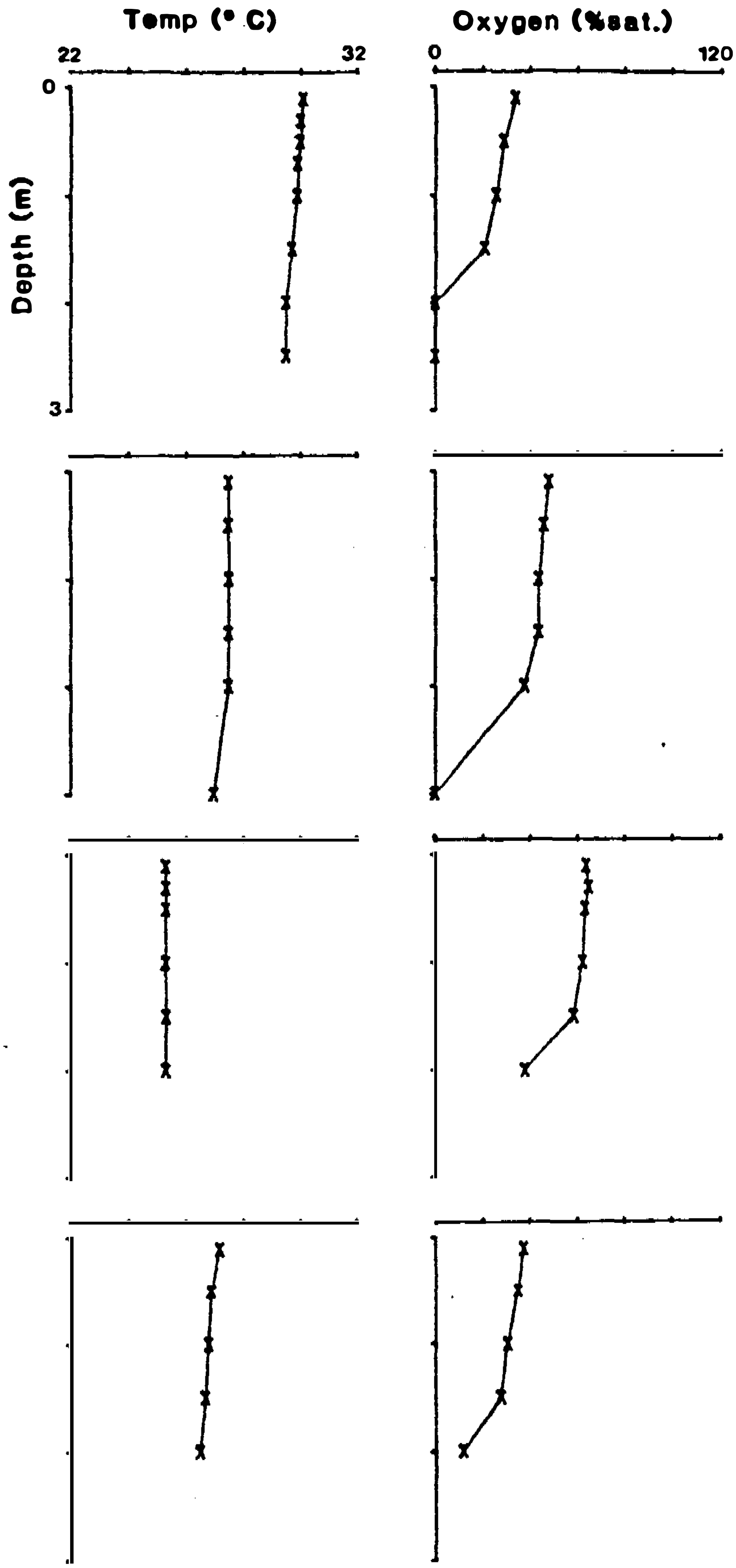
Temperature and oxygen profiles in Jingalla billabong.

FIG. A7



Temp (° C)
Oxygen (%sat.)
24
34
0
120
0
3
Depth (m)
1
25/10/79
x 0735hrs
2
29/11/79
x 0915hrs
3
16/1/80
x 1150hrs
4
23/3/80
x 1250hrs

FIG. A7 (cont.)



5

24/4/80

x 1115hrs

6

30/5/80

x 0820hrs

7

26/6/80

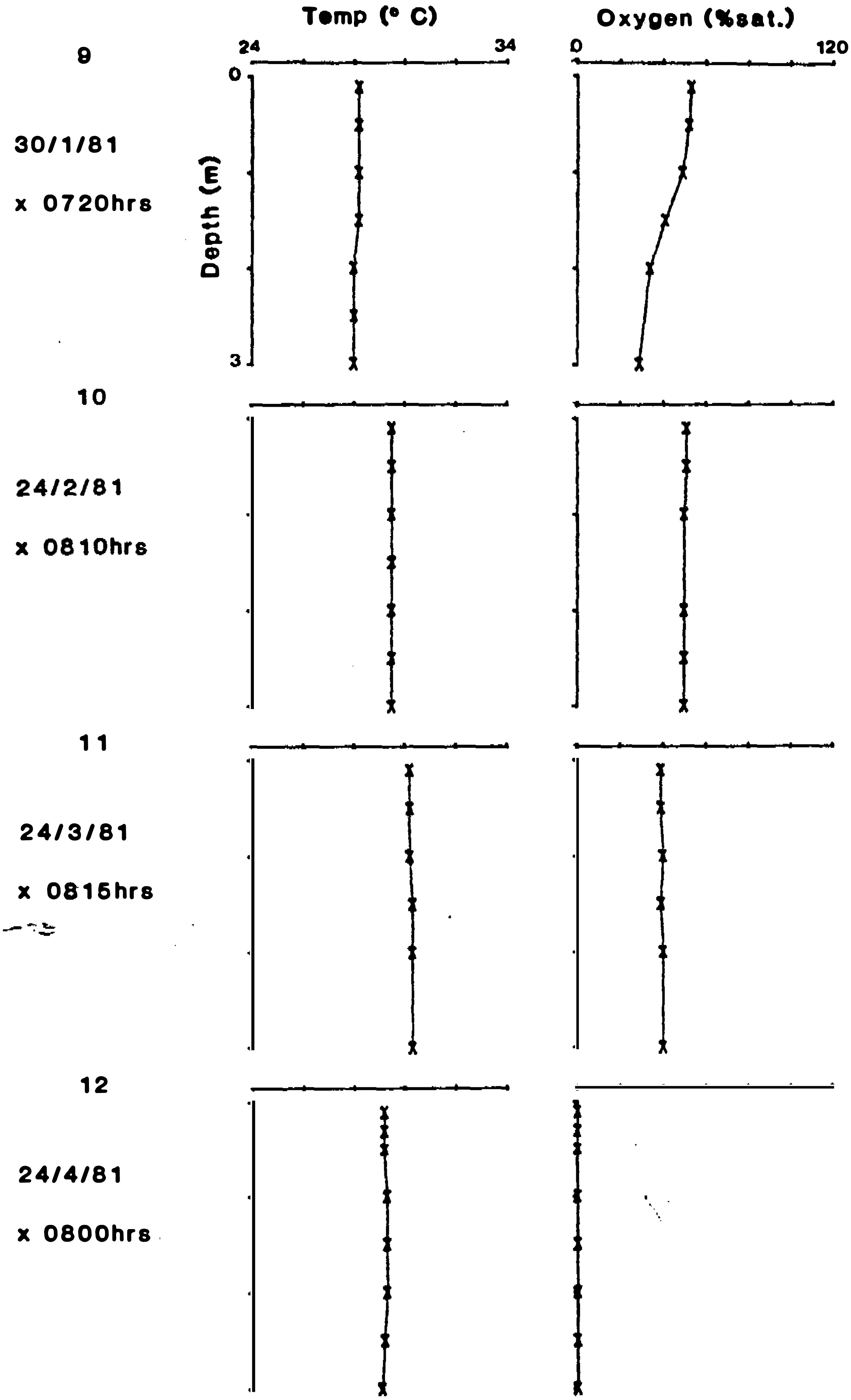
x 0835hrs

8

31/8/80

x 0845hrs

FIG. A7 (cont.)



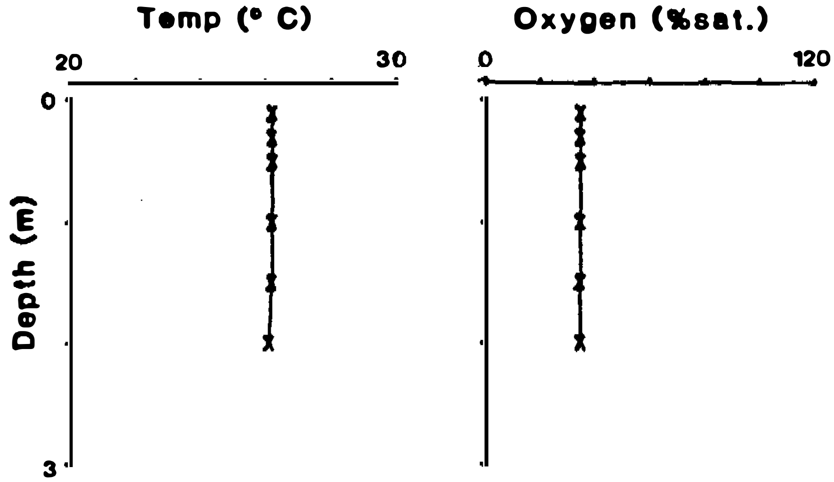
Temp (° C)
Oxygen (%sat.)
24
34
0
120
0
3
Depth (m)
9
30/1/81
x 0720hrs
10
24/2/81
x 0810hrs
11
24/3/81
x 0815hrs
12
24/4/81
x 0800hrs

FIG. A7 (cont.)

13

15/6/81

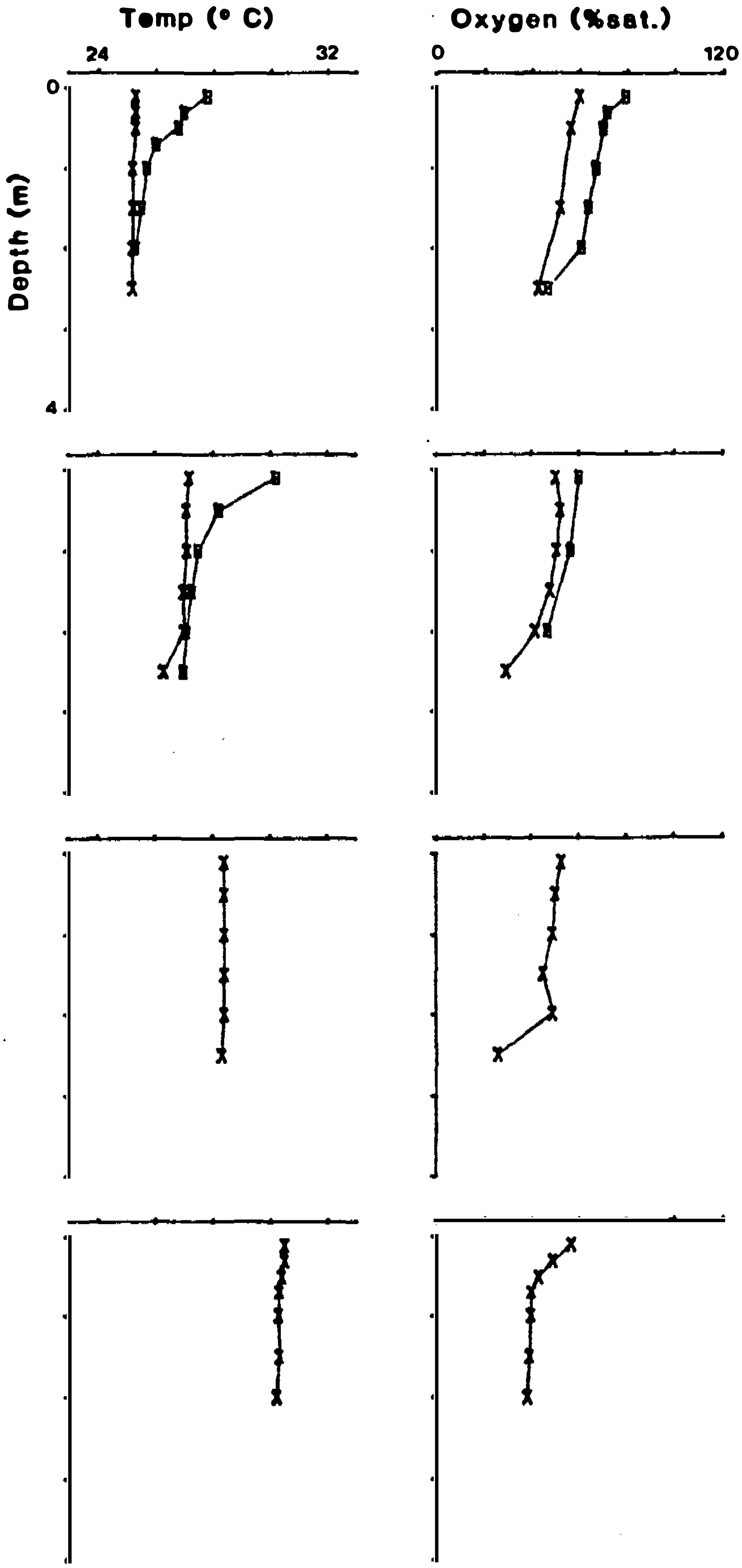
x 0850hrs



APPENDIX 8

Temperature and oxygen profiles in Nimbawah billabong.

FIG.. A8



1

15/8/80

x 0920hrs

o 1400hrs

2

18/9/80

x 0915hrs

o 1400hrs

3

14/10/80

x 0730hrs

4

4/12/80

x 0940hrs

FIG. A8 (cont.)

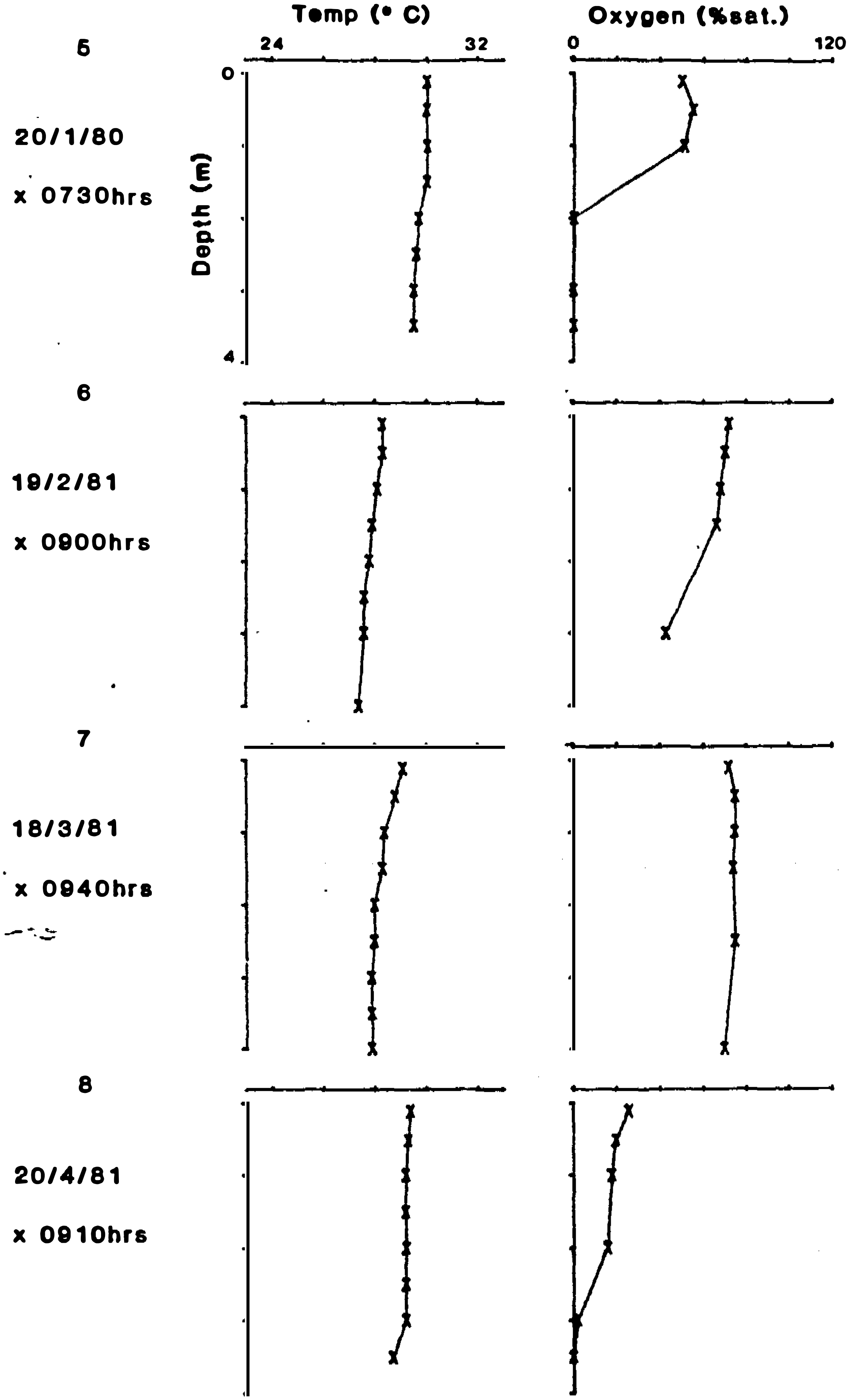
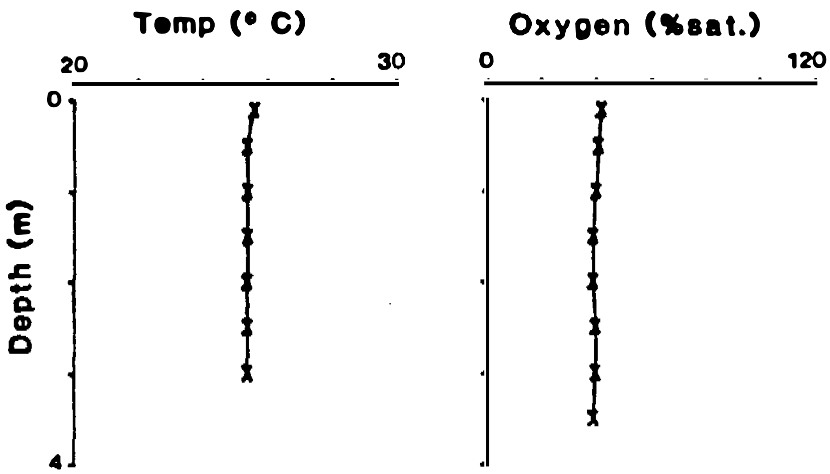

Temp (° C)
Oxygen (%sat.)
24
32
0
120
0
4
Depth (m)
5
20/1/80
x 0730hrs
6
19/2/81
x 0900hrs
7
18/3/81
x 0940hrs
8
20/4/81
x 0910hrs

FIG. A8 (cont.)

9

16/6/81

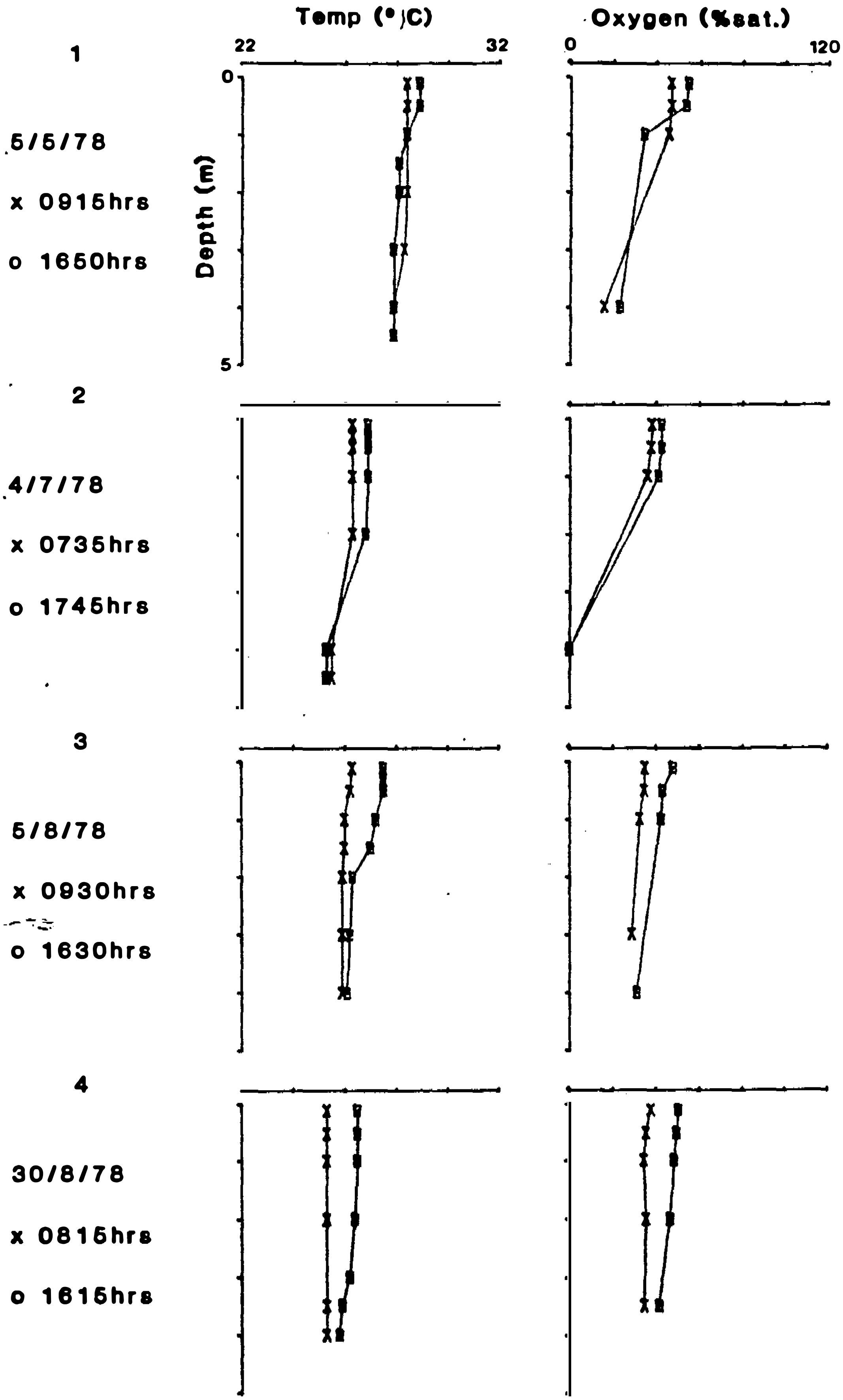
x 0900hrs



APPENDIX 9

Temperature and oxygen profiles in Nankeen billabong.

FIG. A9



Temp (°)C)
Oxygen (%sat.)
22
32
0
120
0
5
Depth (m)
1
5/5/78
x 0915hrs
o 1650hrs
2
4/7/78
x 0735hrs
o 1745hrs
3
5/8/78
x 0930hrs
o 1630hrs
4
30/8/78
x 0815hrs
o 1615hrs

FIG. A9 (cont.)

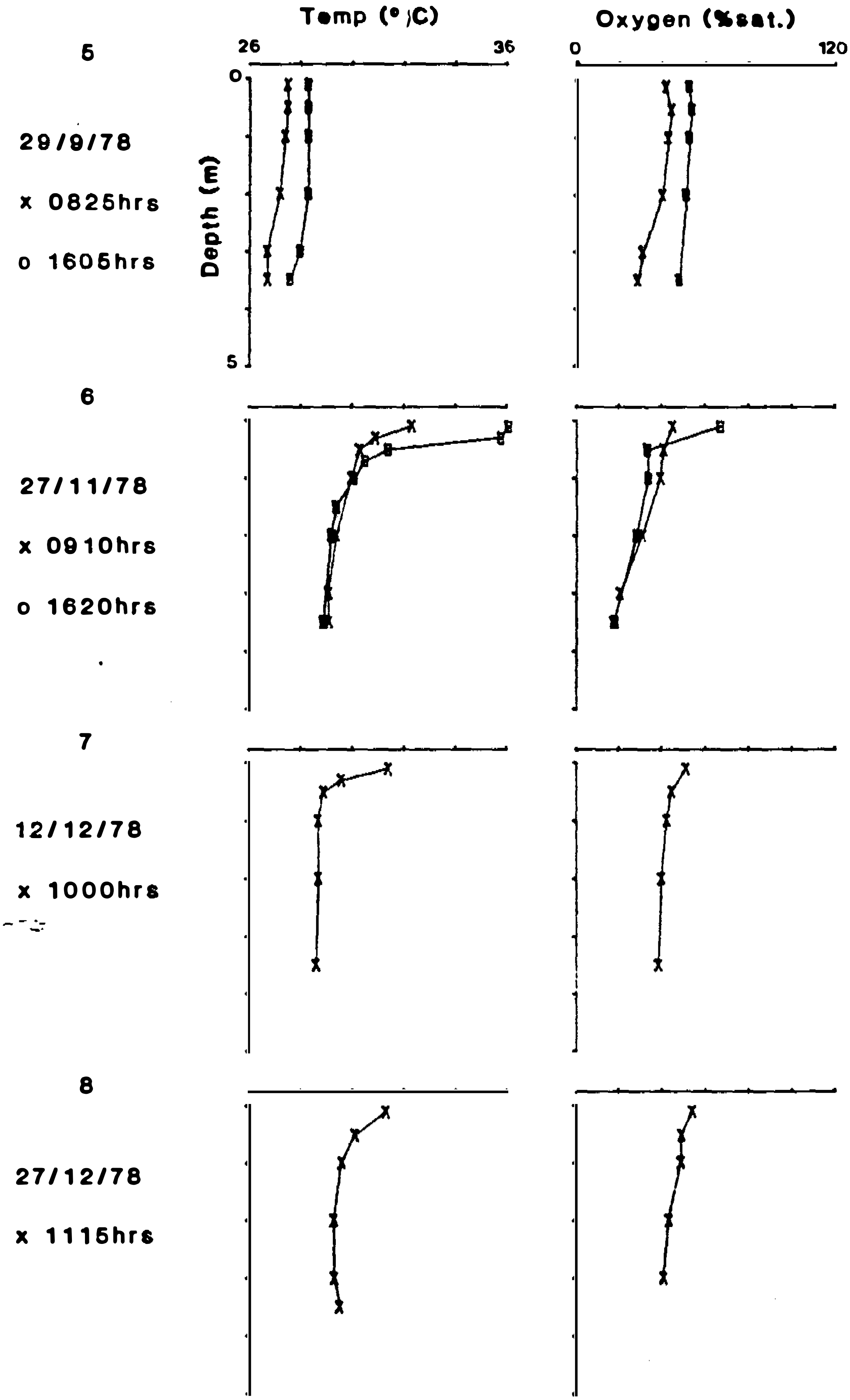

Temp (°C)
Oxygen (%sat.)
26
36
0
120
0
5
Depth (m)
5
29/9/78
x 0825hrs
o 1605hrs
6
27/11/78
x 0910hrs
o 1620hrs
7
12/12/78
x 1000hrs
8
27/12/78
x 1115hrs

FIG. A9 (cont.)

9

11/1/80

x 1105hrs

10

14/1/80

x 1030hrs

11

29/1/80

x 0940hrs

12

2/4/80

x 0825hrs

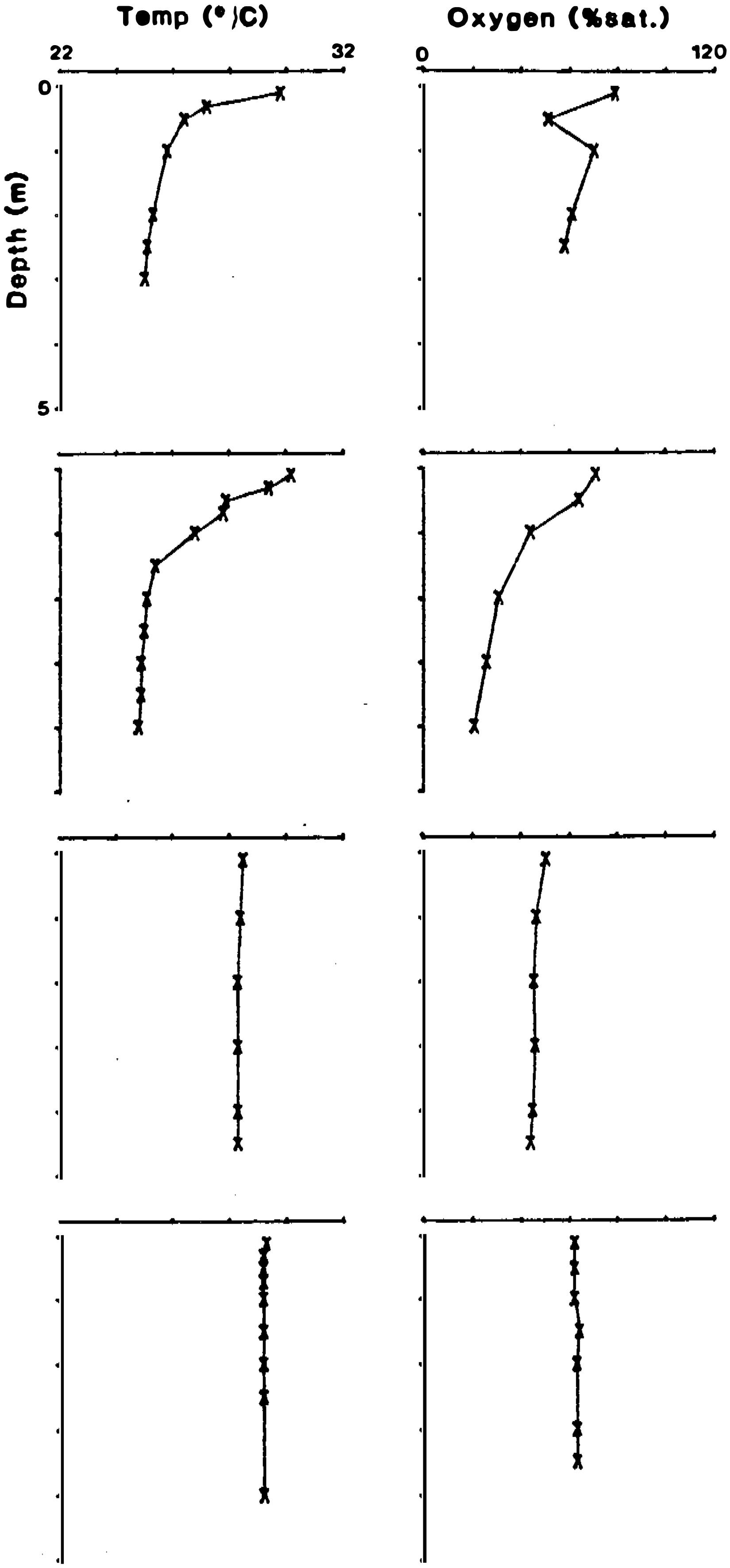


FIG. A9 (cont.)

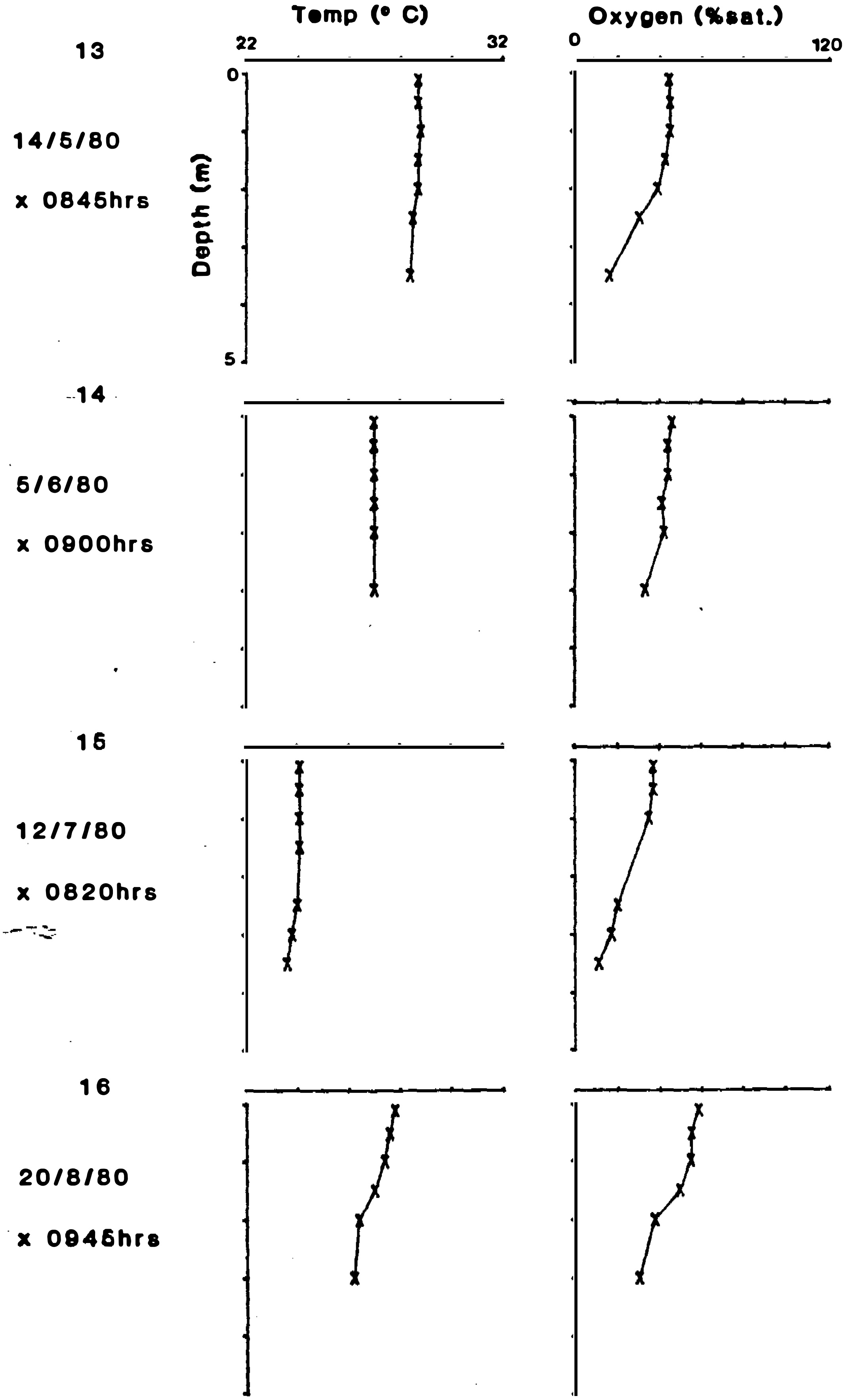

Temp (° C)
Oxygen (%sat.)
22
32
0
120
0
5
Depth (m)
13
14/5/80
x 0845hrs
14
5/6/80
x 0900hrs
15
12/7/80
x 0820hrs
16
20/8/80
x 0945hrs

FIG. A9 (cont.)

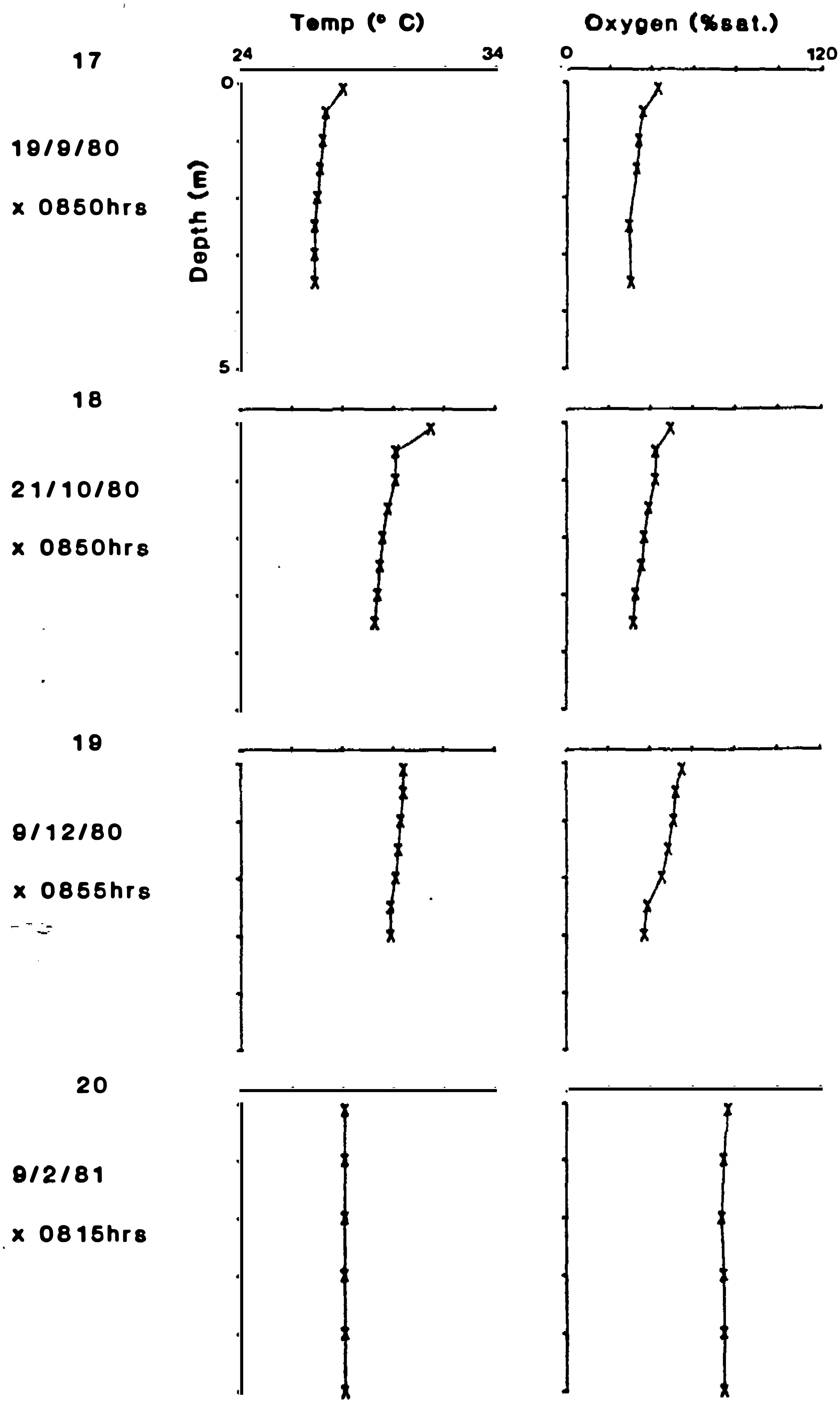

17
19/9/80
x 0850hrs
18
21/10/80
x 0850hrs
19
9/12/80
x 0855hrs
20
9/2/81
x 0815hrs
Temp (° C)
24
34
Oxygen (%sat.)
0
120
Depth (m)
0
5

FIG. A 9 (cont.)

21

18/3/81

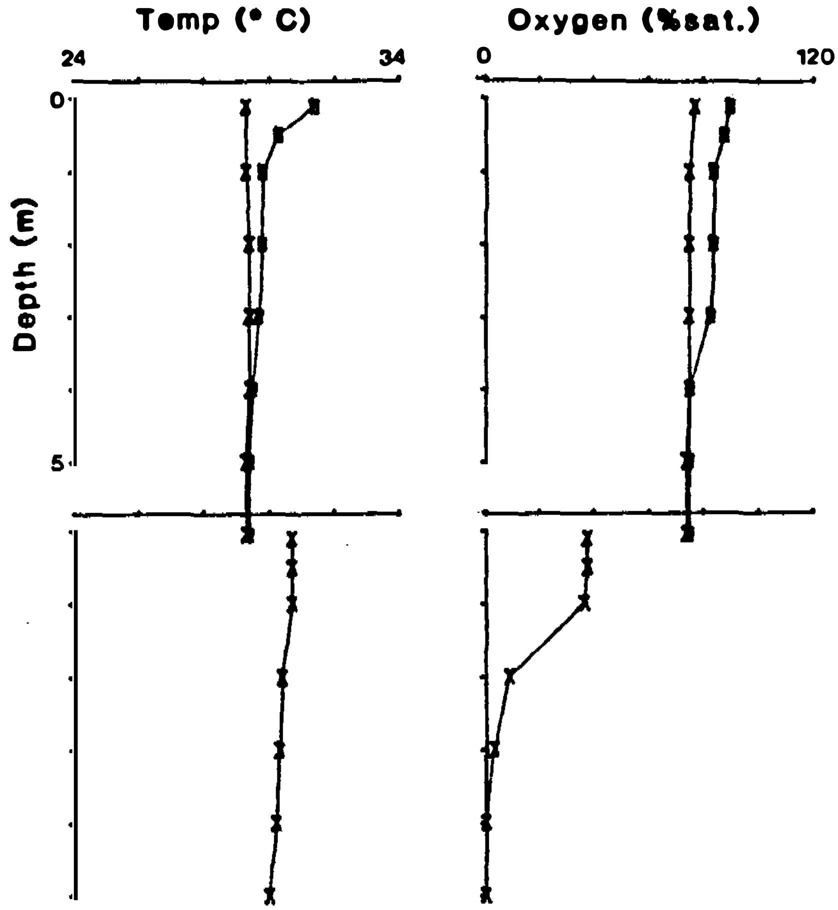
x 0815hrs

o 1400hrs

22

8/4/81

x 0745hrs



APPENDIX 10

Temperature and oxygen profiles in Island billabong.

FIG. A1 0 (cont.)

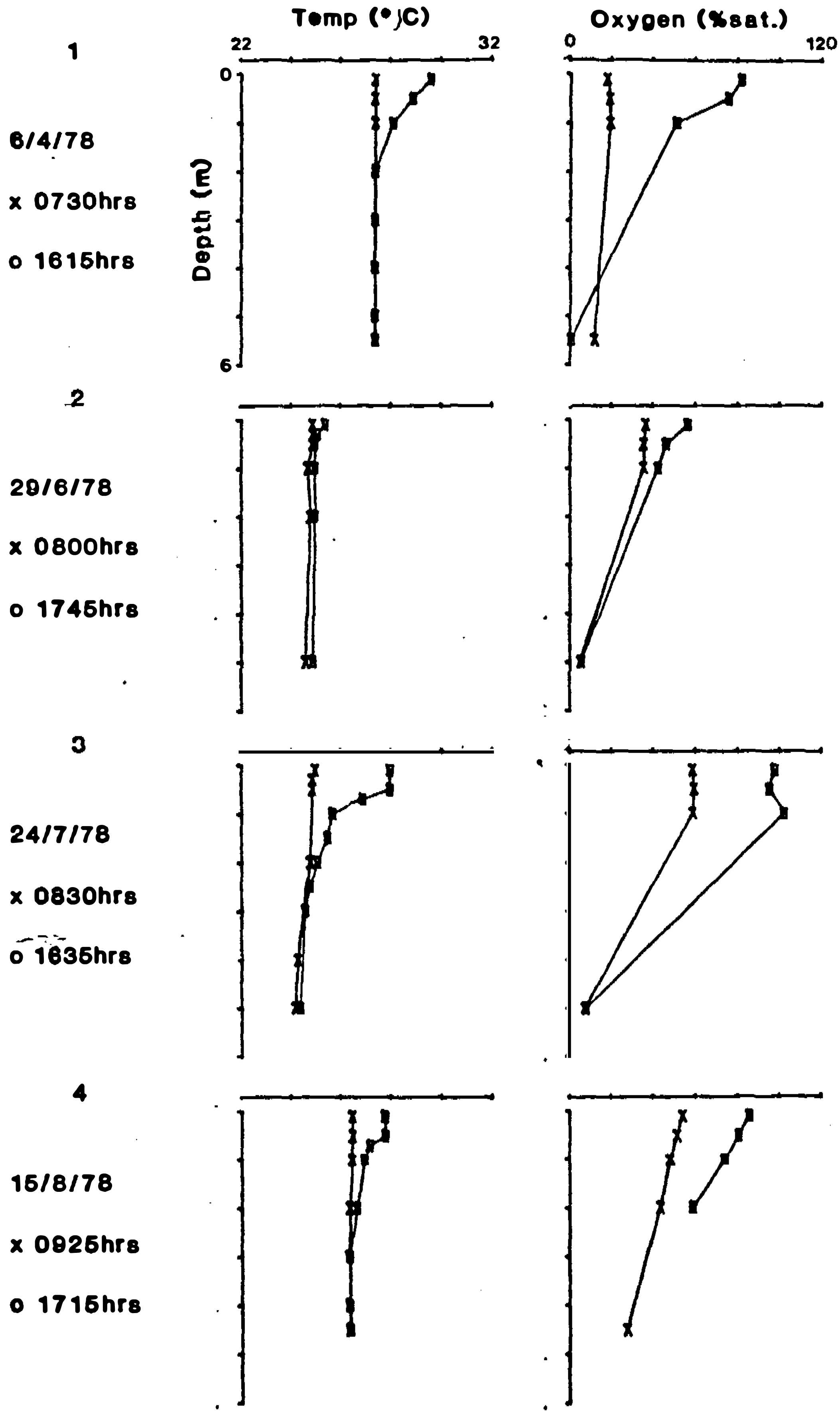

Temp (°C)
22
32
Oxygen (%sat.)
0
120
Depth (m)
0
6
1
6/4/78
x 0730hrs
o 1615hrs
2
29/6/78
x 0800hrs
o 1745hrs
3
24/7/78
x 0830hrs
o 1635hrs
4
15/8/78
x 0925hrs
o 1715hrs

FIG. A1 0 (cont.)

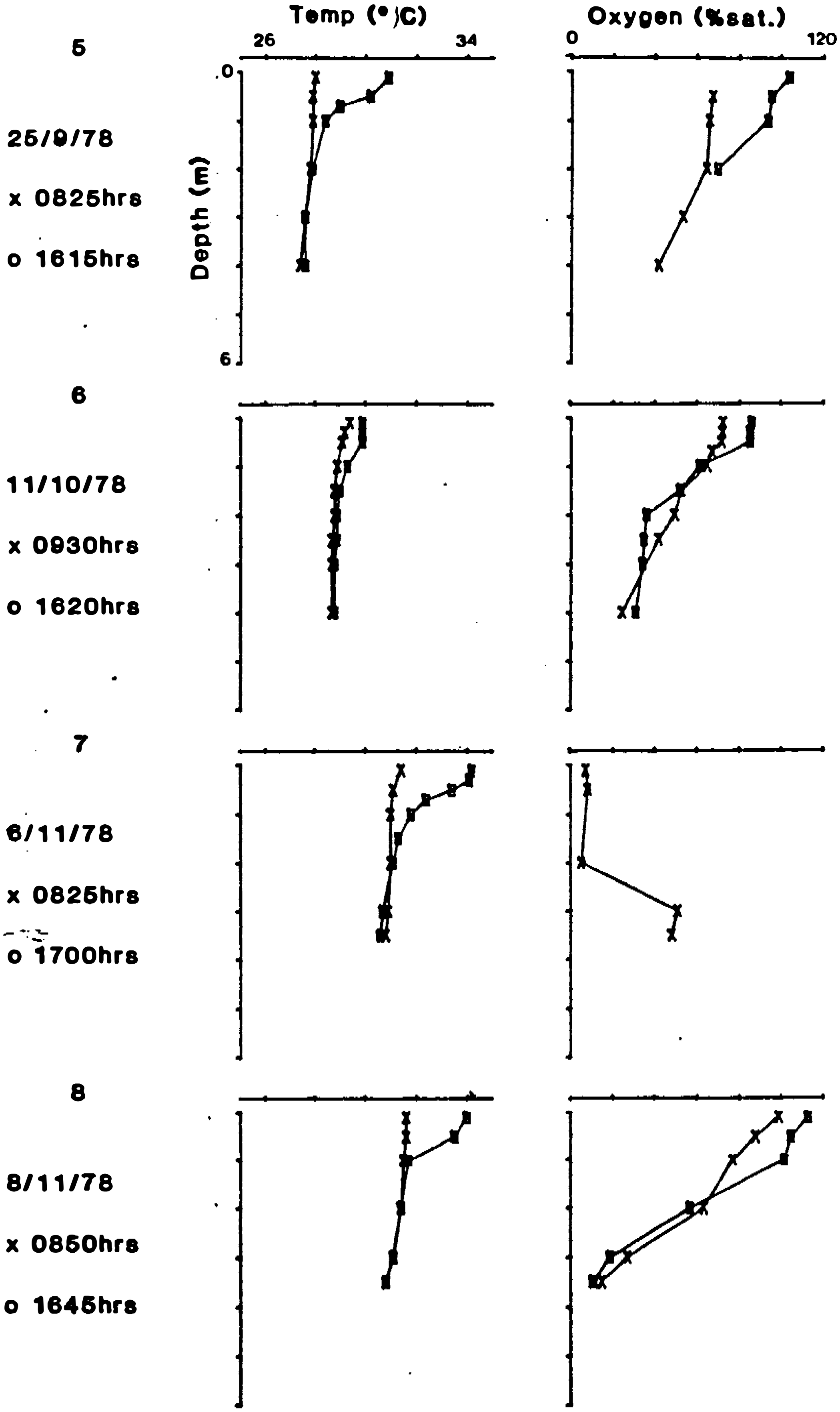

Temp (°)C
26
34
Oxygen (%sat.)
0
120
Depth (m)
0
6
5
25/9/78
x 0825hrs
o 1615hrs
6
11/10/78
x 0930hrs
o 1620hrs
7
6/11/78
x 0825hrs
o 1700hrs
8
8/11/78
x 0850hrs
o 1645hrs

FIG. A10 (cont.)

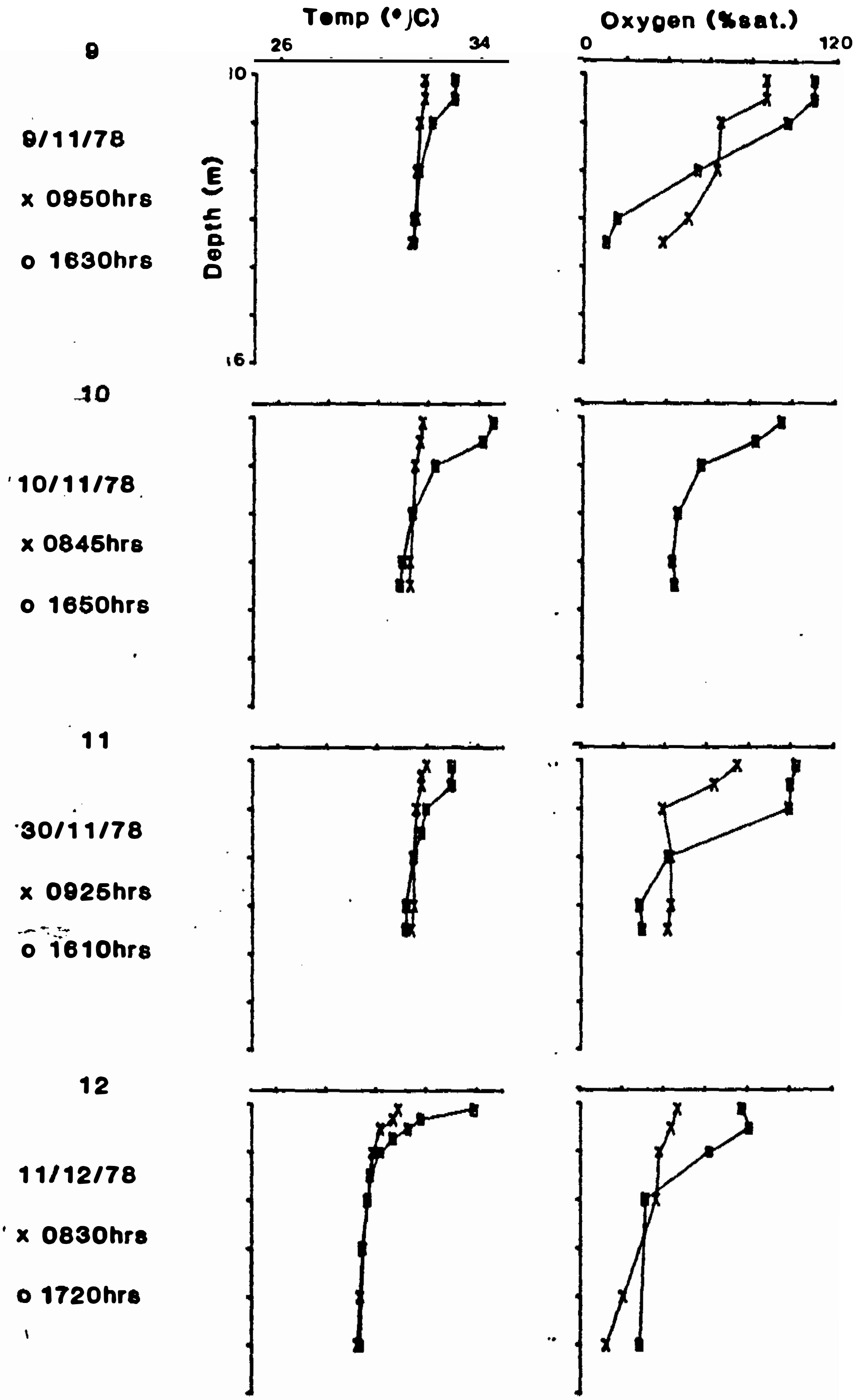

Temp (°C)
26
34
Oxygen (%sat.)
0
120
0
Depth (m)
6
9
9/11/78
x 0950hrs
o 1630hrs
10
10/11/78
x 0845hrs
o 1650hrs
11
30/11/78
x 0925hrs
o 1610hrs
12
11/12/78
x 0830hrs
o 1720hrs

FIG. A10 (cont.)

13

5/1/79

x 0930hrs

14

19/1/79

x 1200hrs

15

1/3/79

x 1400hrs

16

8/5/79

x 0700hrs

o 1610hrs

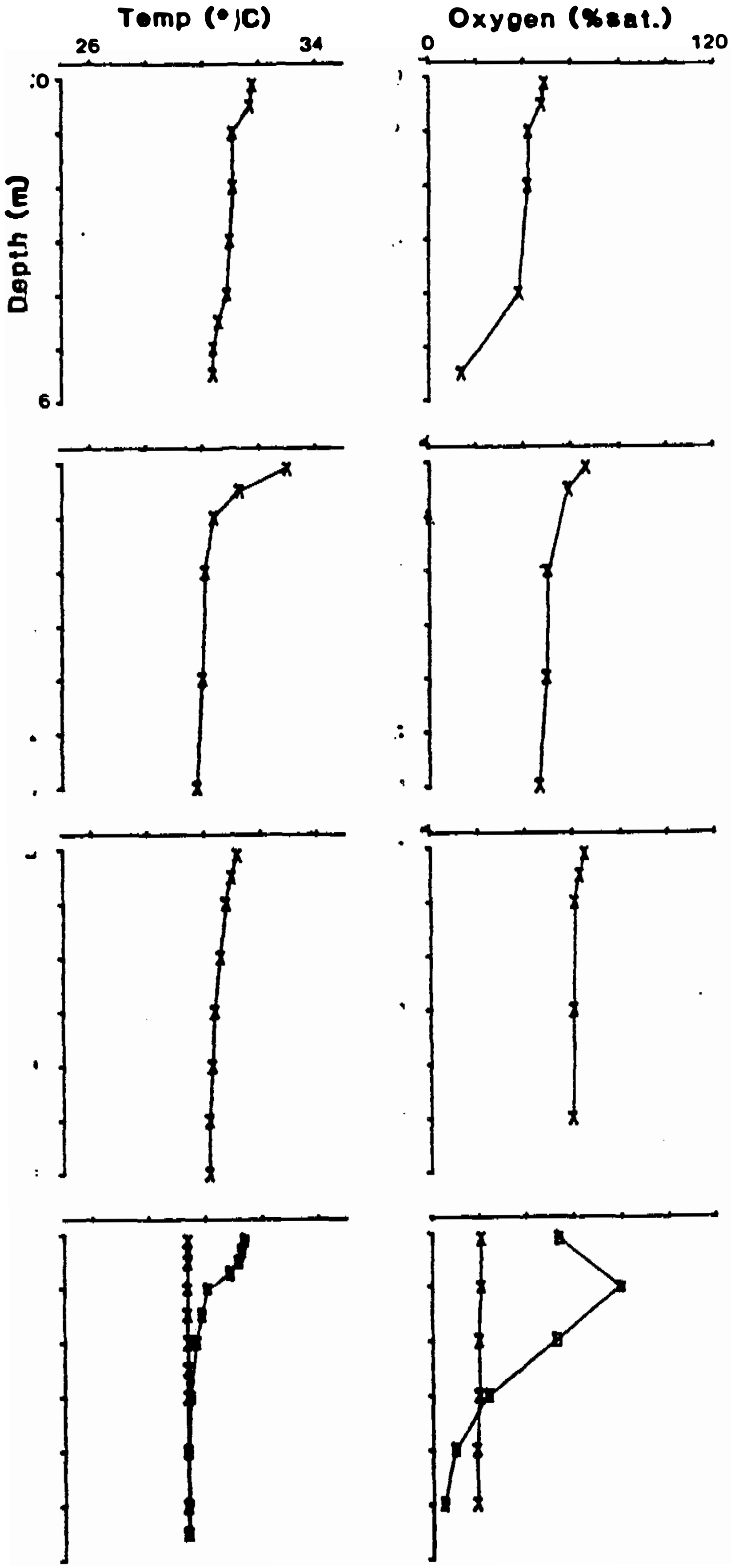


FIG. A10 (cont.)

17

6/7/79

x 0750hrs

o 1540hrs

18

x 0720hrs

o 1540hrs

19

15/8/79

x 0810hrs

o 1540hrs

20

15/10/79

x 0820hrs

o 1430hrs

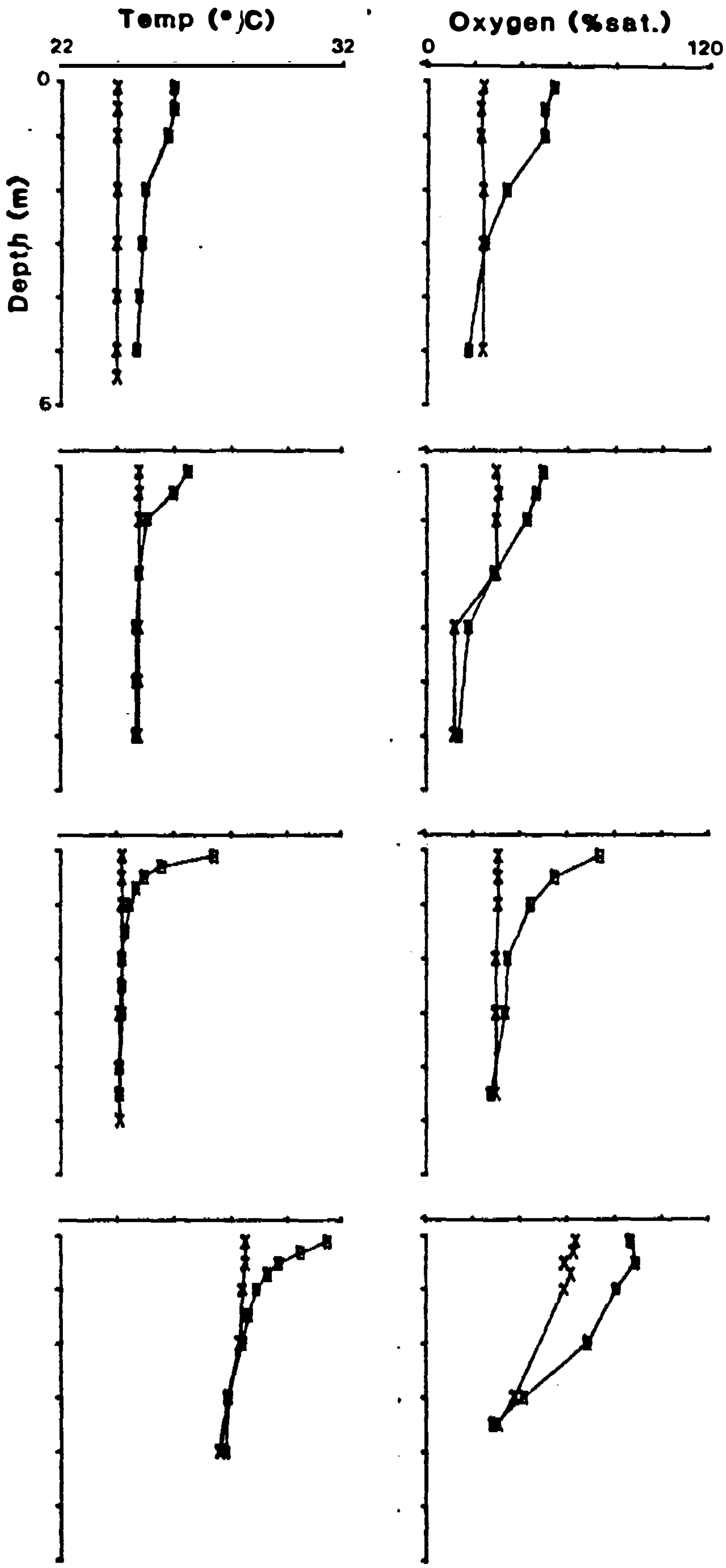


FIG. A10 (cont.)

21

23/11/79

x 0830hrs

o 1500hrs

22

20/12/79

x 0845hrs

23

31/1/80

o 1530hrs

24

9/4/80

x 0850hrs

o 1515hra

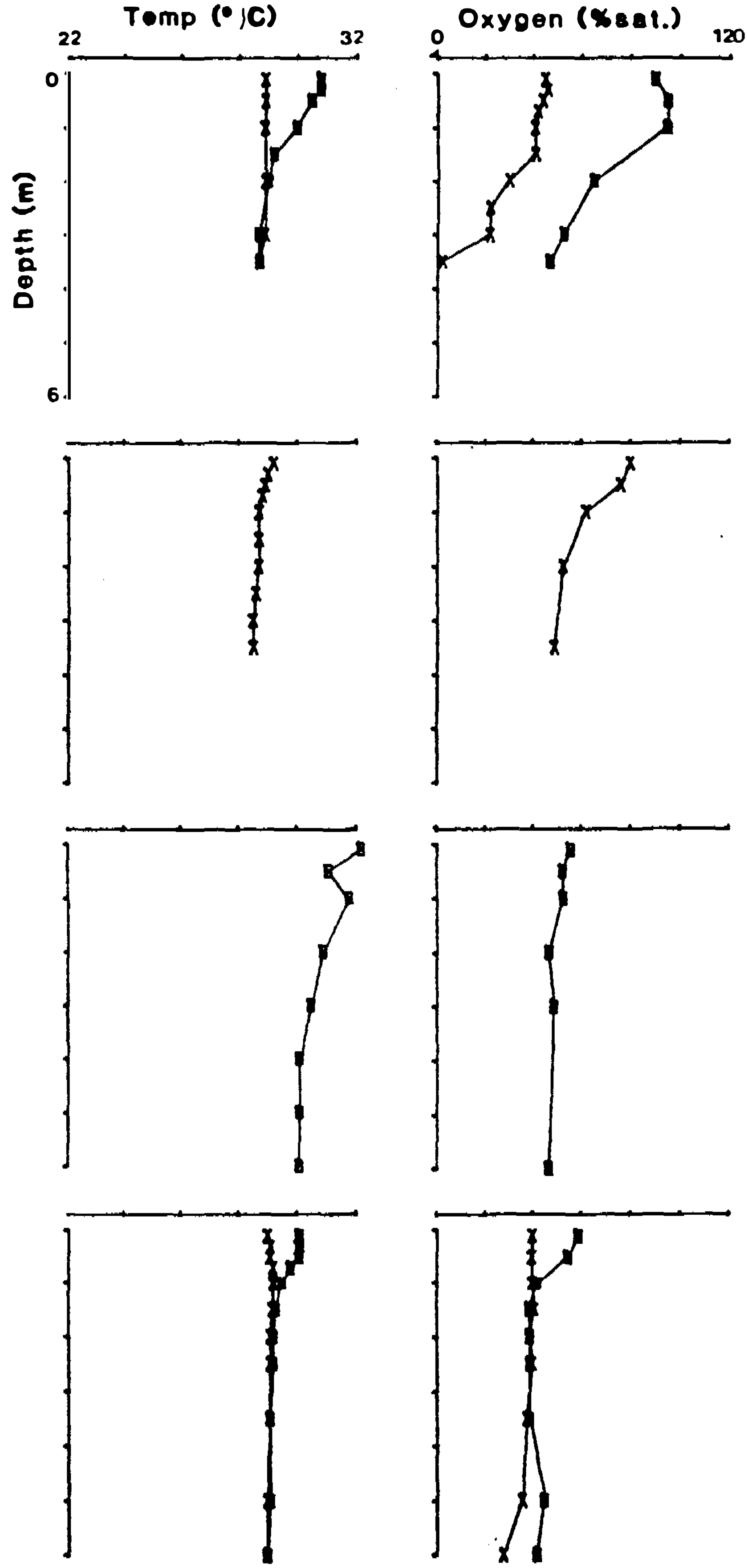


FIG. A 1 0(cont.)

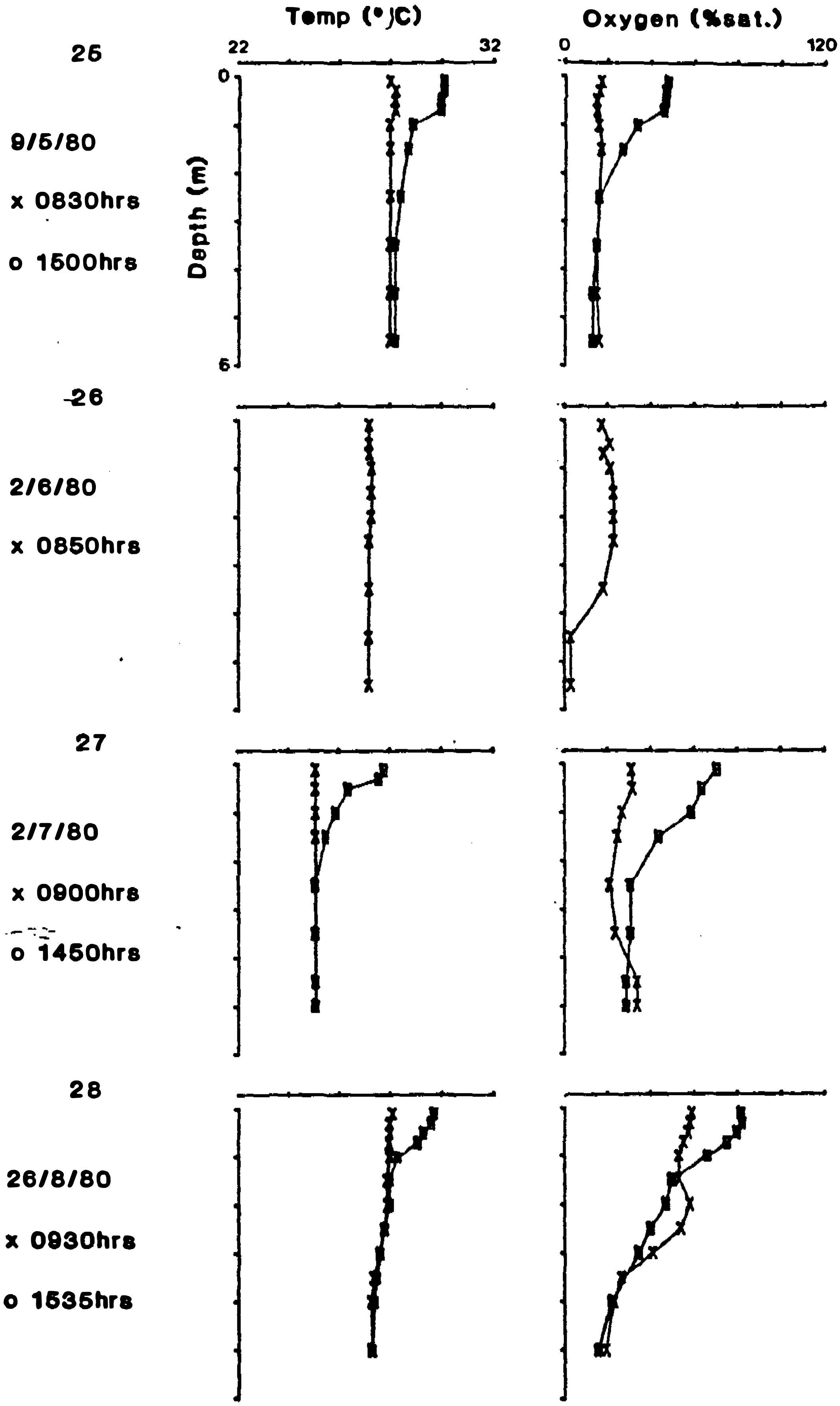
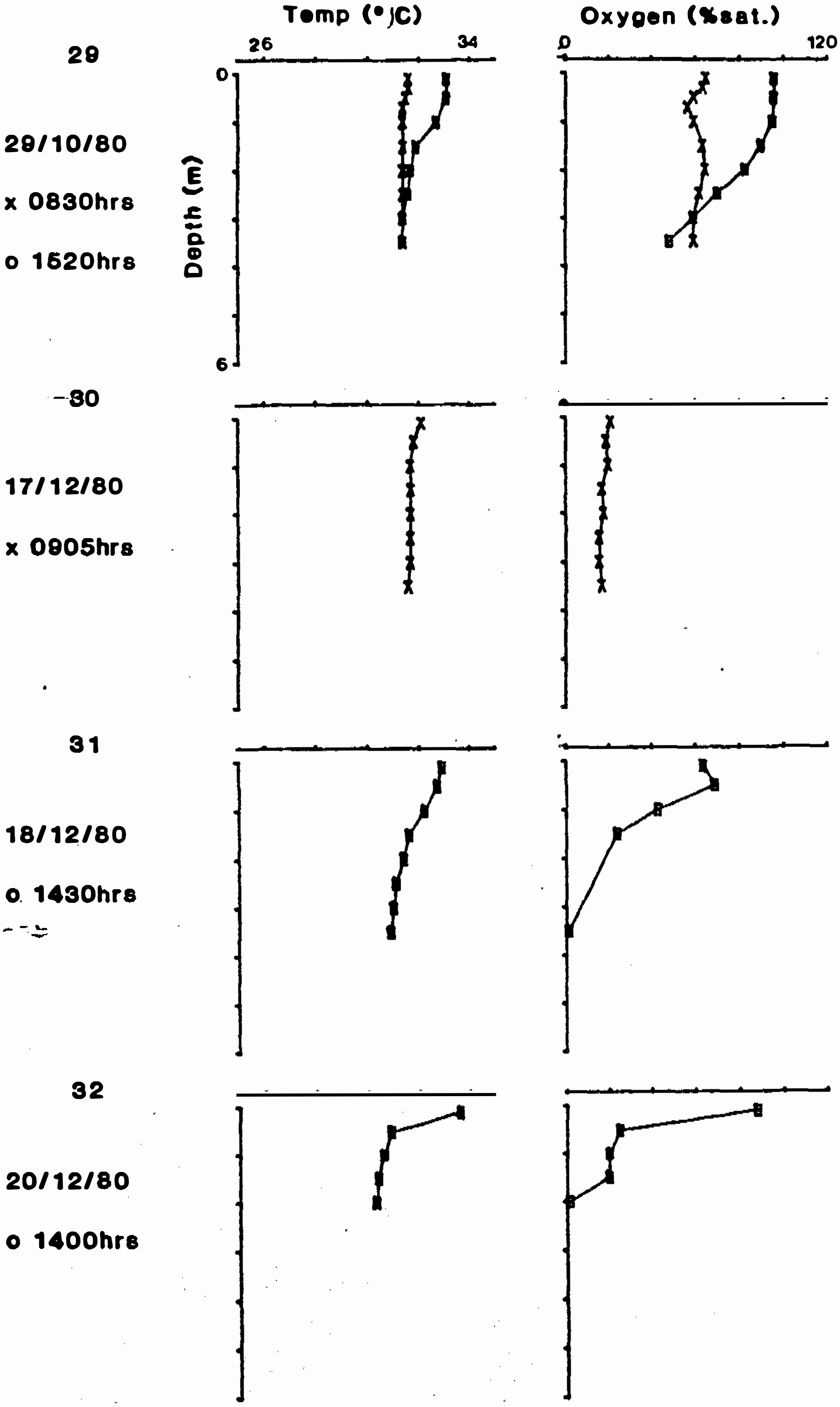
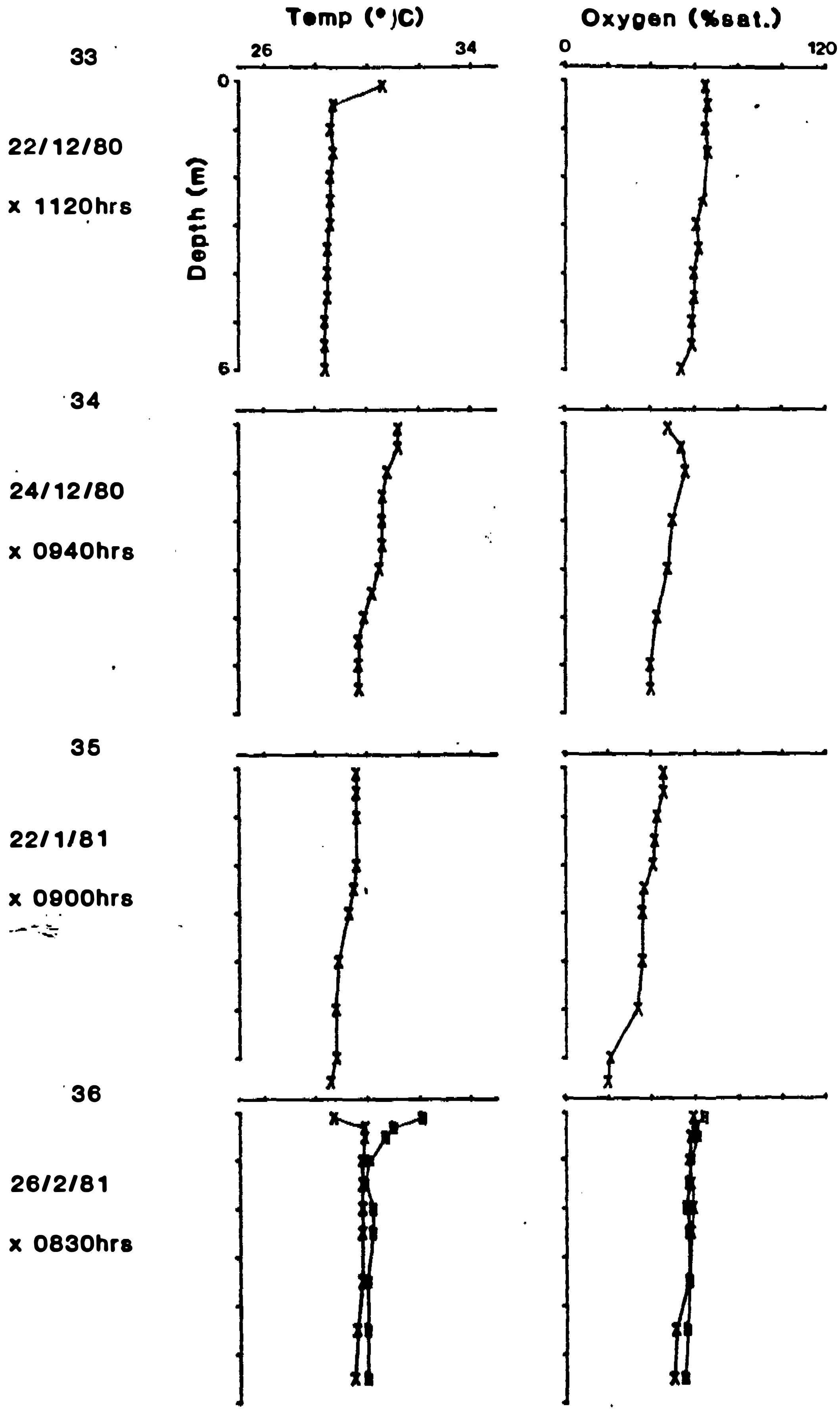

Temp (°)C)
Oxygen (%sat.)
22
32
0
120
0
6
Depth (m)
25
9/5/80
x 0830hrs
o 1500hrs
26
2/6/80
x 0850hrs
27
2/7/80
x 0900hrs
o 1450hrs
28
26/8/80
x 0930hrs
o 1535hrs

FIG.A10 (cont.)



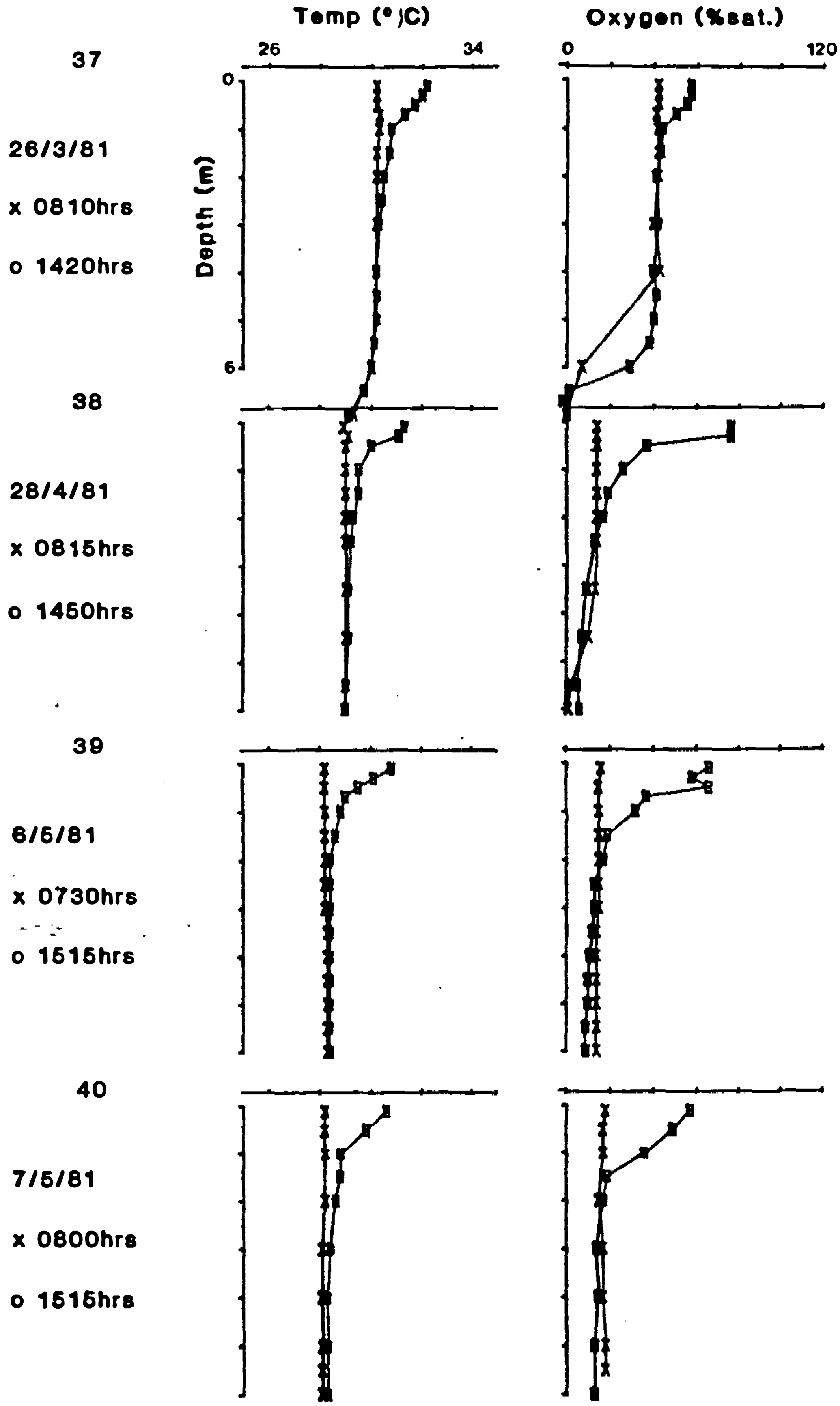
Temp (°)C)
Oxygen (%sat.)
26
34
0
120
0
6
Depth (m)
29
29/10/80
x 0830hrs
o 1520hrs
30
17/12/80
x 0905hrs
31
18/12/80
o 1430hrs
32
20/12/80
o 1400hrs

FIG.A1 0 (cont.)



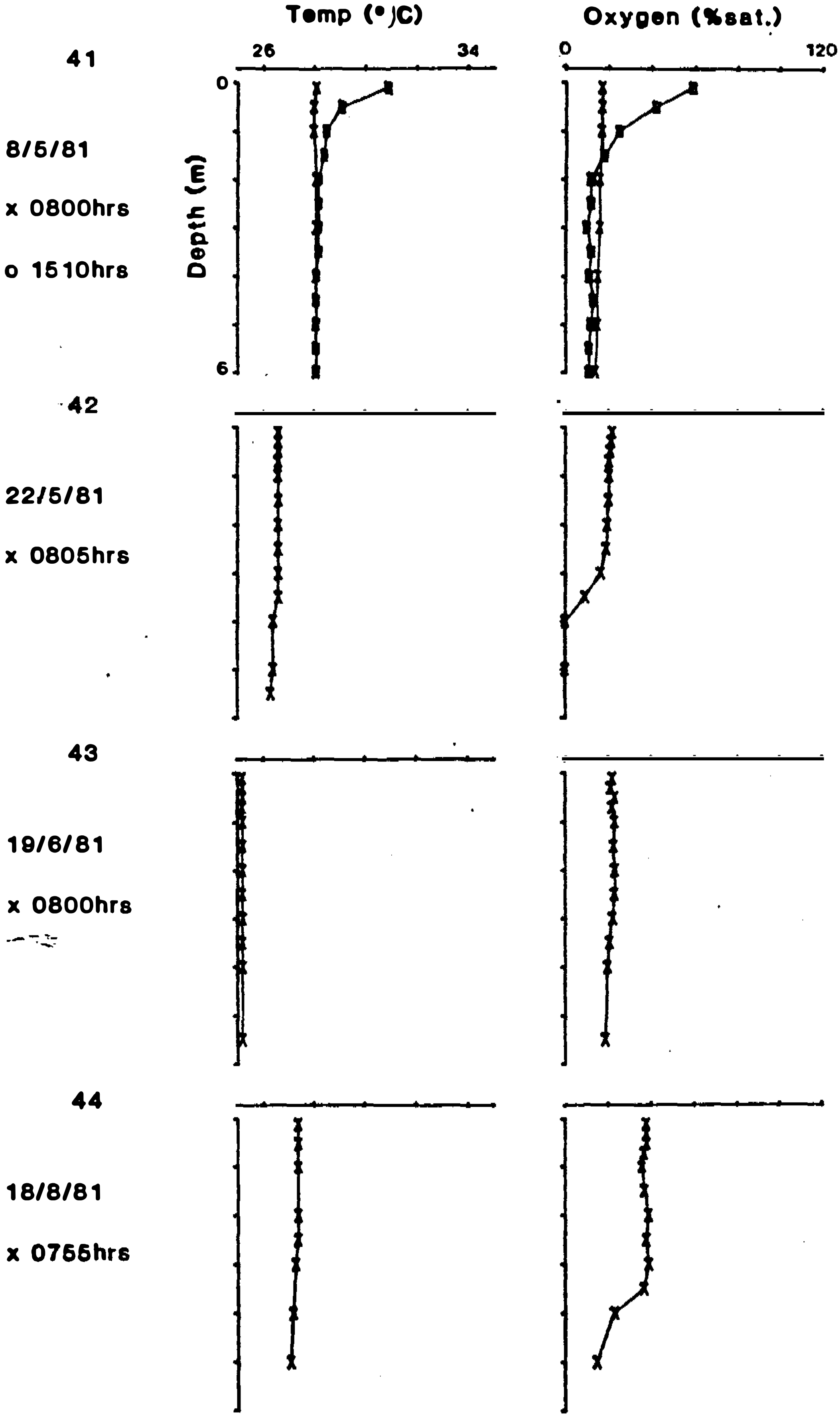
Temp (°)C)
Oxygen (%sat.)
26
34
0
120
0
6
Depth (m)
33
22/12/80
x 1120hrs
34
24/12/80
x 0940hrs
35
22/1/81
x 0900hrs
36
26/2/81
x 0830hrs

FIG. A10 (cont.)



Temp (°)C
Oxygen (%sat.)
26
34
0
120
0
6
Depth (m)
37
26/3/81
x 0810hrs
o 1420hrs
38
28/4/81
x 0815hrs
o 1450hrs
39
6/5/81
x 0730hrs
o 1515hrs
40
7/5/81
x 0800hrs
o 1515hrs

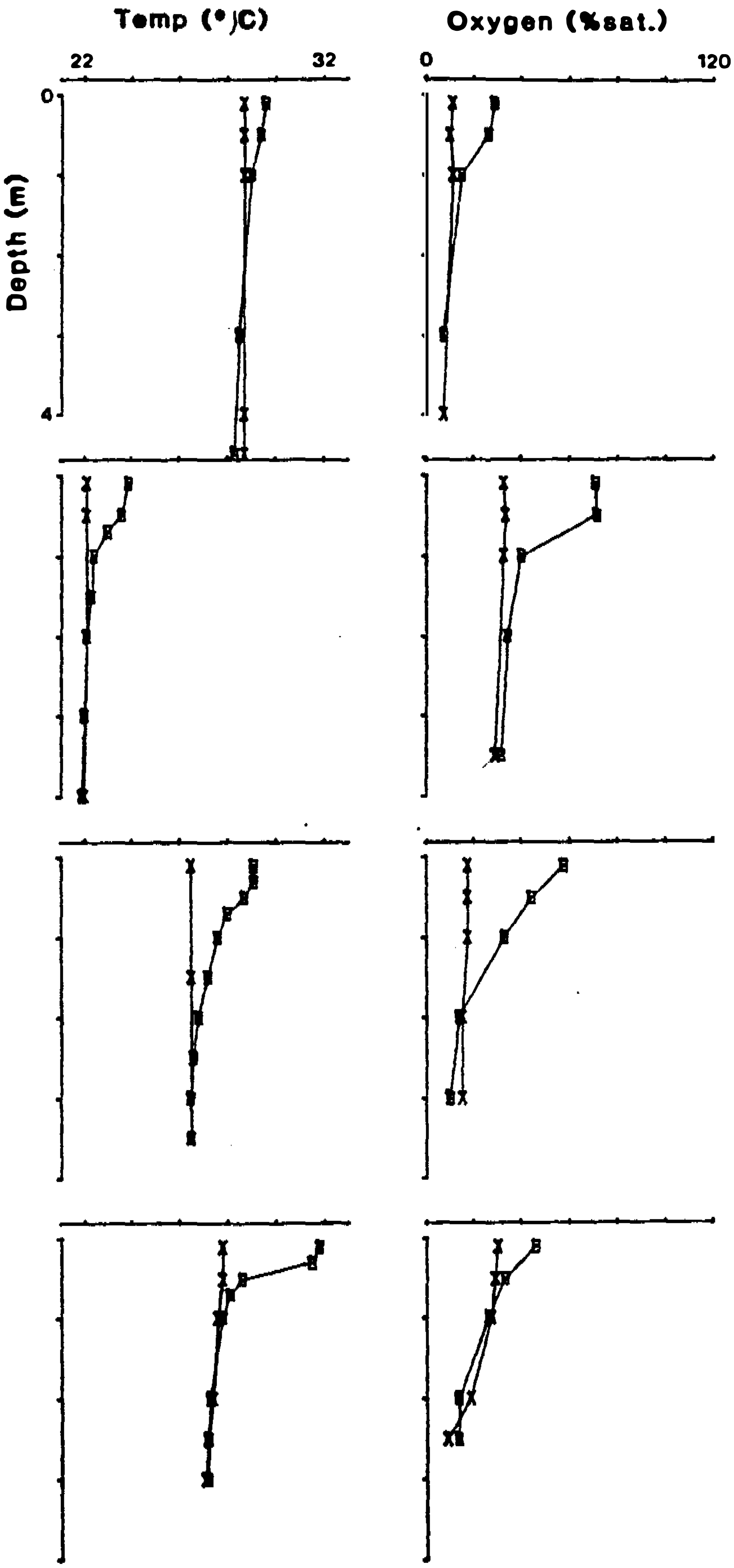
FIG. A1 0 (cont.)


Temp (°)C)
Oxygen (%sat.)
26
34
0
120
0
6
Depth (m)
41
8/5/81
x 0800hrs
o 1510hrs
42
22/5/81
x 0805hrs
43
19/6/81
x 0800hrs
44
18/8/81
x 0755hrs

APPENDIX 11

Temperature and oxygen profiles in Ja Ja billabong.

FIG. A1 1



1

14/4/78

x 0900hrs

o 1715hrs

2

17/6/78

x 0810hrs

o 1820hrs

3

29/8/78

x 0915hrs

o 1700hrs

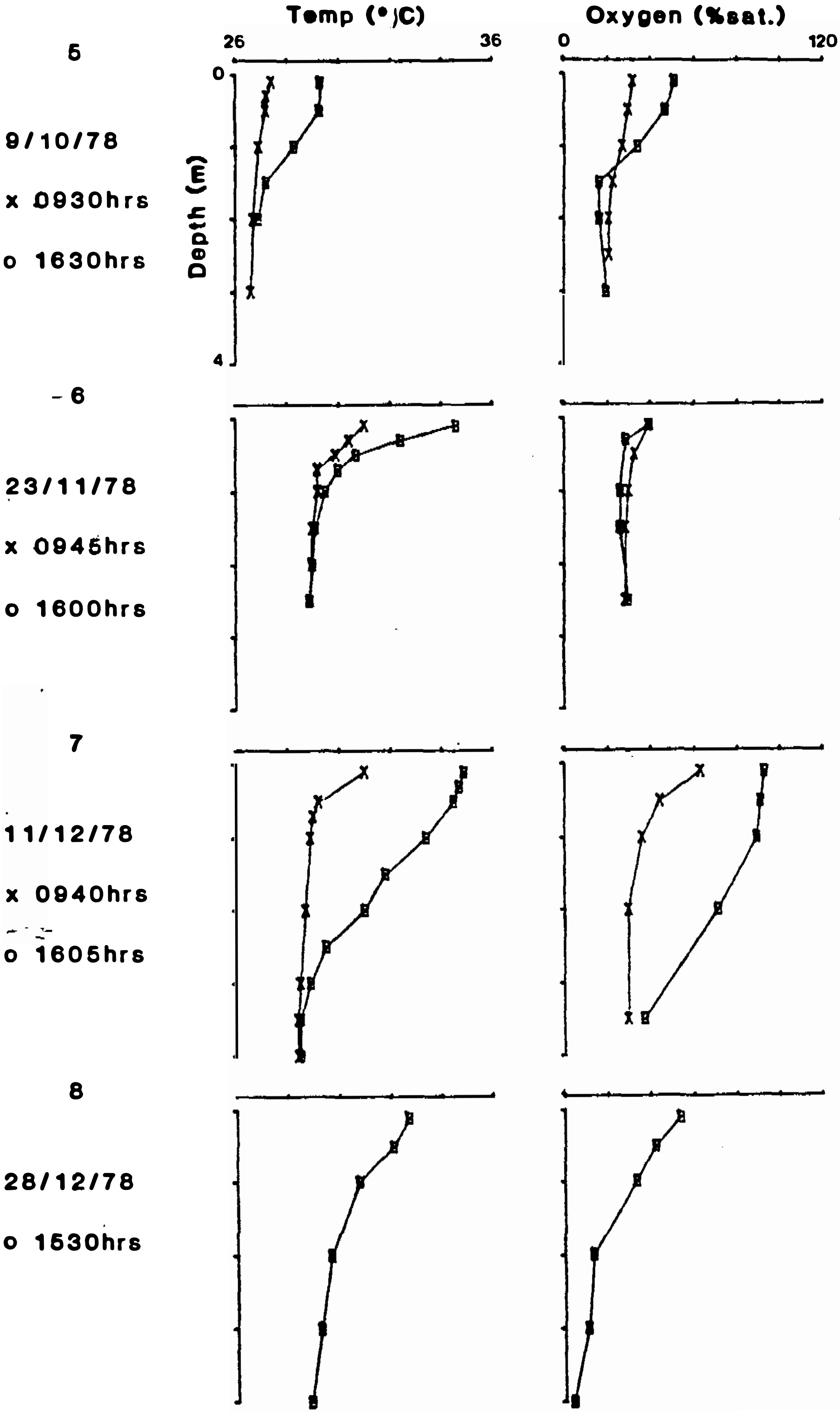
4

27/9/78

x 0945hrs

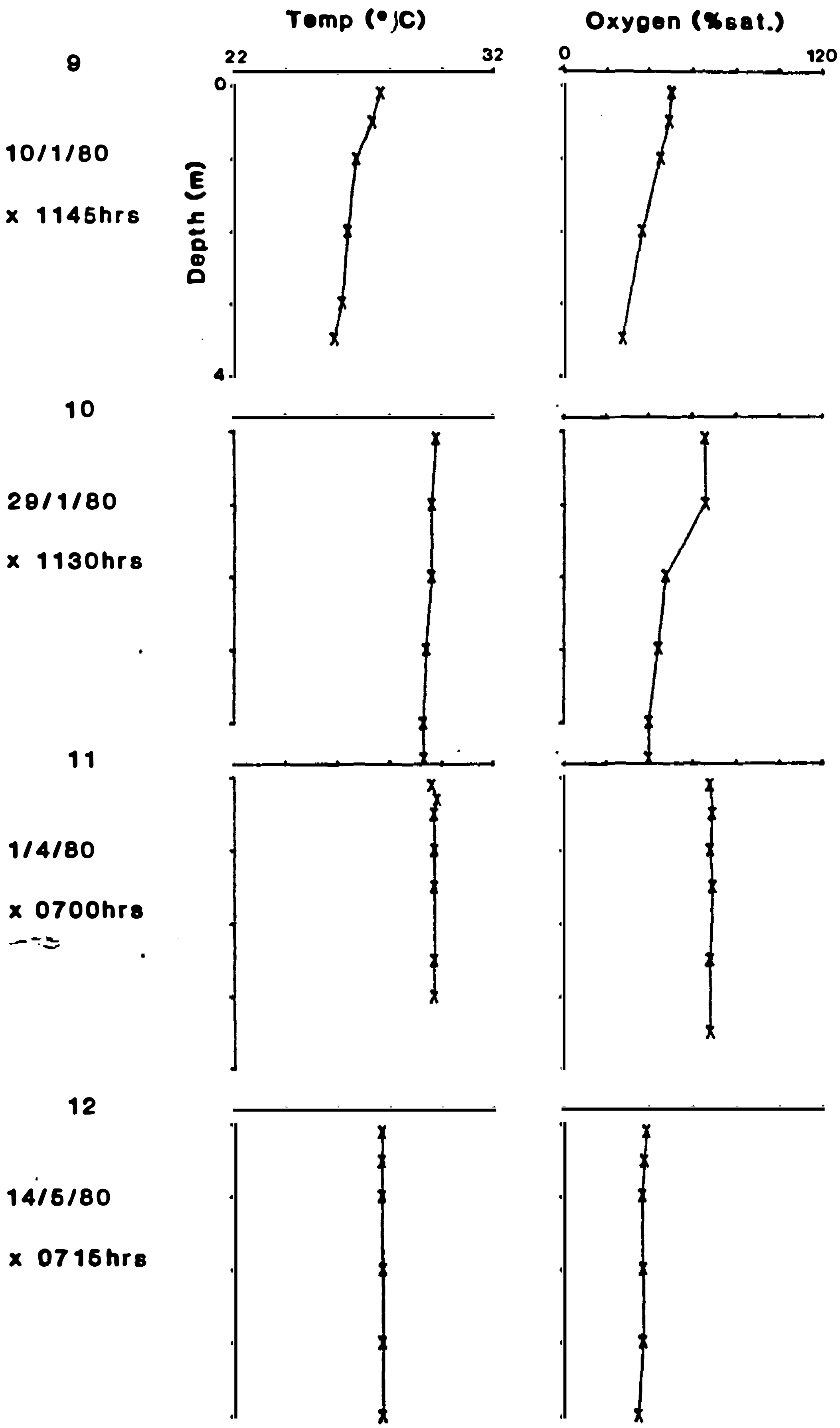
o 1625hrs

FIG. A11 (cont.)



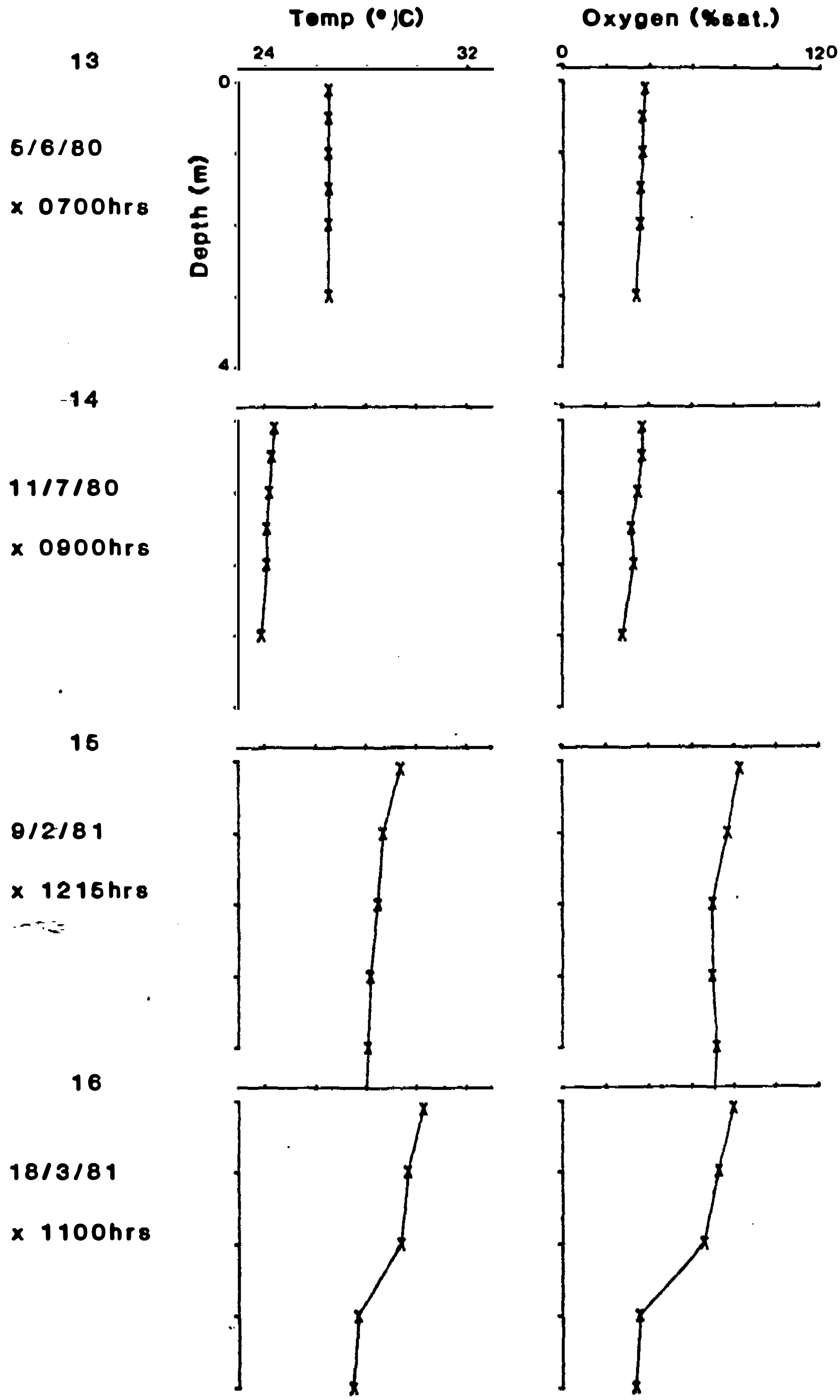
Temp (°)C
Oxygen (%sat.)
26
36
0
120
0
4
Depth (m)
5
9/10/78
x 0930hrs
o 1630hrs
6
23/11/78
x 0945hrs
o 1600hrs
7
11/12/78
x 0940hrs
o 1605hrs
8
28/12/78
o 1530hrs

FIG. A11 (cont.)



Temp (°)C)
Oxygen (%sat.)
22
32
0
120
0
4
Depth (m)
9
10/1/80
x 1145hrs
10
29/1/80
x 1130hrs
11
1/4/80
x 0700hrs
12
14/5/80
x 0715hrs

FIG. A1 1 (cont.)



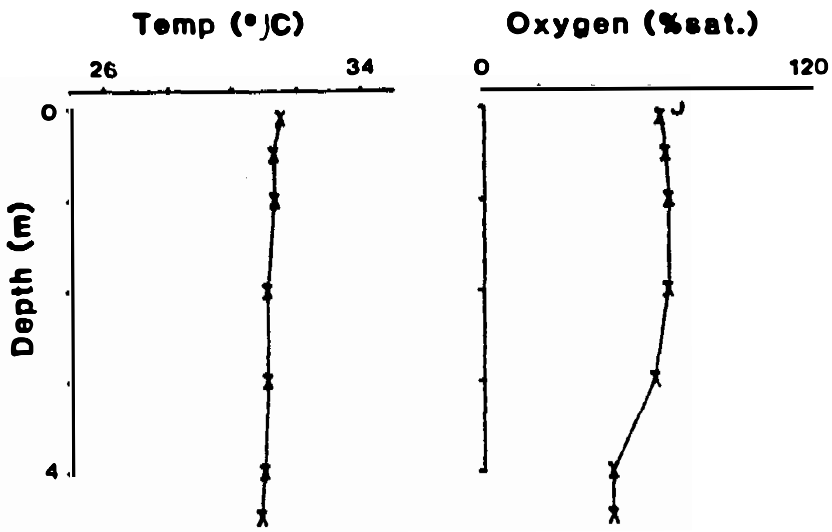
Temp (°)C)
Oxygen (%sat.)
24
32
0
120
0
4
Depth (m)
13
5/6/80
x 0700hrs
14
11/7/80
x 0900hrs
15
9/2/81
x 1215hrs
16
18/3/81
x 1100hrs

FIG. A1 1 (cont.)

17

6/4/81

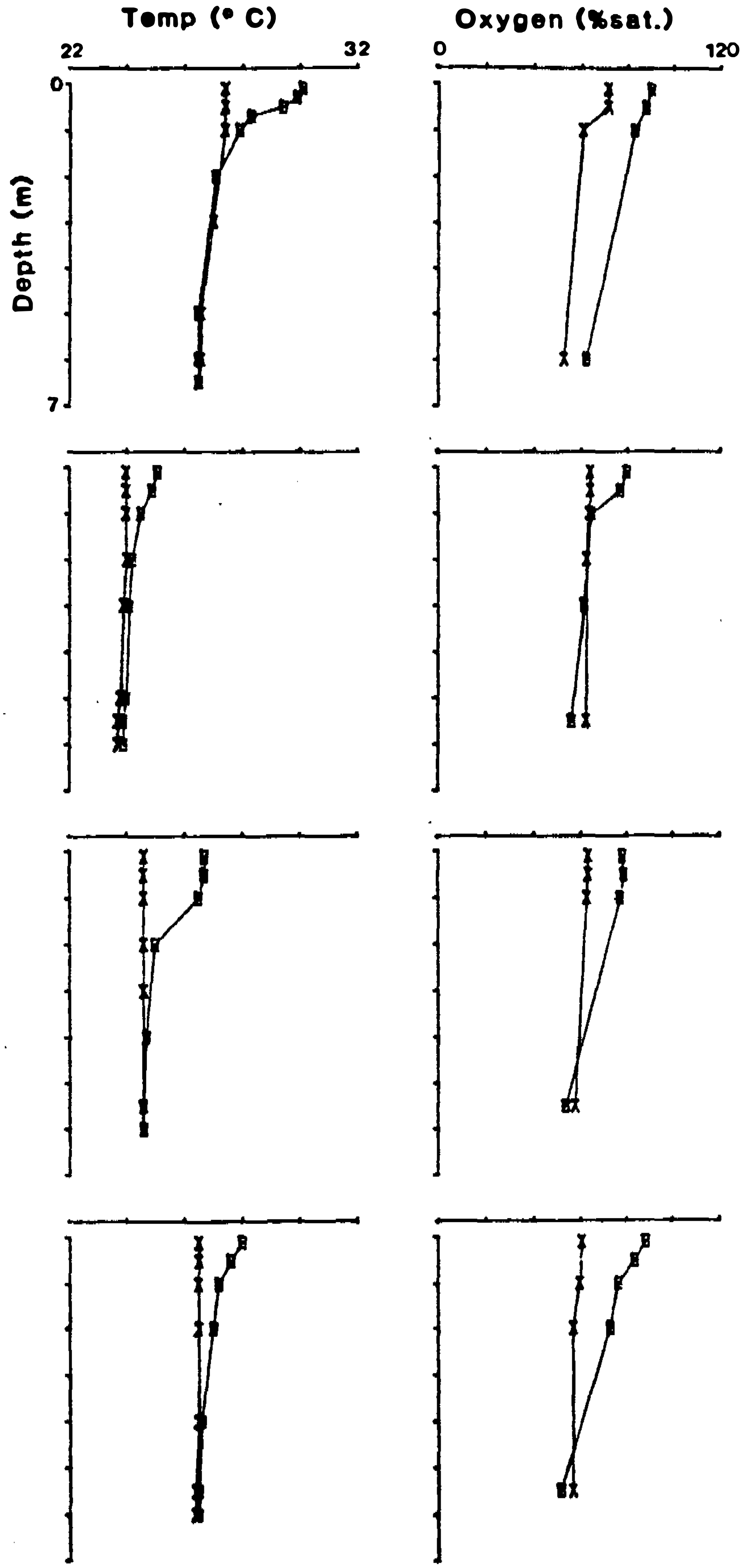
x 0925hrs



APPENDIX 12

Temperature and oxygen profiles in Mudginberri billabong.

FIG. A12



1

28/4/78

x 0730hrs

o 1600hrs

2

20/6/78

x 0850hrs

o 1715hrs

3

21/7/78

x 0835hrs

o 1715hrs

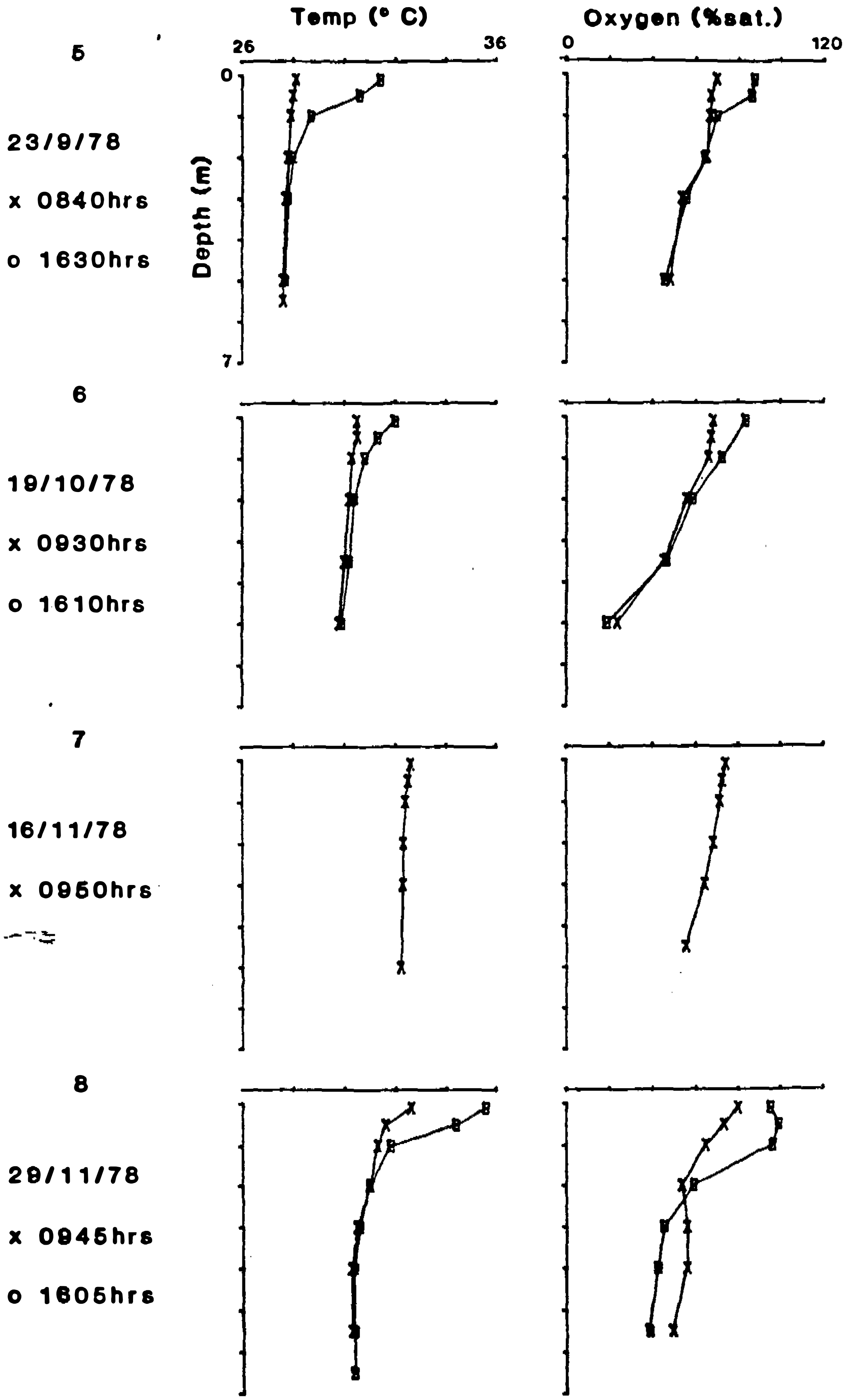
4

14/8/78

x 0845hrs

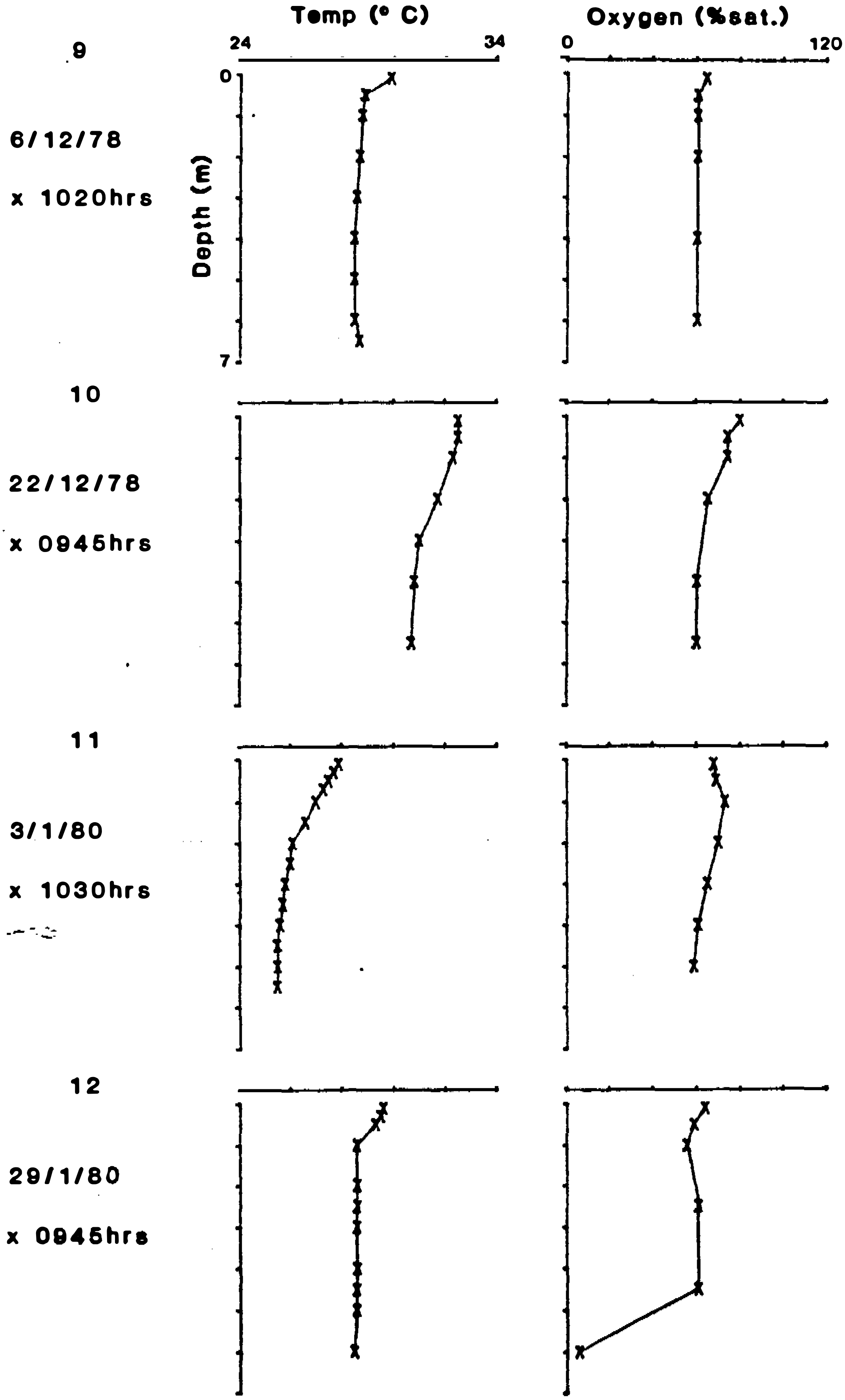
o 1705hrs

FIG. A12 (cont.)



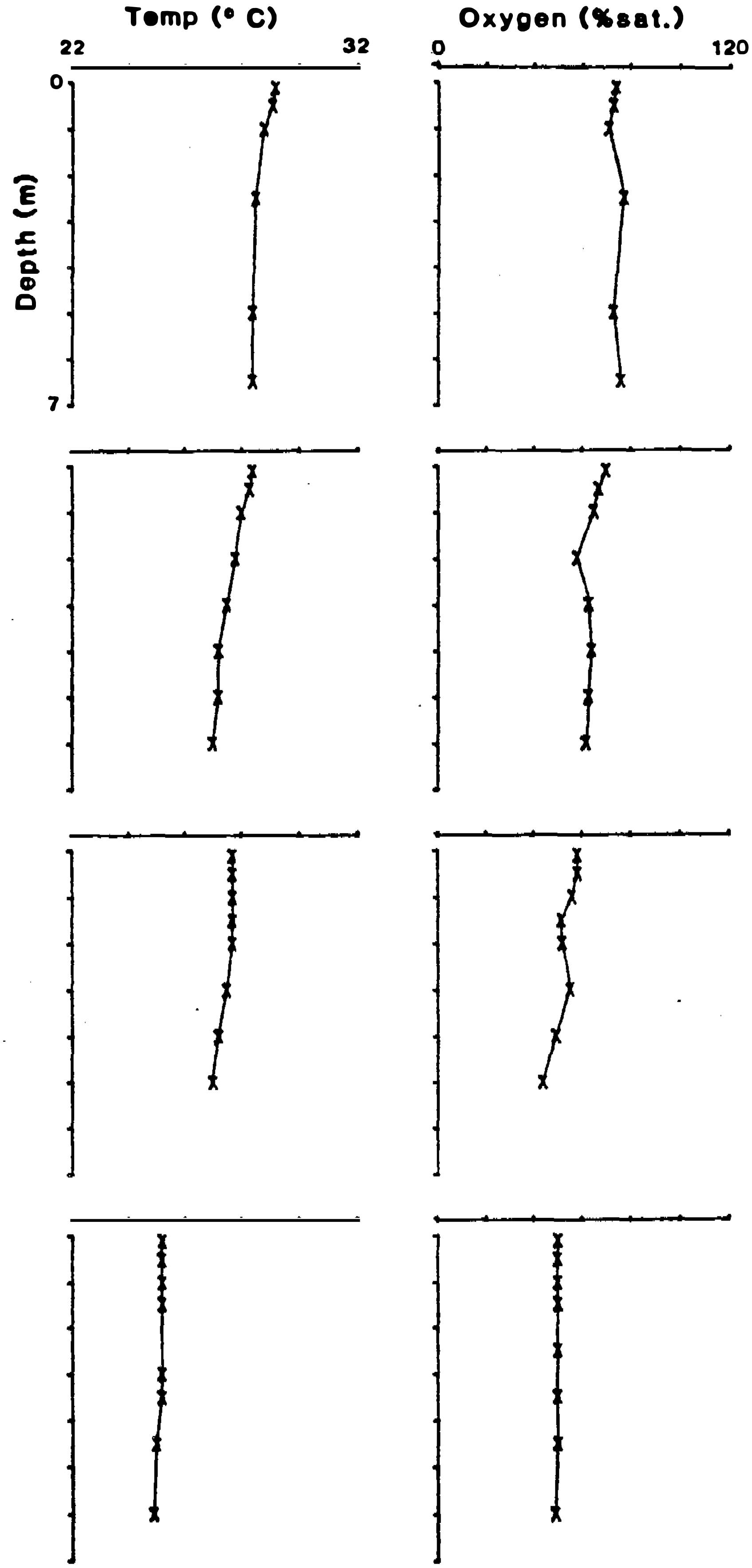
Temp (° C)
Oxygen (%sat.)
26
36
0
120
0
7
Depth (m)
5
23/9/78
x 0840hrs
o 1630hrs
6
19/10/78
x 0930hrs
o 1610hrs
7
16/11/78
x 0950hrs
8
29/11/78
x 0945hrs
o 1605hrs

FIG. A12 (cont.)



Temp (° C)
Oxygen (%sat.)
24
34
0
120
0
7
Depth (m)
9
6/12/78
x 1020hrs
10
22/12/78
x 0945hrs
11
3/1/80
x 1030hrs
12
29/1/80
x 0945hrs

FIG. A12 (cont.)



13

9/4/80

x 0930hrs

14

9/5/80hrs

x 0930hrs

15

2/6/80

x 0930hrs

16

3/7/80

x 0845hrs

FIG. A12 (cont.)

17

7/8/80

x 0830hrs

18

25/9/80

x 0825hrs

19

23/10/80

x 0815hrs

20

21/11/80

x 0840hrs

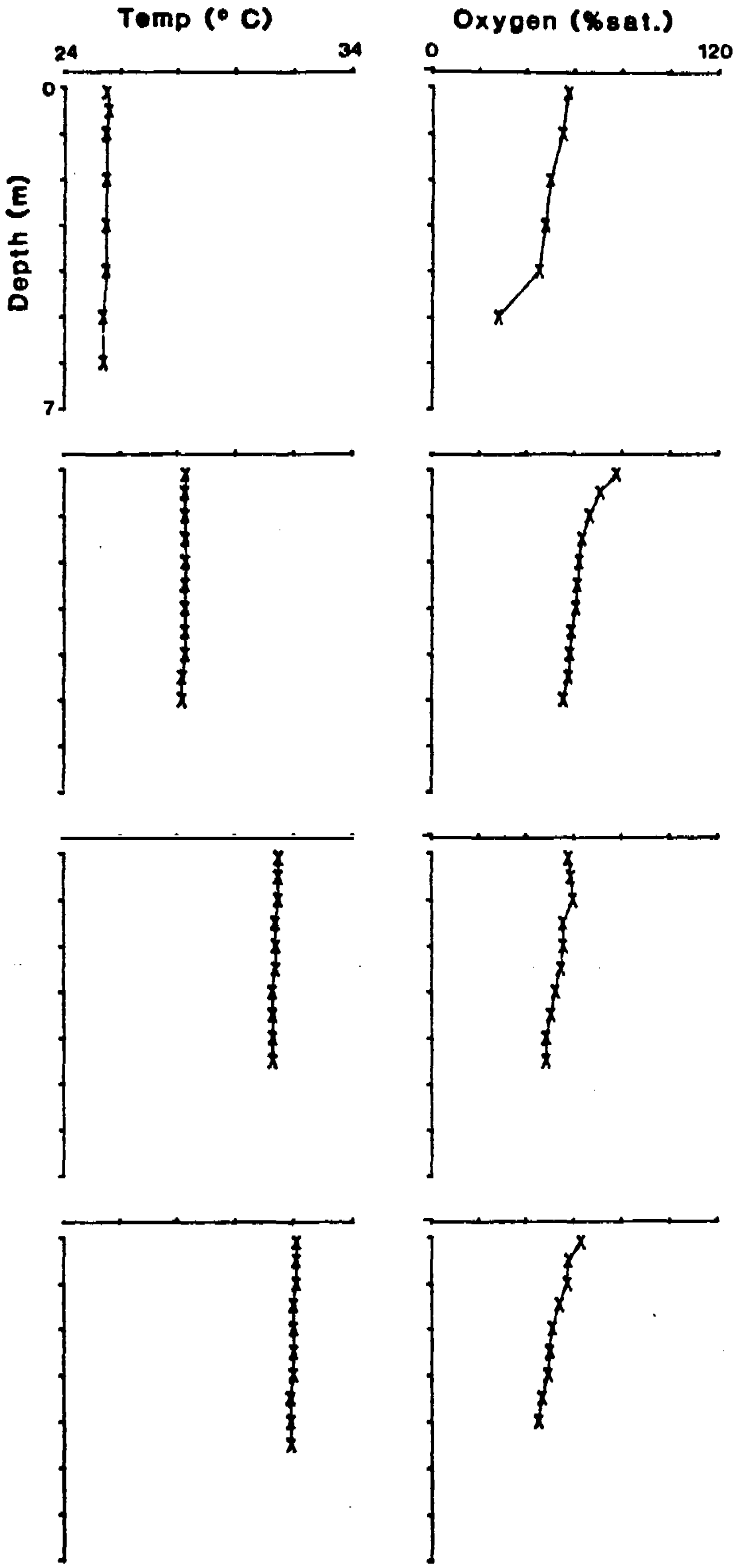
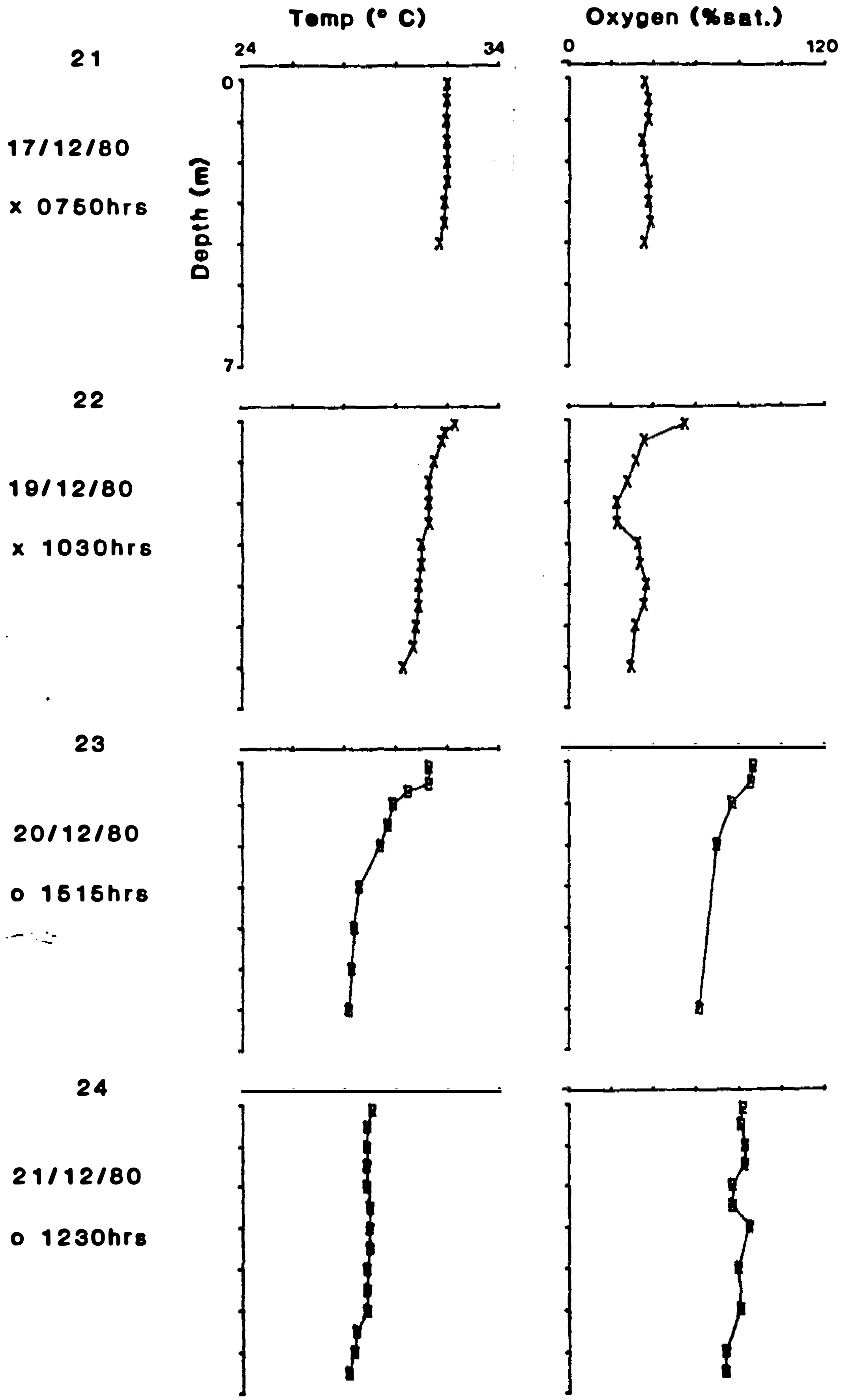
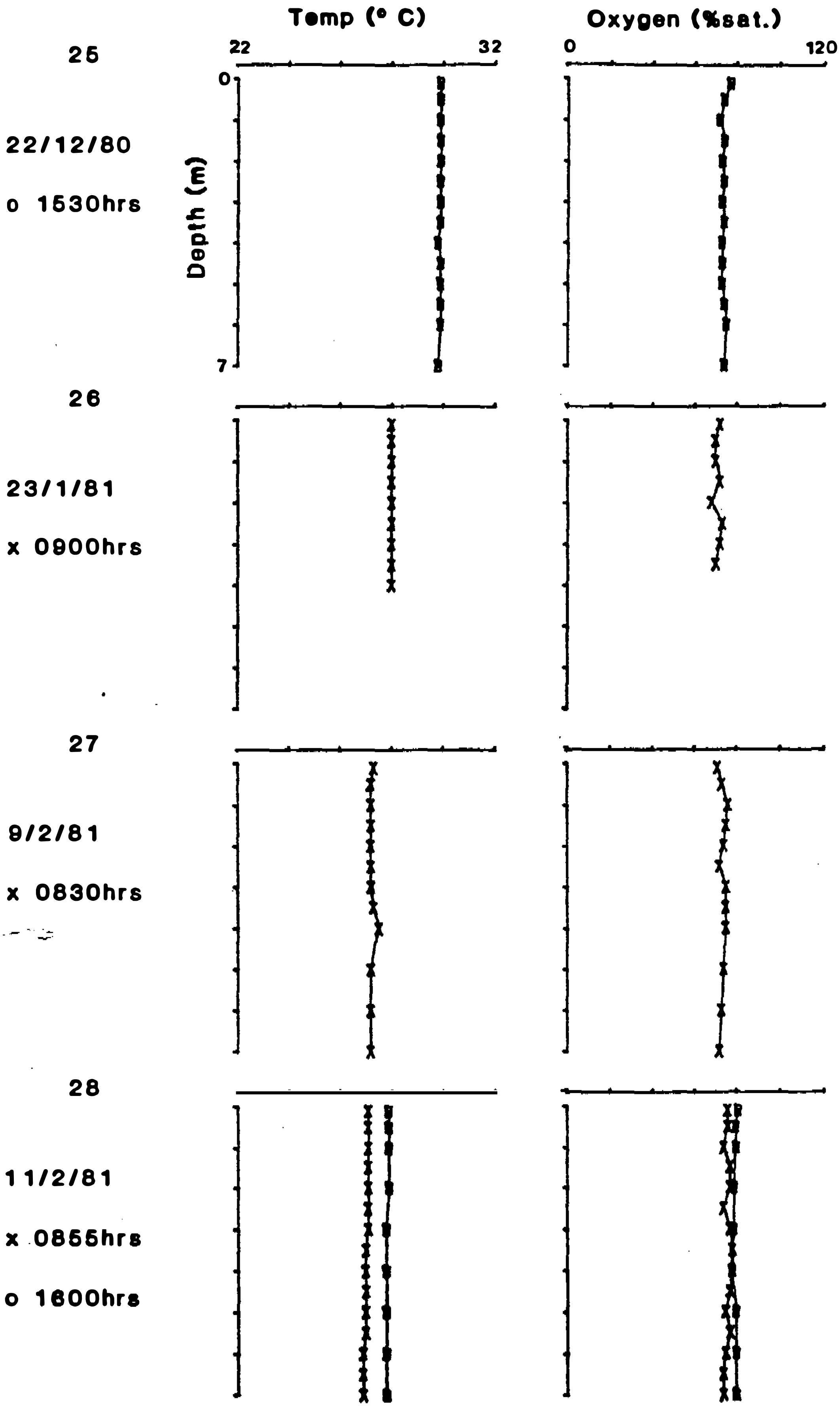


FIG. A12 (cont.)



Temp (° C)
24
34
Oxygen (%sat.)
0
120
Depth (m)
0
7
21
17/12/80
x 0750hrs
22
19/12/80
x 1030hrs
23
20/12/80
o 1515hrs
24
21/12/80
o 1230hrs

FIG. A12 (cont.)



Temp (° C)
Oxygen (%sat.)
22
32
0
120
0
7
Depth (m)
25
22/12/80
o 1530hrs
26
23/1/81
x 0900hrs
27
9/2/81
x 0830hrs
28
11/2/81
x 0855hrs
o 1600hrs

FIG. A12 (cont.)

29

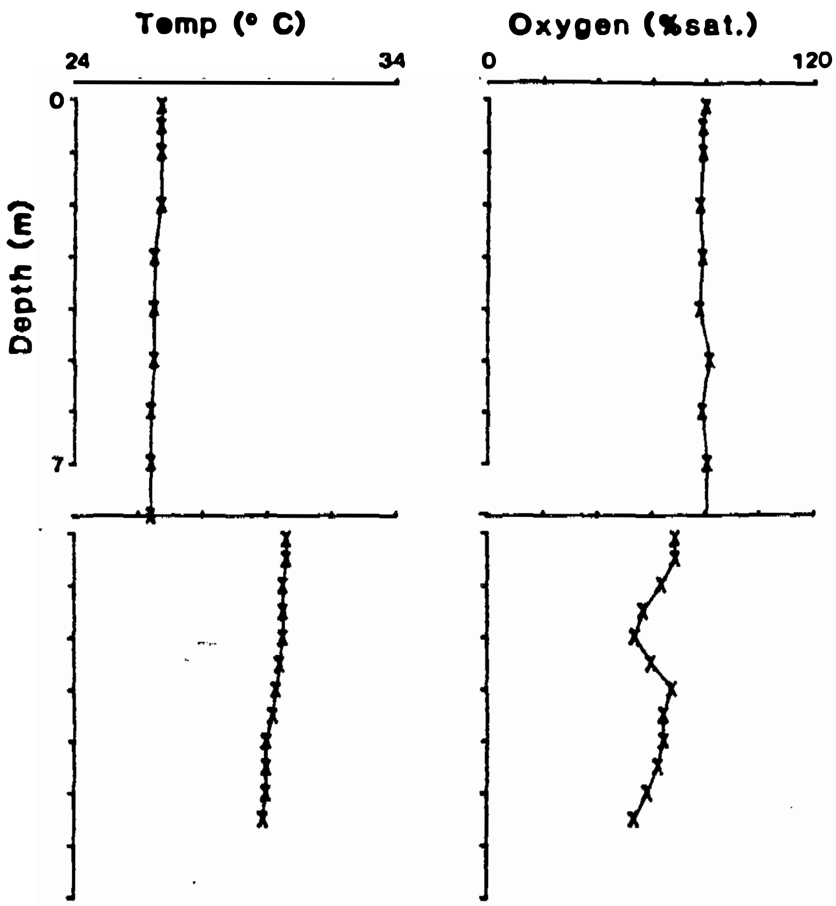
13/3/81

x 0855hrs

30

10/4/81

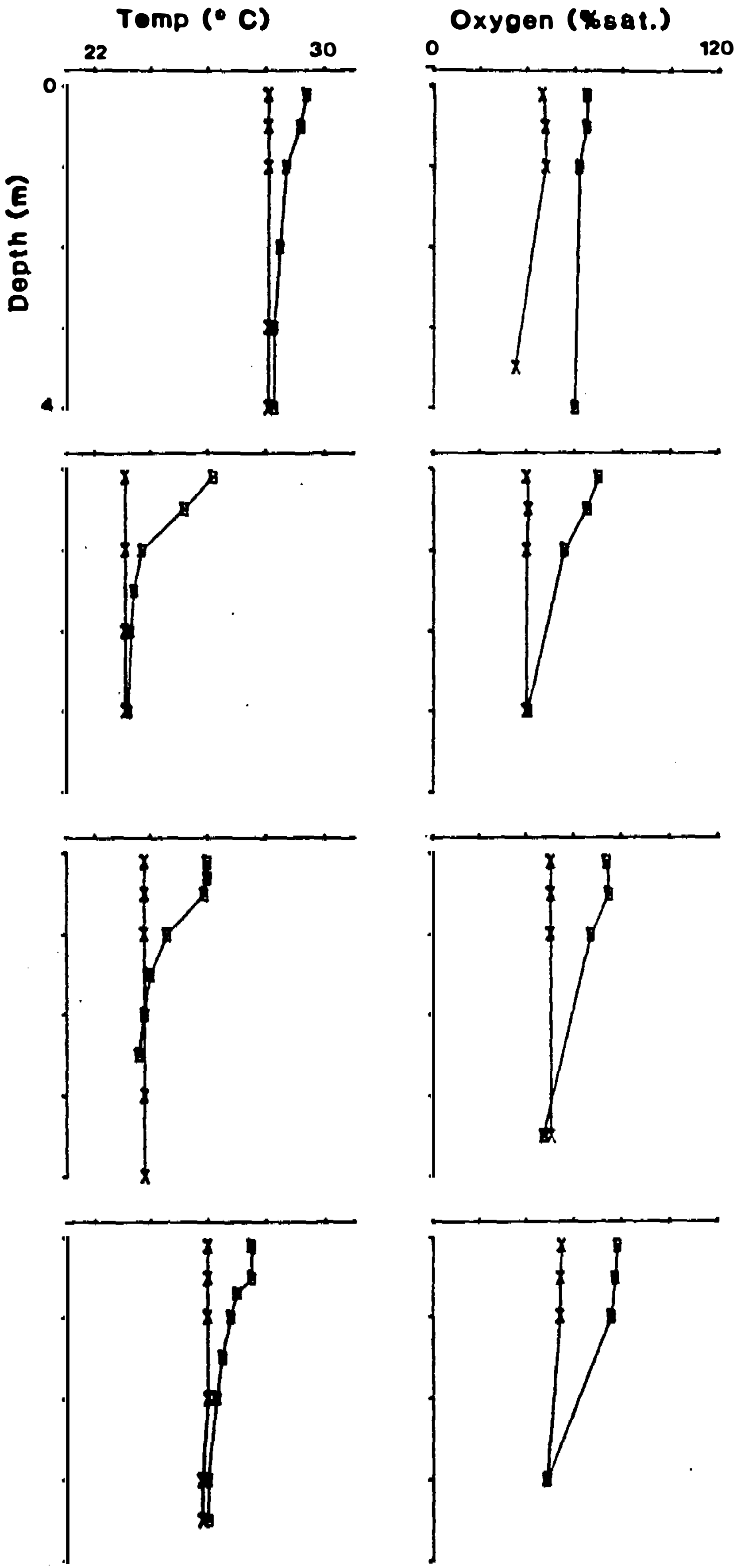
x 0810hrs



APPENDIX 13

Temperature and oxygen profiles in Buffalo billabong.

FIG. A1 3



1

6/5/78

x 0645hrs

o 1700hrs

2

23/6/78

x 0800hrs

o 1630hrs

3

20/7/78

x 0810hrs

o 1730hrs

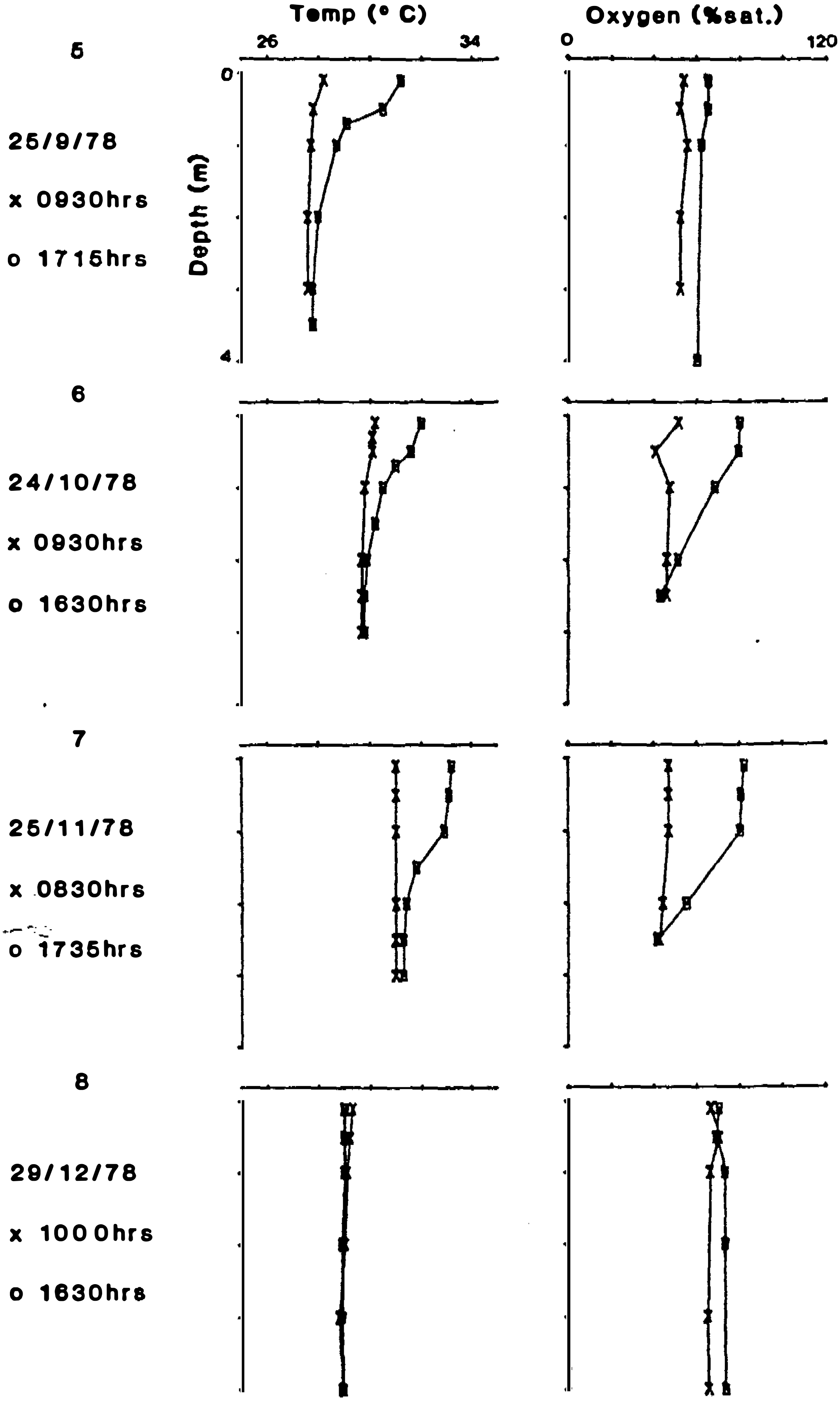
4

16/8/78

x 0835hrs

o 1825hrs

FIG. A13 (cont.)


Temp (° C)
26
34
Oxygen (%sat.)
0
120
Depth (m)
0
4
5
25/9/78
x 0930hrs
o 1715hrs
6
24/10/78
x 0930hrs
o 1630hrs
7
25/11/78
x 0830hrs
o 1735hrs
8
29/12/78
x 1000hrs
o 1630hrs

APPENDIX 14

Temperature and oxygen profiles in the backflow billabongs -
Gulungul (Figs A26.1-30),
Georgetown (Figs A26.31-38), and
Goanna (channel/backflow; Figs A26.39, 40).

FIG.A14 (cont.)

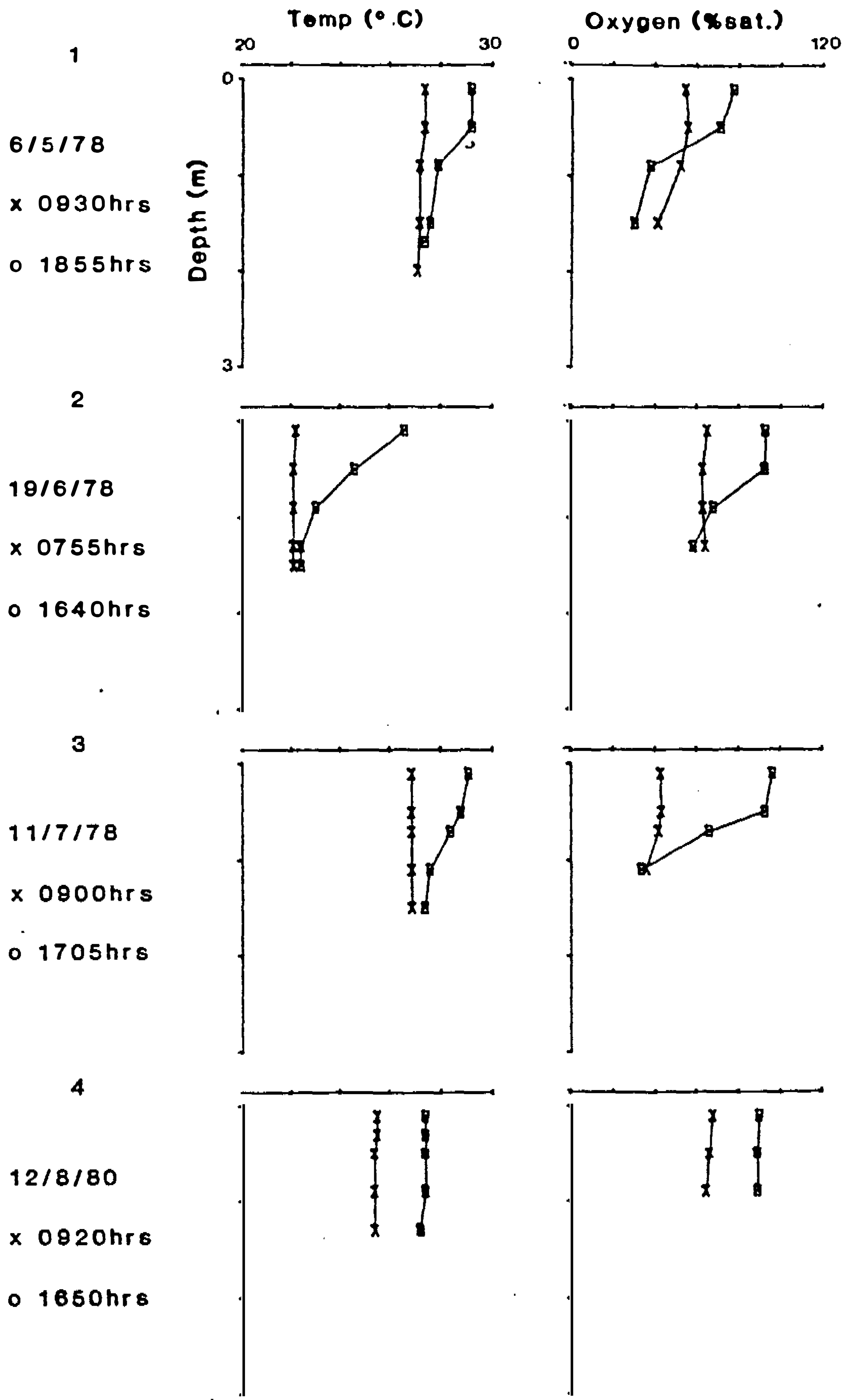

Temp (°C)
Oxygen (%sat.)
20
30
0
120
0
3
Depth (m)
1
6/5/78
x 0930hrs
o 1855hrs
2
19/6/78
x 0755hrs
o 1640hrs
3
11/7/78
x 0900hrs
o 1705hrs
4
12/8/80
x 0920hrs
o 1650hrs

FIG.A14 (cont.)

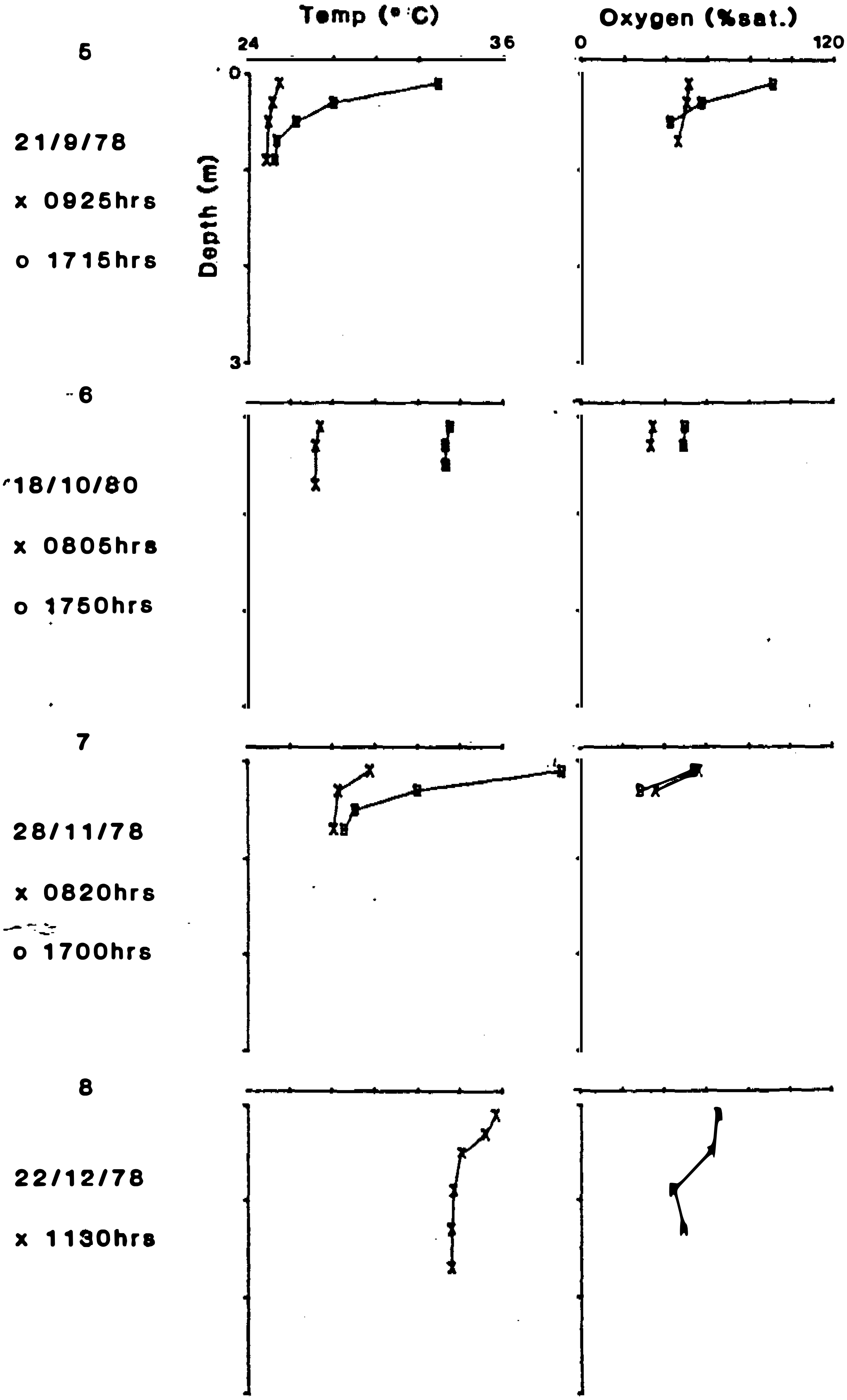
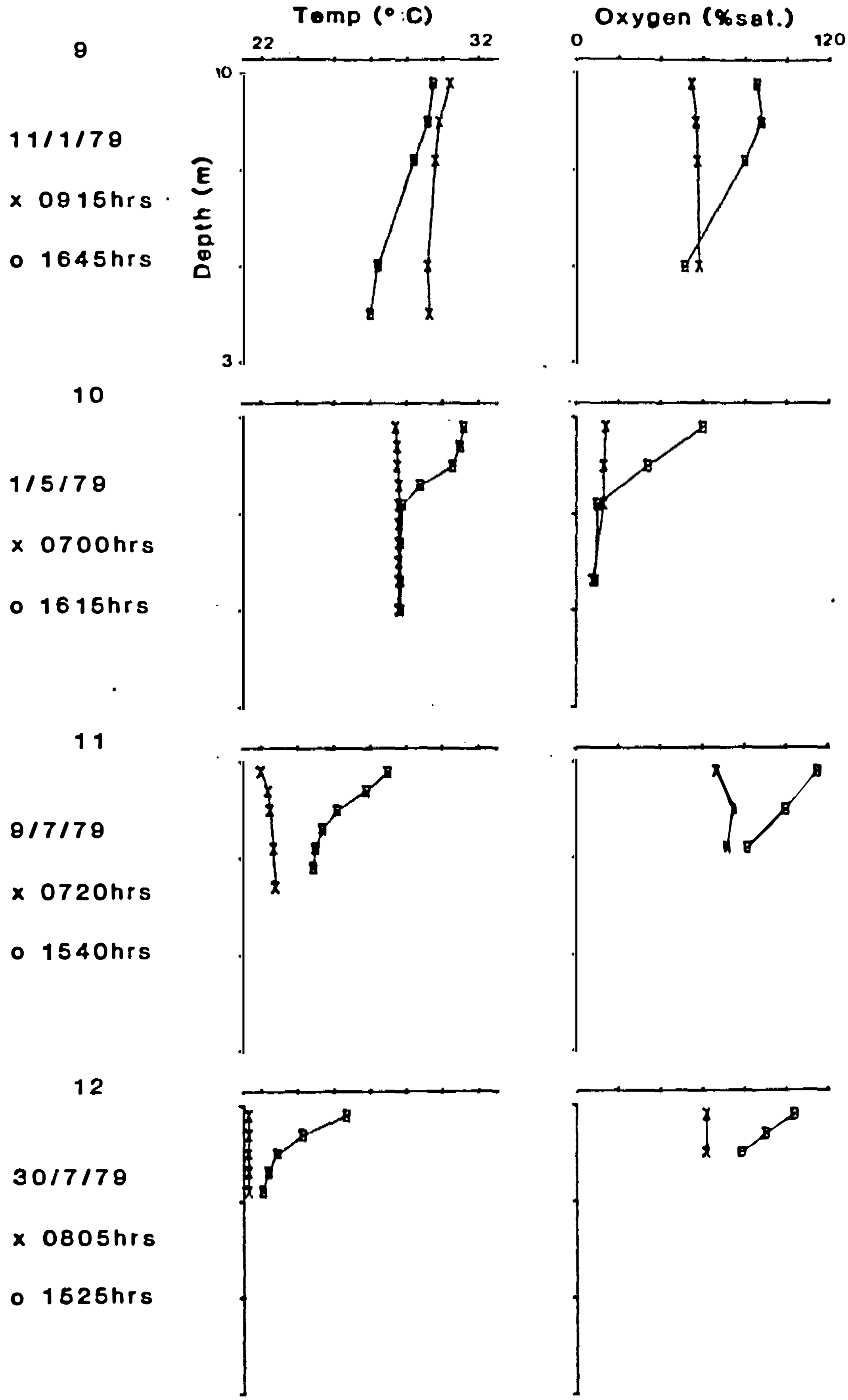

Temp (°C)
24
36
Oxygen (%sat.)
0
120
Depth (m)
0
3
5
21/9/78
x 0925hrs
o 1715hrs
6
18/10/80
x 0805hrs
o 1750hrs
7
28/11/78
x 0820hrs
o 1700hrs
8
22/12/78
x 1130hrs

FIG. A14 (cont.)



Temp (°C)
Oxygen (%sat.)
22
32
0
120
10
3
Depth (m)
9
11/1/79
x 0915hrs
o 1645hrs
10
1/5/79
x 0700hrs
o 1615hrs
11
9/7/79
x 0720hrs
o 1540hrs
12
30/7/79
x 0805hrs
o 1525hrs

FIG. A14 (cont.)

13

17/10/79

x 0945hrs

o 1445hrs

14

29/1/80

o 1430hrs

15

20/2/80

x 1000hrs

16

21/2/80

x 0915hrs

o 1630hrs

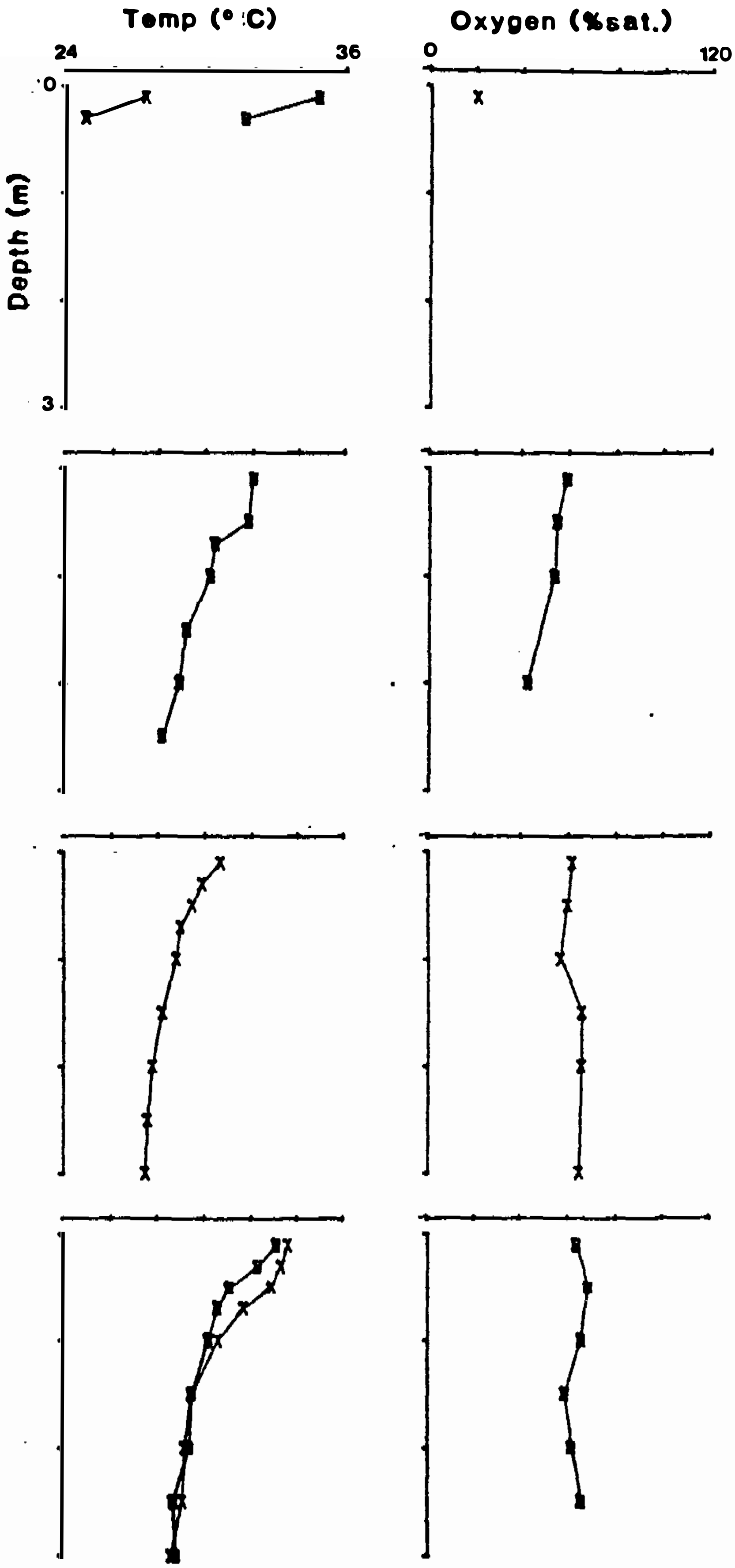
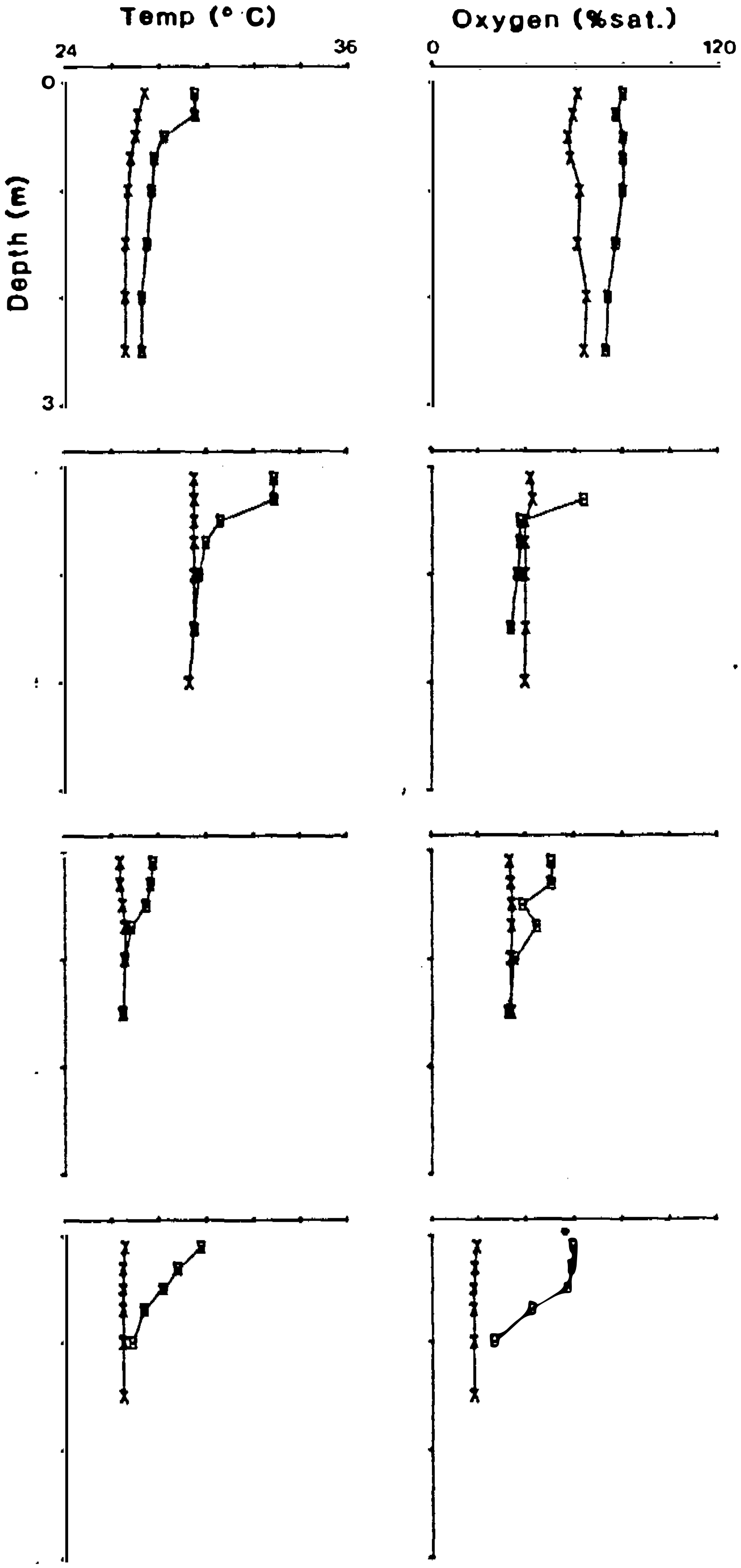


FIG. A14 (cont.)



17

21/3/80

x 0920hrs

o 1525hrs

18

16/4/80

x 0850hrs

o 1500hrs

19

21/5/80

x 0905hrs

o 1430hrs

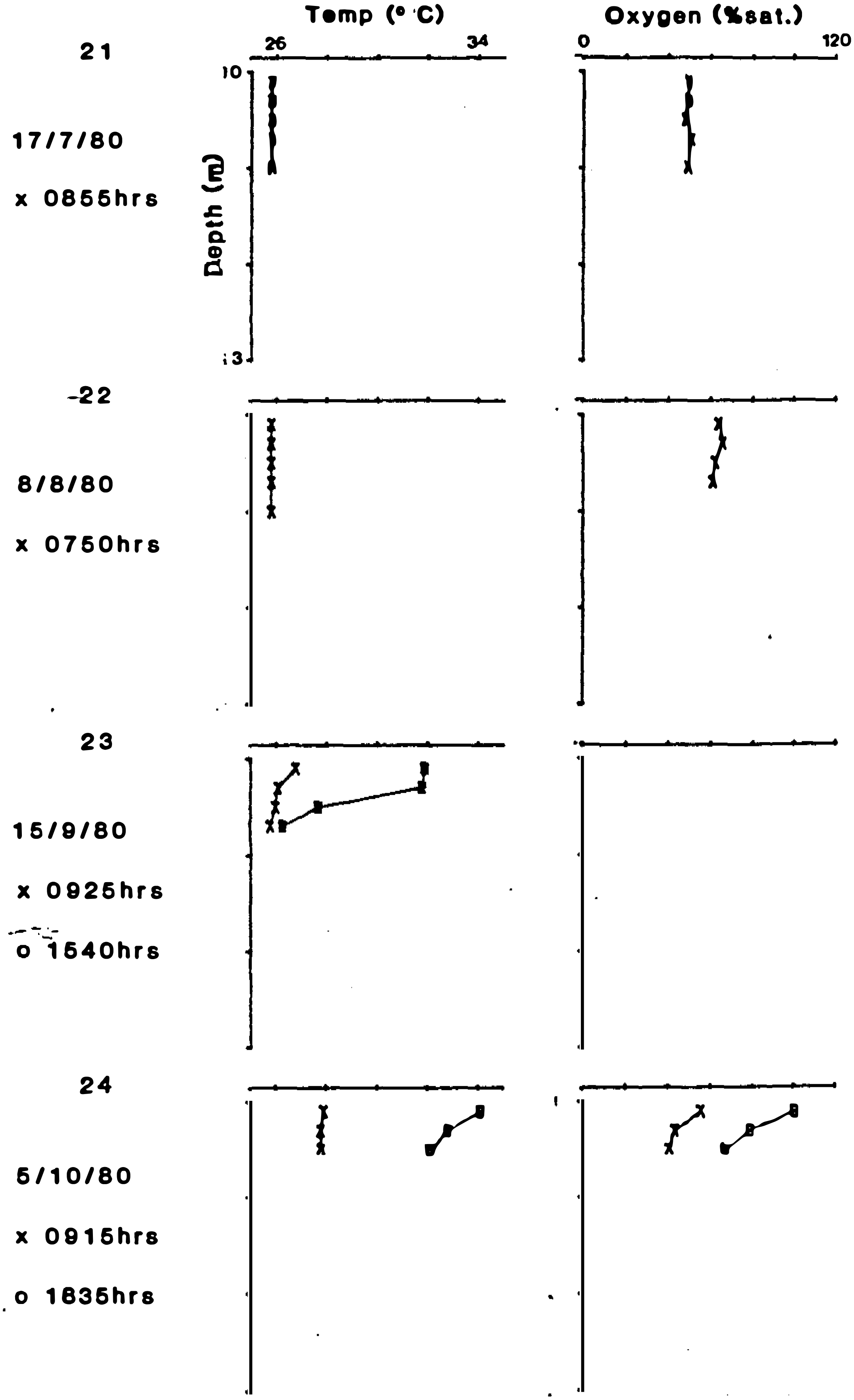
20

12/6/80

x 0835hrs

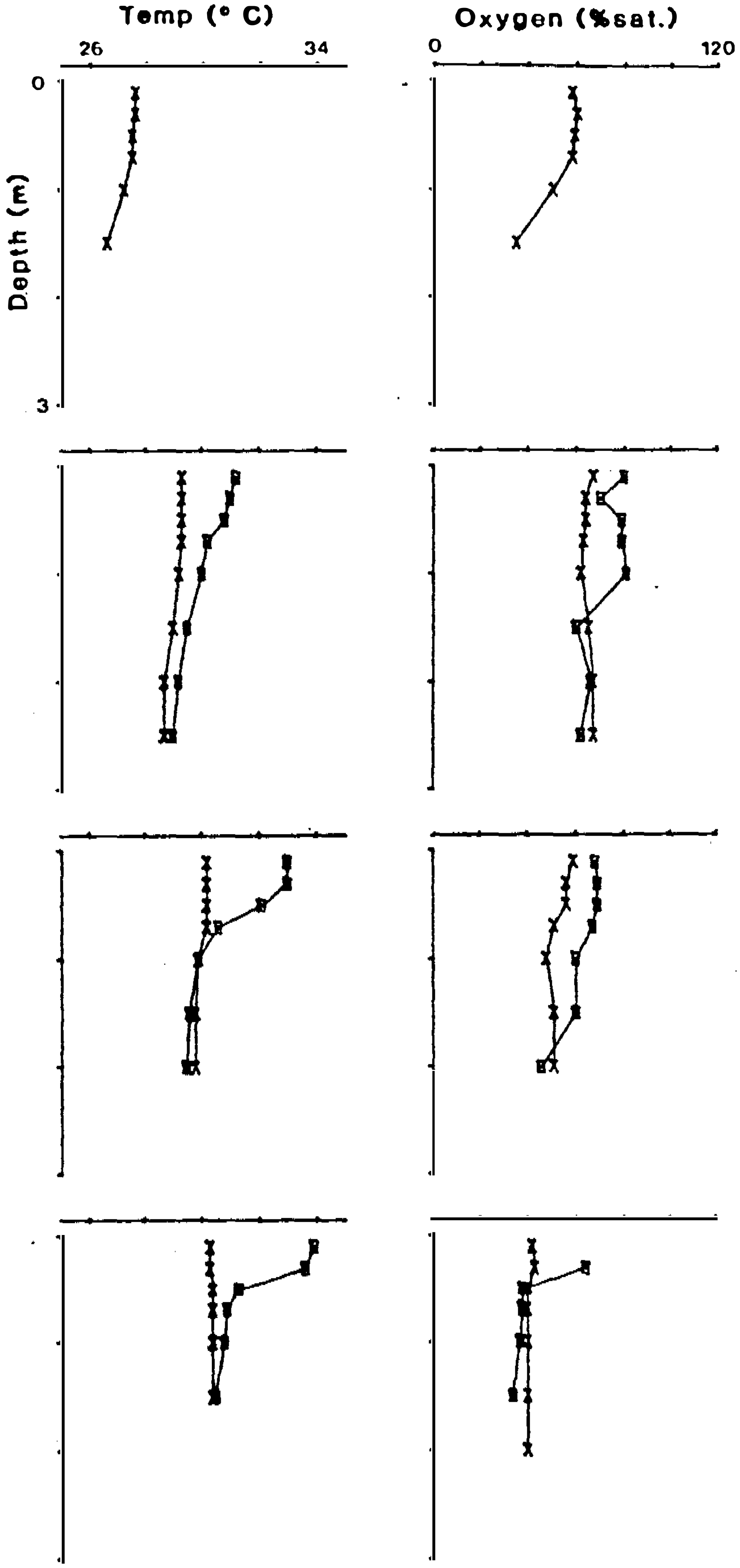
o 1525hrs

FIG. A14 (cont.)



Temp (° C)
Oxygen (%sat.)
26
34
0
120
10
Depth (m)
3
21
17/7/80
x 0855hrs
22
8/8/80
x 0750hrs
23
15/9/80
x 0925hrs
o 1540hrs
24
5/10/80
x 0915hrs
o 1835hrs

FIG. A14 (cont.)



25

20/12/80

x 1000hrs

26

17/2/81

x 0745hrs

o 1440hrs

27

17/3/81

x 0845hrs

o 1450hrs

28

16/4/81

x 0820hrs

o 1430hrs

FIG. A14 (cont.)

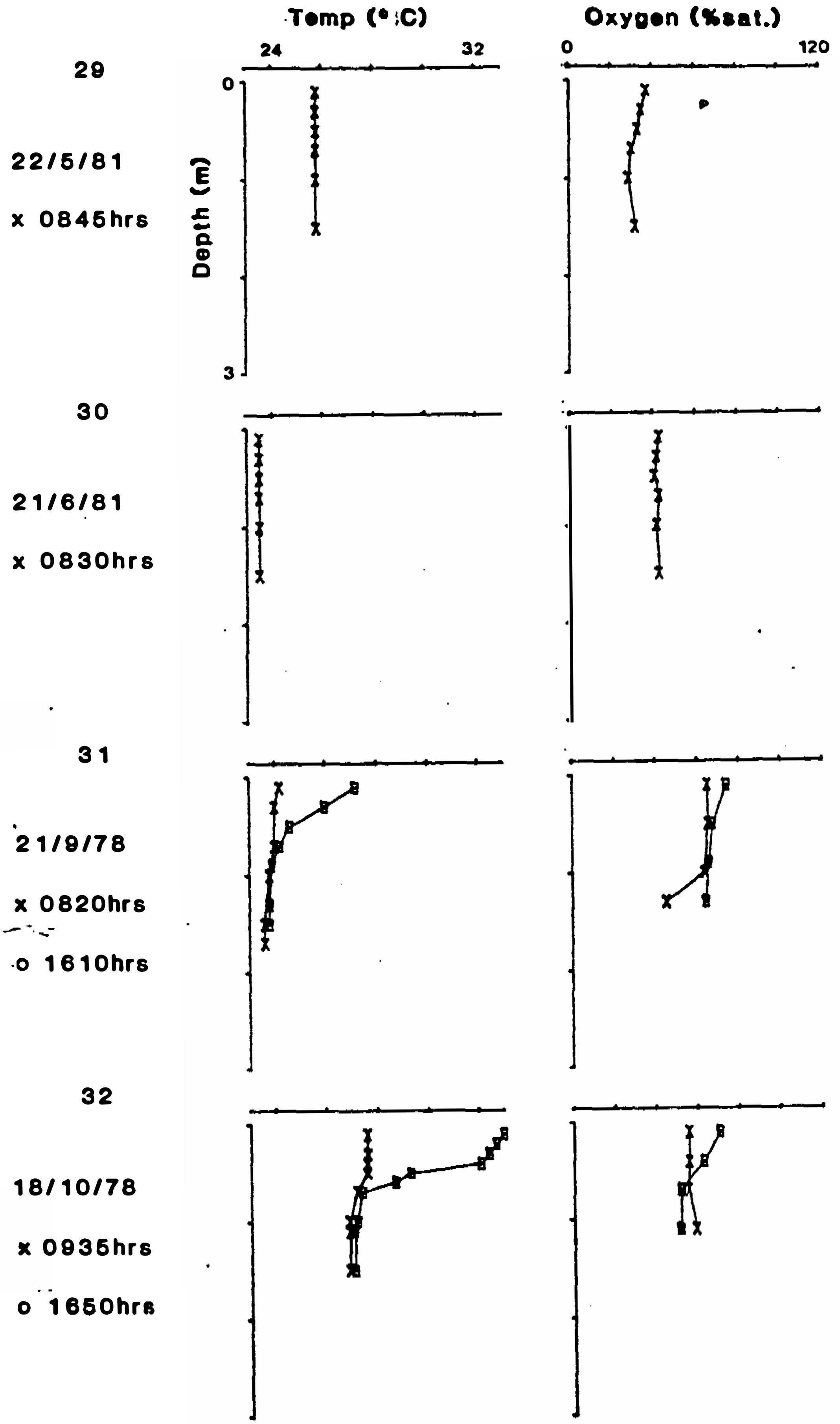
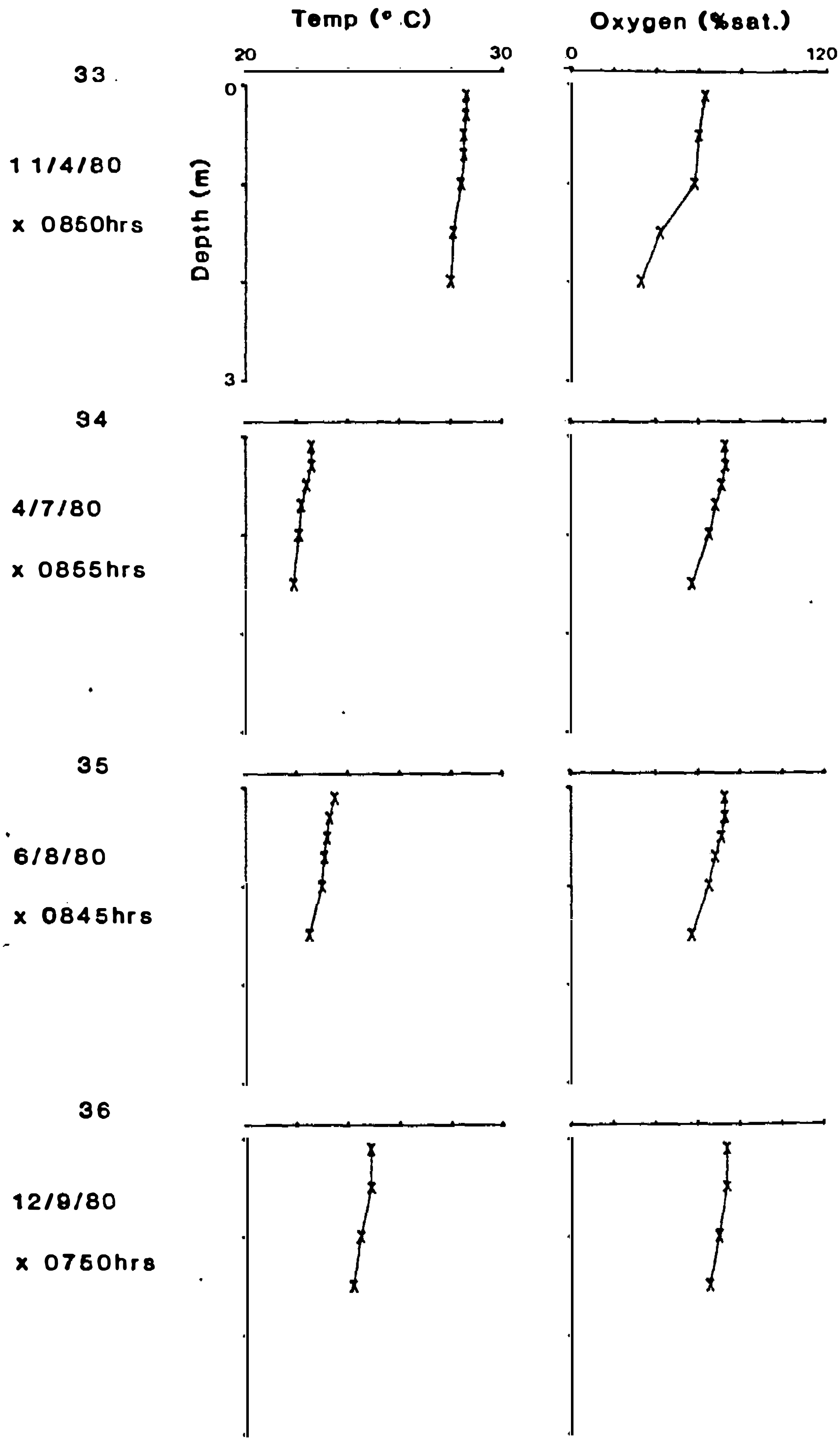
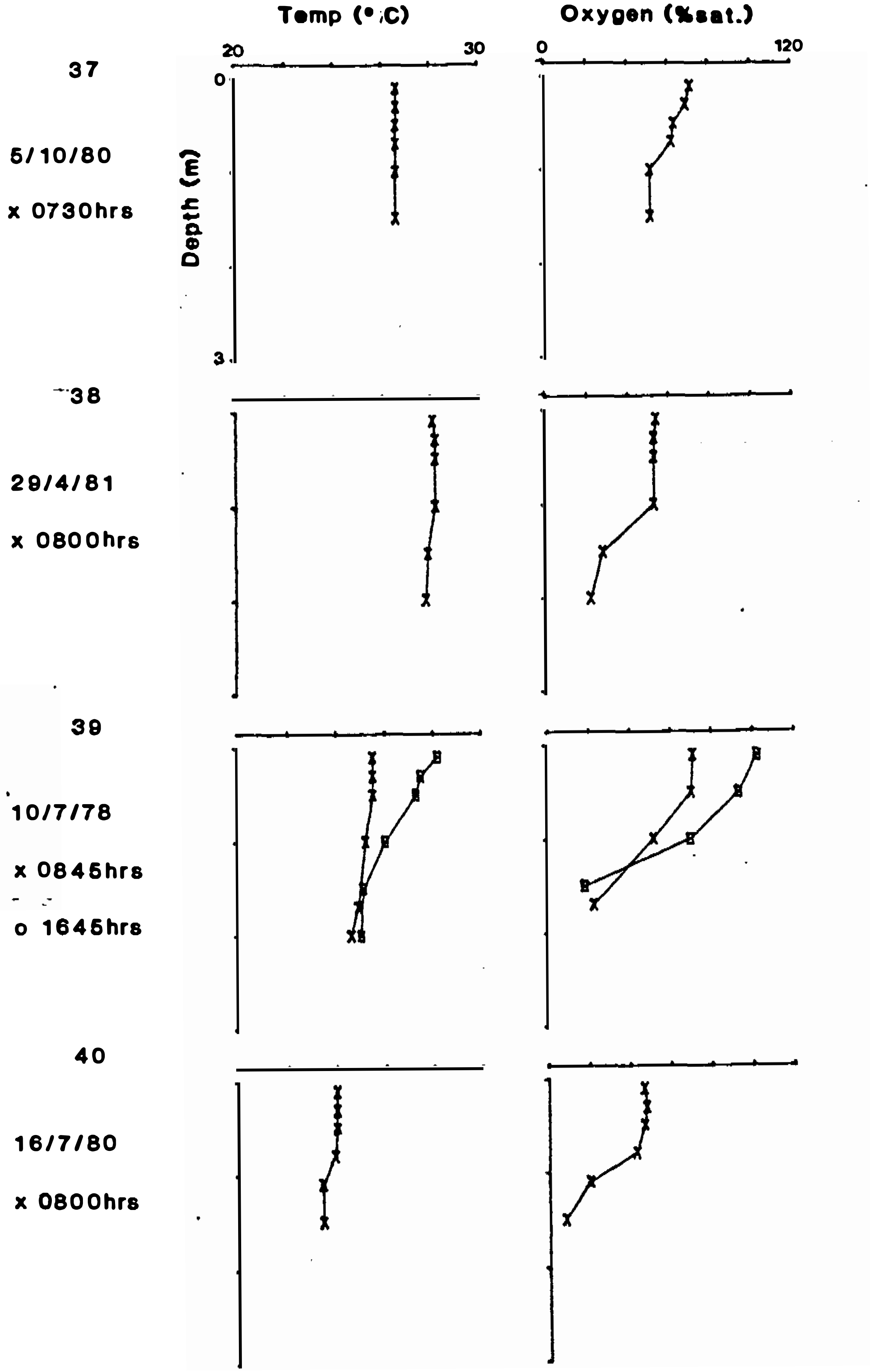

Temp (°C)
Oxygen (%sat.)
24
32
0
120
0
3
Depth (m)
29
22/5/81
x 0845hrs
30
21/6/81
x 0830hrs
31
21/9/78
x 0820hrs
o 1610hrs
32
18/10/78
x 0935hrs
o 1650hrs

FIG. A14 (cont.)



Temp (°C)
Oxygen (%sat.)
20
30
0
120
0
3
Depth (m)
33
11/4/80
x 0850hrs
34
4/7/80
x 0855hrs
35
6/8/80
x 0845hrs
36
12/9/80
x 0750hrs

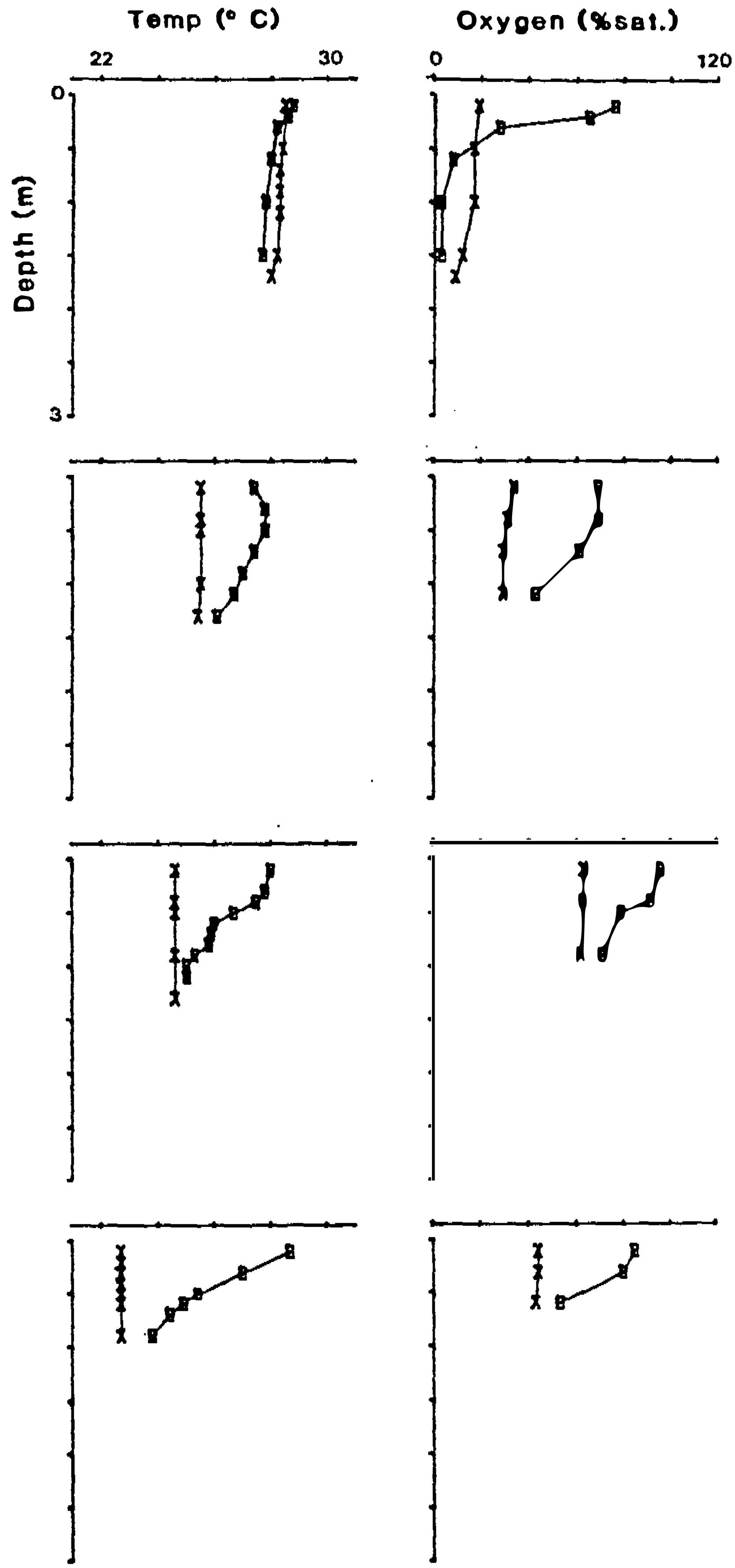
FIG. A14 (cont.)


Temp (°C)
Oxygen (%sat.)
20
30
0
120
Depth (m)
0
3
37
5/10/80
x 0730hrs
38
29/4/81
x 0800hrs
39
10/7/78
x 0845hrs
o 1645hrs
40
16/7/80
x 0800hrs

APPENDIX 15

Temperature and oxygen profiles in Mine Valley billabong.

FIG. A1 5



1

14/5/79

x 0715hrs

o 1530hrs

2

19/6/79

x 0730hrs

o 1535hrs

3

17/7/79

x 0740hrs

o 1540hrs

4

20/8/79

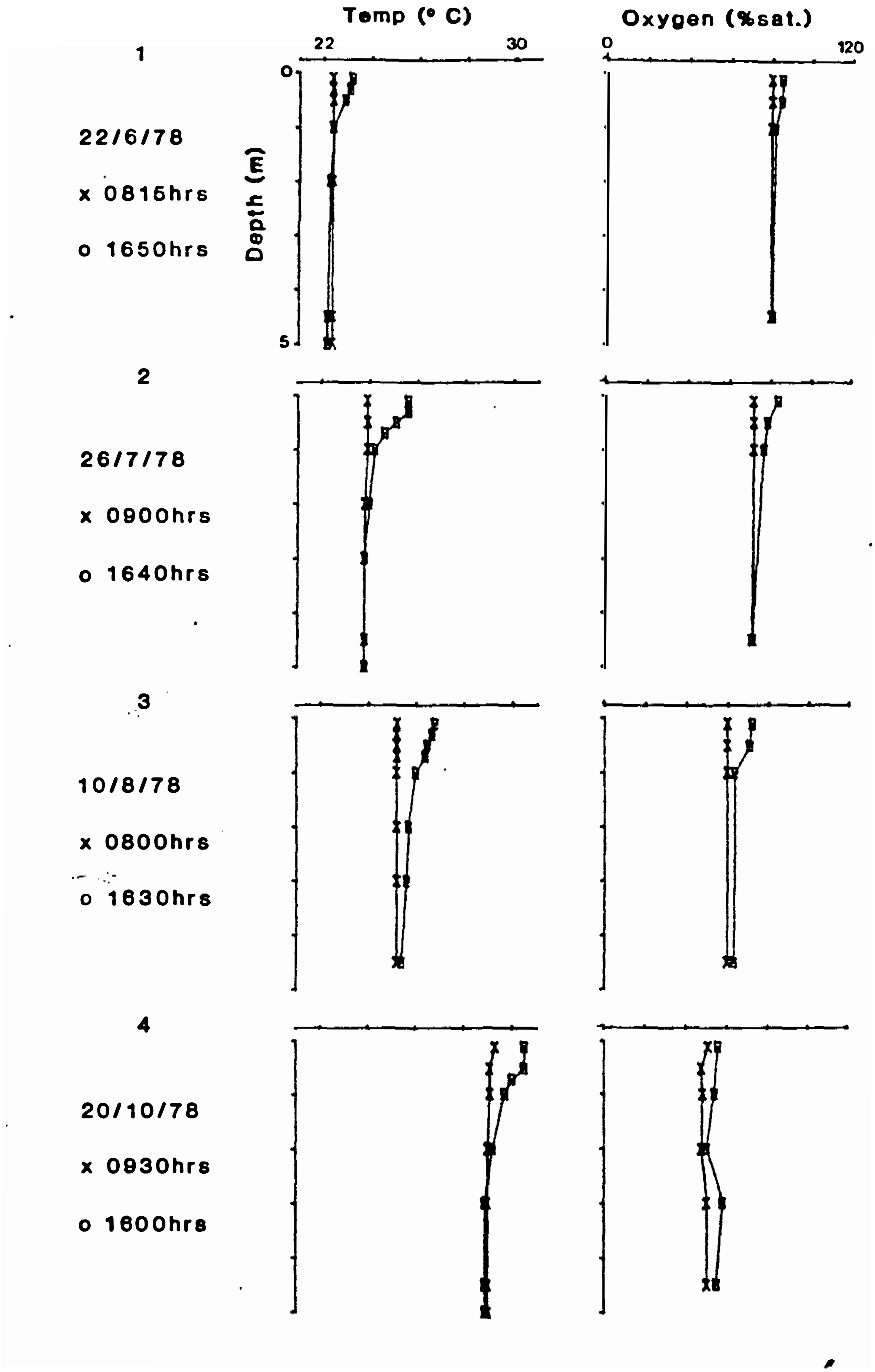
x 0840hrs

o 1555hrs

APPENDIX 18

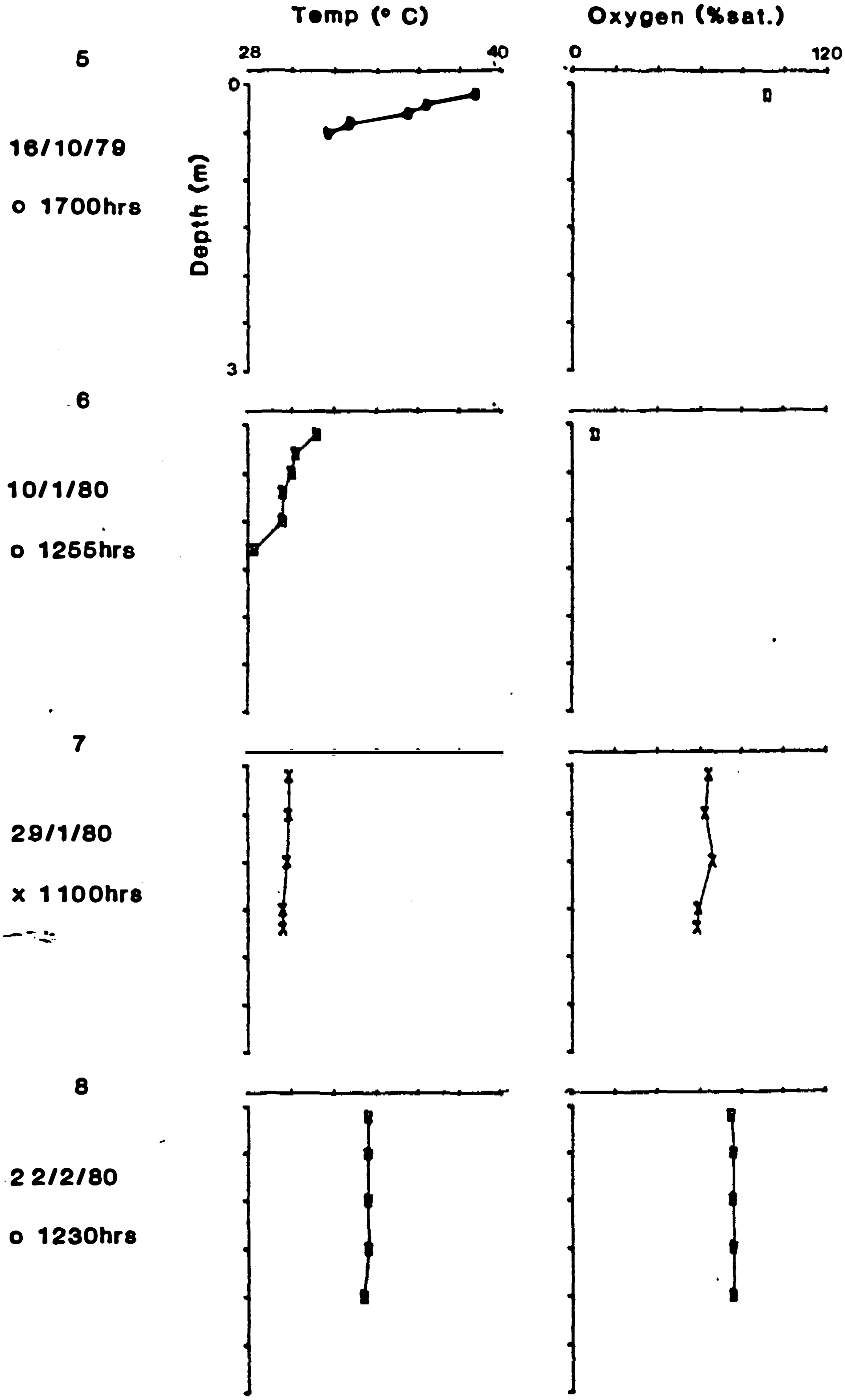
Temperature and oxygen profiles in Bowerbird billabong.

FIG. A16



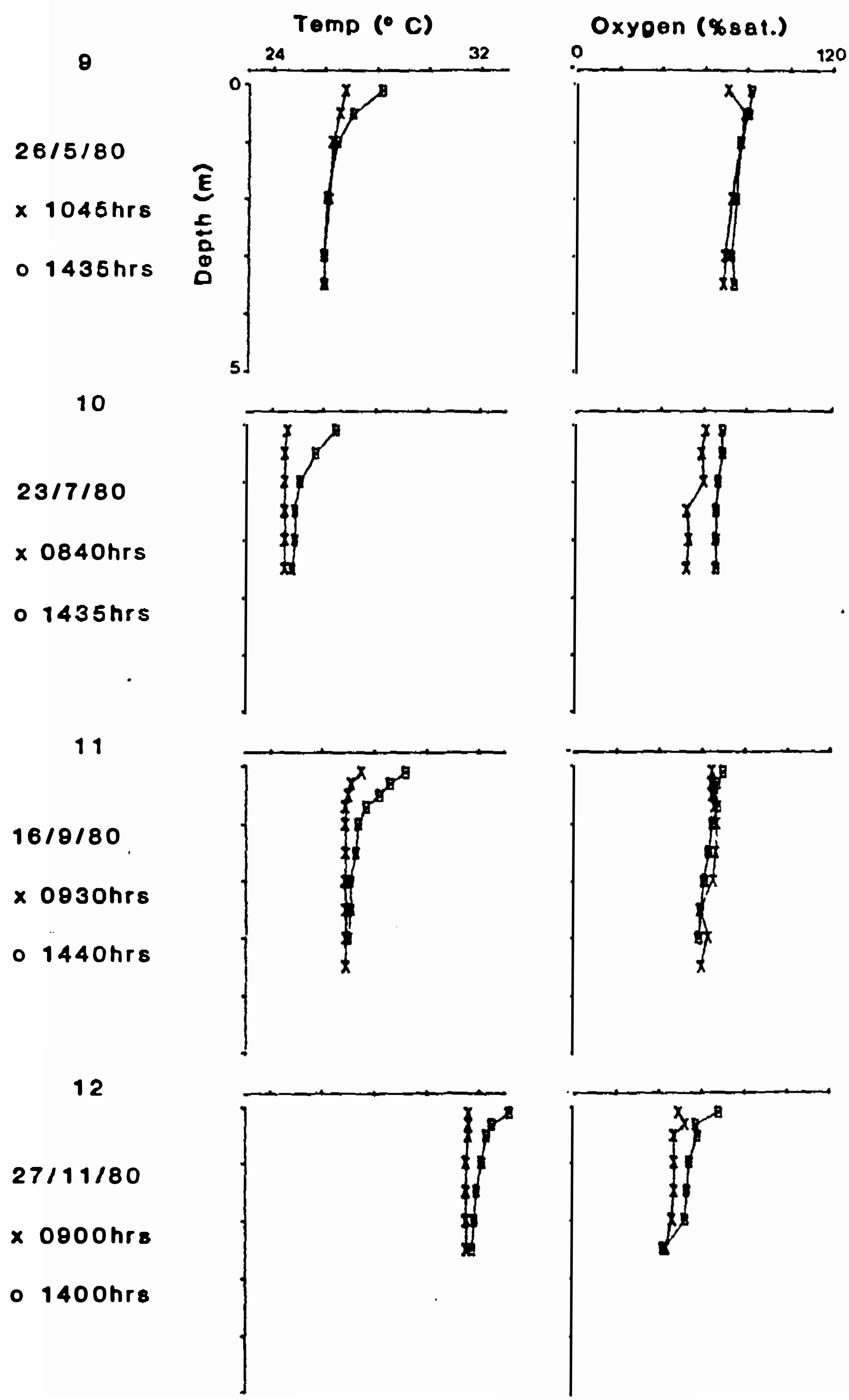
Temp (° C)
Oxygen (%sat.)
22
30
0
120
0
5
Depth (m)
1
22/6/78
x 0815hrs
o 1650hrs
2
26/7/78
x 0900hrs
o 1640hrs
3
10/8/78
x 0800hrs
o 1630hrs
4
20/10/78
x 0930hrs
o 1600hrs

FIG. A15 (cont.)



Temp (° C)
Oxygen (%sat.)
28
40
0
120
Depth (m)
0
3
5
16/10/79
o 1700hrs
6
10/1/80
o 1255hrs
7
29/1/80
x 1100hrs
8
22/2/80
o 1230hrs

FIG. A16 (cont.)



Temp (° C)
Oxygen (%sat.)
24
32
0
120
0
5
Depth (m)
9
26/5/80
x 1045hrs
o 1435hrs
10
23/7/80
x 0840hrs
o 1435hrs
11
16/9/80
x 0930hrs
o 1440hrs
12
27/11/80
x 0900hrs
o 1400hrs

FIG. A18 (cont.)

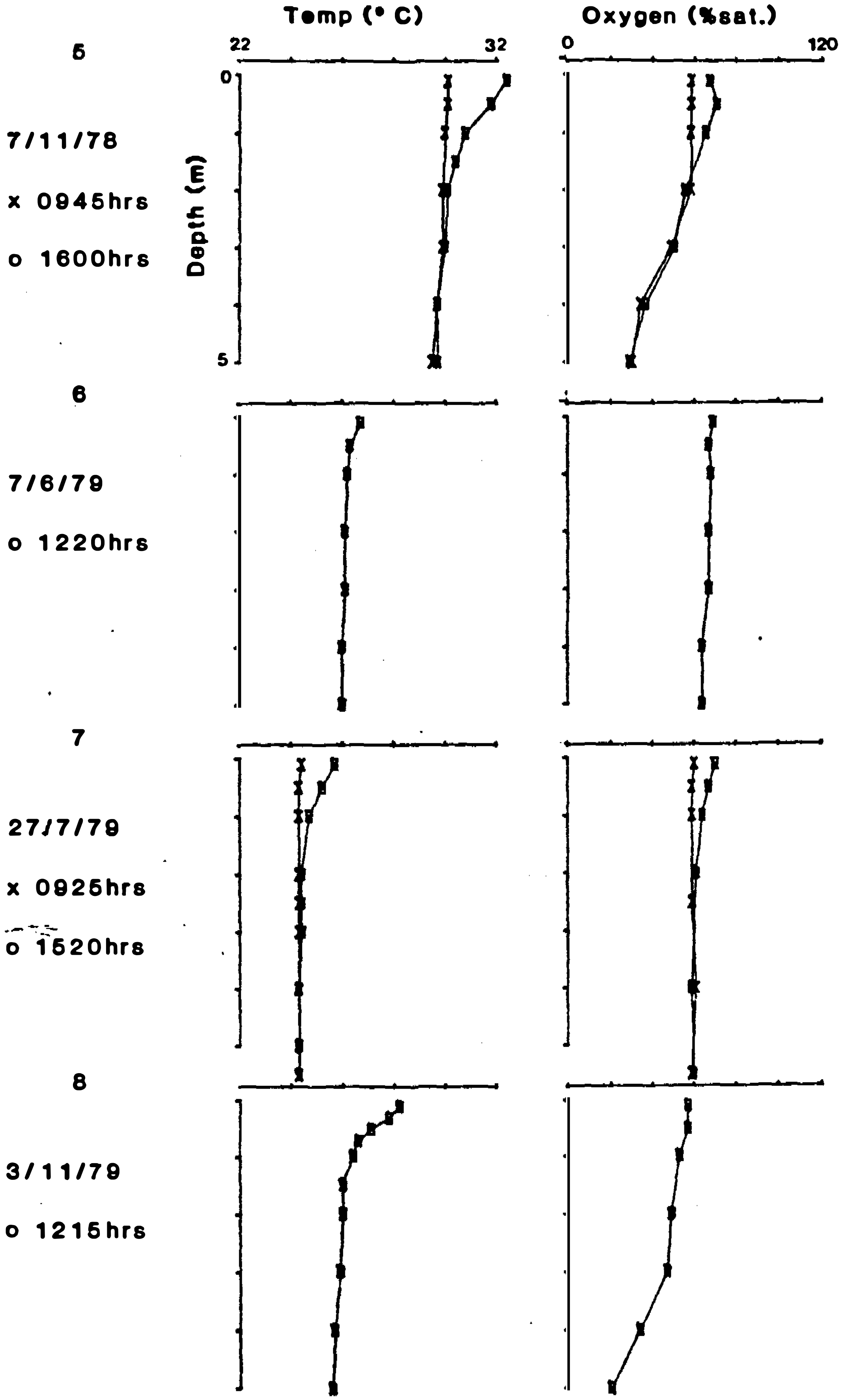

Temp (° C)
Oxygen (%sat.)
22
32
0
120
0
5
Depth (m)
5
7/11/78
x 0945hrs
o 1600hrs
6
7/6/79
o 1220hrs
7
27/7/79
x 0925hrs
o 1520hrs
8
3/11/79
o 1215hrs

FIG. A10 (cont.)

13

27/1/81

x 0930hrs

14

2/4/81

x 0915hrs

o 1415hrs