Berowra Creek: a hydrodynamic investigation. June 1998.

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Publication details:
Commissioning Body: Department of Land and Water Conservation
Report No. UNSW Water Research Laboratory Report No. 197
085824300 (ISBN)

Publication Date:
1998

DOI:
https://doi.org/10.4225/53/57a42ed890634

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A HYDRODYNAMIC INVESTIGATION

by

D A Luketina, D C van Senden and D Piper

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BIBLIOGRAPHIC DATA SHEET

Report No. 197	Report Date: June 1998	ISBN: 0/85824/30/0

Title

BEROWRA CREEK : A HYDRODYNAMIC INVESTIGATION

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Sponsoring Organisation

Department of Land and Water Conservation

Supplementary Notes

Abstract

This report outlines the methodology for the analysis and interpretation of the results of a field investigation carried out in 1995 and funded by Department of Land and Water Conservation into the hydrodynamics of Berowra Creek, New South Wales. This investigation is centred around a 3-month set of data collected from May to August in 1995. The data analysis is used to elucidate dominant physical processes so that models can be developed to predict flushing rates within the estuary.

Distribution Statement

For general distribution

Descriptors

Estuary; Hydrodynamics; Tidal currents; Wind-driven currents

Identifiers

Berowra Creek, New South Wales

Number of Pages: 22 plus Figures	Price: On Application.

https://doi.org/10.4225/53/57a42ed890634

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

1. INTRODUCTION

Berowra Creek is a drowned river valley estuary north of Sydney and is surrounded mainly by bushland. There are many houses dotted along the shores of the creek, most of which are accessed by water only. There is a relatively major development at Berowra Ferry which includes a marina, several restaurants, and a reserve. A map of the estuary and its bathymetry can be seen in Figures 2, 3 and 4.

The aim of this report is to investigate the hydrodynamics of the estuary. Berowra Creek suffers water quality problems such as algal blooms, and it is hoped that a greater understanding of the hydrodynamics will be of assistance in understanding the processes governing water quality. This report is produced as a component of a larger study being conducted by Manly Hydraulics Laboratory for the Berowra Creek Estuary Management Committee, the Berowra Creek Estuary Processes Study.

This investigation of hydrodynamics is centred around a three month set of data collected from May to August in 1995.

2. DATA COLLECTION

The data used in this report came from a number of sites both within and outside Berowra Creek. The Berowra Creek data is of primary interest. Data from the other sites is supplementary and is used for comparison or to help interpret the primary data. A summary of data collected at each site can be seen in Table 1.

The Berowra Creek data is recorded over the 99 day period from 26 May to 1 September 1995 inclusive. Data from the external locations is also over this period, but is taken from records extending beyond this period. Data collection intervals vary, as seen in Table 1.

Table 1: List of Data Collection Sites

Site Name	Sampling Interval	Sampling Period	No. of Parameters	Parameter Description
Cunio Point	5 minutes	26 May to 1 Sep	6	Longitudinal and Lateral velocities ($m.s^{-1}$), Pressure (m), Density ($kg.m^3$), Salinity (psu), Temperature (°C)
Berowra Ferry	5 minutes	"	"	"
Oaky Point	1 hour	"	5	Conductivity (mS/cm), Temperature (°C), Salinity (psu), Dissolved Oxygen (% Saturation), pH
Sydney Harbour	1 hour	long-term	1	Water level (m AHD)
Sydney Airport	30 minutes	"	2	Air temperature (°C), Relative humidity (%)
Penrith Lakes	1 hour	"	2	Wind speed (m/s), Direction. Values are hourly averaged
Offshore	1 hour	"	"	"
Berowra Creek	1 day	"	1	Discharge (m^3/s)
Berowra Creek	Variable	10-11 June	3	*Depth profile of:* Pressure (m), Temperature (°C), Salinity (psu)

The data from the three primary Berowra Creek sites is the same data set that appears in the report 'Berowra Creek Tidal Data Collection' (MHL, 1997). The location of these three Berowra Creek Sites is shown in Figure 1. What follows is a brief description of each form of data collected.

2.1. Description of Data Sets

2.1.1. S4 Current Meters

The S4 current meters at Cunio Point and Oaky Point are placed in sets of two, one above the other. The meters are anchored to the creek bed and, are kept at static height above the bed by a sub-surface buoy. The configuration and typical positions of the meters relative to the bed and surface can be seen in Figure 4.

The measuring accuracy of the S4 gauges deteriorates over its time in the water. Thus, there were two gauge changeovers and three deployment periods, each lasting approximately one month. The changeover dates are 29 June and 27 July. The depth of the current meters is different in each deployment because the meters cannot be replaced in the water at exactly the same position. The top and bottom meters do, however, maintain a constant distance relative to one another.

Each S4 meter measures gauge pressure. A water level relative to the average water level is found from this data; the average pressure is simply subtracted from the actual pressure. There were some difficulties in getting this relative water level, and these are discussed in Appendix A ('Corrections to S4 Data').

As mentioned previously, there are other more significant inaccuracies in parts of the S4 records of salinity and temperature. Again, refer to Appendix A to see how these inaccuracies were dealt with. Note that the corrections are most useful for making the data more coherent; bringing the observed behaviour into line with physical reality, and reducing discontinuities at the changeover points. It cannot be certain that the corrections bring the readings to the true values.

A problem frequently encountered with S4 meters is that of the readings 'decaying' over time. That is, the meters give less accurate readings as the deployment period goes on. This is often seen as a 'slump' in the time-series plot.

2.1.2. Hydrolab Recorder

There is only one Hydrolab recorder situated at Oaky Point. Its depth in the water is unknown. Unlike the S4 current meters, this recorder stayed in the same position throughout the period in question. This is a more accurate recorder than the S4 meters.

2.1.3. Discharge Data

The discharge data for Berowra Creek is measured in cubic meters per second. This data is used to produce a hydrograph (see Figure 5). The discharge measurements were derived from a catchment runoff model provided by Australian Water Technologies – Environment, Science and Technology.

Sydney water level data was taken from the Department of Public Works and Services (DPWS) water level recorder at Balmoral. The water level is expressed relative to Australian Height Datum (AHD). This data was included simply for comparison with the Berowra Creek water level data and are shown in Figures 9 to 12.

2.1.4. Wind Data

The wind data was taken, with permission, from Sydney Water Corporation records. Records were taken from two locations in Sydney; from the Ocean Reference Station (east of Bondi beach), and from Penrith Lakes.

Data from the Berowra area would have been preferable, but none was available. The offshore and Penrith locations lie to the South-east and South-west respectively. If precise wind velocities and directions were required, both of these stations would be of little use. As it is, however, it is expected that taken together they should provide a general picture of wind directions and intensities for Sydney in general, including Berowra. The wind data is presented in the form of progressive vector plots for the period 25 May to 1 September 1995 in Figures 6 and 7.

2.1.5. Meteorological Data

Air temperature and relative humidity data was obtained for Sydney Airport at Mascot (see Figure 8). This data was obtained from the Australian Bureau of Meteorology. As with the wind data, no specific meteorological data is available for the Berowra area, but the Airport values are taken as representative of general conditions in Sydney.

2.1.6. Seacat CTD Data

The Seacat CTD produces vertical profiles of water quality parameters at a given point in time. This data was used in this report only to correct the S4 data (see Section 2.1.1 above). A more comprehensive view of this data can be seen in 'Berowra Creek Tidal Data Collection' (MHL, 1997).

3. DISCUSSION

The 'Berowra Point Tidal Data Collection' report (MHL, 1997) presents the previously mentioned data, and some additional data in a number of ways. These presentations, however, were not suitable for this hydrodynamic investigation, and so many new plots of the available data have been produced. A summary of the data contained in these plots can be seen in Tables 2 and 3.

This section will give an account of each plot produced, why it was produced, and a description of features of interest. All of the presentations discussed in this section were produced using the data processing and visualisation program *IDL version 5.0*.

There are five core sets of data considered throughout this section. These are the pairs of shallow and deep measurements taken from the S4 gauges at Berowra Ferry and Cunio Point, and the single gauge at Oaky Point. Note that because of the problems with the S4 data, as discussed above, the details shown in some of the plots cannot necessarily be relied upon. Thus, comments will be limited to more general characteristics. Occasional gaps and spurious data occur in the data sets.

It is important to keep in mind the bathymetry at the three recording sites when looking at the data (see Figure 2). In particular, note that the Cunio Point gauges are located at a deep hole. This deep hole is the site of some interesting hydrodynamics, as shall be seen.

3.1. Short-Term Investigation: 9 - 22 June

The first steps in the data investigation were to look at a relatively short period. The week of 16 - 22 June was the initial focus of the investigation because there was a large storm event, resulting in higher flows, at the start of this week. As seen in the hydrograph, this storm occurred around 15-16 June (Figure 5). A second set of plots covering the previous week, 9 - 15 June, was added to show the prevailing conditions before this storm event. Table 2 summarises the figures discussed in this section.

Table 2: Figures Relating to Short-Term Data

Figure Title	Fig.	Locations Plotted *	Period Plotted	Parameters in Each Plot
Five Time-Series Plots	9,10 11,1 2	Cunio Pt + Oaky Pt + Sydney Hbr; Berowra Fy + Oaky Pt + Sydney Hbr	9-15 Jun; 16-22 Jun	*Time series for*: Salinity (psu), Water temperature (°C), Density (kg/m^3), Water level (m), Longitudinal velocity (m.s^{-1}).
Progressive Vector Plots	13	Cunio Pt + Berowra Fy	9-22 Jun	Longitudinal distance (km) vs. Lateral distance from origin (km)
Longitudinal displacement versus time	14	"	"	Longitudinal distance from origin (km) vs. Time (days)
Temperature - Salinity Plot	15,1 6	Cunio Pt + Oaky Pt; Berowra Fy + Oaky Pt	"	Temperature (°C), Salinity (psu)

3.1.1. 'Five Time-Series Plots'

These were the first plots produced, covering the weeks of 16 - 22 June 1995 (Figures 9 and 10) and 9 -15 June (Figures 11 and 12). Note that the Berowra Ferry and Cunio Point data has a higher resolution than the Oaky Point data because the former data sets were collected every five minutes, while the latter is only hourly data. A discussion of each of the five plots follows.

Pressure

The 'pressure' plot actually represents the depth of water about some datum. For the Berowra Ferry and Cunio Point data, the datum is the average pressure value over the period. For the Cunio Point and Sydney data, it is Australian Height Datum (AHD). It is evident that water depth is influenced predominantly by the tides, as would be expected in a short estuary.

Salinity

One would expect Oaky Point to have the highest salinities because it is closest to the ocean, and Berowra Point the lowest since it is furthest downstream. Furthermore, the bottom should have higher salinity than the top since the water at the bottom will be more dense. This is the behaviour that we see in general, though there are notable exceptions.

* Cunio Pt and Berowra Fy data includes top and bottom data unless otherwise stated.

At Cunio Point, from 9-15 June, the bottom salinity starts off relatively high but has dropped to a more 'normal' level by the end of the week. The initial large difference between top and bottom salinity indicates strong stratification, which is not unexpected at this deep hole. This difference is reduced by mixing.

At Berowra Ferry, from 16-22 June, several downward 'spikes' can be seen in the top salinity. By comparing with the pressure data, we see that these occur at low tide. Recalling that this is just after a major storm, it becomes evident that this spike of low salinity is due to the freshwater layer flowing at the water surface. At low tide, this layer has dropped down and is passing the top gauge, causing the salinity to drop. At high tide, the fresh water layer is above the gauge and, accordingly, a higher salinity is recorded.

Another feature to note is the small, periodical fluctuation in salinity with the tides. This is especially evident at Cunio Point for the period 9-15 June. It is evident that the salinity remains relatively constant during the flood tide flow at Cunio Bottom but reduces around the peak of the ebb flow. The jagged nature of salinity plot during this peak and the decrease in salinity tends to indicate that tidally induced mixing is taking place between the deeper salty water and the overlying fresh water during around the peak of the ebb flow. This hypothesis is reinforced by the fact that the degree of mixing (as indicated by the decrease in salinity on the ebb flow) is proportional to the tidal amplitude (and longitudinal velocities). This is particularly apparent for the period 9 to 13 June. It is difficult to say whether mixing between the deeper salty water and the overlying water at Cunio Point occurs during the peak of the flood flow. If it is not occurring, there must be a considerable asymmetry in nature of the flow on the ebb and flood tides.

Temperature

Throughout both weeks there is a downwards trend in temperature, particularly after the storm on the 15-16 June. This drop is particularly evident at Oaky Point and Cunio Point bottom (the deep hole).

One of the more interesting features is the significant drop in Cunio Point bottom temperature from 9-15 June. This drop corresponds to the salinity drop at the same location. It would appear that a source of relatively fresh cold water is entering the deep hole at Cunio Point. Further, as there is no evidence of this cold water upstream or downstream of Cunio Point, it is hypothesised that this cooler fresher water is entering laterally. A possible mechanisms for 'generating' this water are: differential cooling in the shallows; local runoff following rainfall; and groundwater inflows.

Density

Density is a function of salinity and temperature, and is related especially to salinity*. Thus, the density shows the same features as temperature and salinity. For example, the stratification at Cunio Point is clearly seen.

Longitudinal velocity

This is the velocity of the current in the upstream-downstream directions. (Question: were the meters placed in mid-stream?). Velocities were not measured at Oaky Point. The relationship between top and bottom velocities is significantly different between Berowra Ferry and Cunio Point.

At Berowra Ferry, the velocities at top and bottom are virtually identical. Positive values of velocity indicate flow in the upstream direction. This is confirmed by the fact that maximum positive velocities occur during mid flood tide as depth is increasing, and vice versa for negative velocities.

The Berowra Ferry velocities show the behaviour of a uniform mass of water (ie plug flow), but the Cunio Point velocities are quite different. For most of the two weeks, the top and bottom are out of phase to some extent. This movement of top and bottom water at different speeds, and even in opposite directions, is called 'decoupling'. Some interesting implications of these Cunio Point velocities will be discussed further in following sections.

3.1.2. Progressive Vector Plot

Figure 13 illustrates the direction of water flow over time at Cunio Point and Berowra Ferry. A progressive vector for a particular location traces the path a particle would take if it were allowed to float along at the velocity of that location. The path is traced by measuring the distance from the point where the particle started. The positive longitudinal direction indicates movement in the flood direction (ie. upstream movement).

The progressive vector diagrams for Berowra Ferry and Cunio Point indicate something very interesting. The periodical upstream-downstream movements with the tide are evident. Even more evident, however, is the strong net movement in the upstream direction, particularly at Cunio Point bottom. This suggests that water near the bed at Cunio Point is almost always travelling *into* the creek, but rarely out of it. This may

* For a visual representation of this relationship, see the plot of temperature versus salinity with density contours (Figure 36).

possibly be an artefact due to measurement error (an instrument offset of 1 cms^{-1} would account for the observed behaviour). Lateral flows may also be occurring in this region. The effect of wind on lateral flows is covered in Section 3.1.6.

3.1.3. Longitudinal Distance – Time Plot

Figure 14 shows the same information to that in the progressive vector plots. The strong upstream movement at Cunio Point bottom is again very clear. Another feature to note is that the average upstream velocity at the Cunio Point top gauge drops noticeably from about 17 June, just after the storm event.

3.1.4. Velocity Correlation – Stratification Plot

Velocity correlation plots were produced in response to something seen earlier in the Cunio Point velocity data (see Section 3.1.1). That is, large phase differences between top and bottom velocities seemed to occur at the same time as significant stratification.

The velocity correlation shown in Figure 25 consists of taking 1 day of data and correlating the top velocity with the bottom velocity over that period. The level of stratification is measured by averaging the top and bottom densities over a one day period, and then taking the difference. This averaging and correlation period is moved forward in one-hour steps from 26 May until 1 September is reached. Figure 26 shows something similar except that the correlation/averaging period is now 10 days, and the same time-step of one hour is kept.

Perfectly out of phase data (ie., out of phase by half of a cycle) gives a correlation coefficient of negative unity (−1), while in-phase data gives a coefficient of unity. These two plots (ie Figure 25 and Figure 26) show similar behaviour. However, it is easier to discern trends from Figure 26. These trends show that Cunio Point top and bottom are decoupled during periods of high stratification that occurred during the periods 9-15 and 16-22. Berowra Ferry top and bottom were strongly coupled during this period.

3.1.5. Temperature – Salinity Plots

Water can be characterised by its temperature and salinity. For this reason, temperature verses salinity plots are useful for looking at what sort of mixing could occur between locations. Waters generally do not mix across strong density gradients (water density is determined by its temperature and salinity). Thus, waters with similar temperature and salinity (ie. plotted in the same area of the graph) can mix, whereas dissimilarity indicates that mixing is unlikely.

Figures 15 and 16 show temperature-salinity data for the period 9-22 June. These temperature – salinity plots from Cunio Point and Berowra Ferry (with Oaky Point data overlaid) indicate that:

- Berowra top is generally fresher than Berowra bottom,
- Cunio top is generally fresher than Cunio bottom,
- Cunio bottom, at times, has particularly warm salty water that can not have originated from upstream or downstream of Cunio Point. It is presumed that this warm salty water is entering laterally due to warming and subsequent evaporation in the shallows of Cunio Point.
- Top and bottom temperature-salinity values are frequently quite different. This means that mixing between top and bottom waters has been somewhat limited.

3.1.6. Progressive Vector Plots of Wind

The progressive vector plots of wind (Figures 6 and 7) were produced in a manner similar to the current velocity progressive vectors (see Section 3.1.1). The line on the plot indicates the path that would be traced by a particle driven by the velocity and direction of the wind at a particular location. Because the plot of offshore wind is so large relative to the Penrith plot, the latter is also reproduced separately in Figure 7. As there is no data for the Berowra area, the data from these two locations only gives an indication of general wind intensities and directions in the Sydney area.

It is important to note that a southerly wind means that the wind is coming *from* the south and heading north. Thus, a strong movement to the north indicates a strong southerly wind. The same principle applies in the east-west direction.

Recall that at Cunio Point, from 9-15 June, there was gradual change from highly stratified to unstratified conditions. The causes of mixing are uncertain, and it was thought that strong winds may be a significant cause of mixing and water movement. The wind progressive vector plots indicate that from about 15 - 22 June there were strong southerlies blowing over Sydney. It seems possible, then, that the strong southerly wind for the period 15-22 July may have been a significant factor in Cunio Point mixing. Figure 11 shows falling water levels at Sydney and Oaky point for this period.

3.1.7. Temperature Data

Figure 8 shows air temperature and relative humidity data plotted along with water temperatures at all three Berowra Creek locations. The main purpose of this chart is to see if the drop in water temperatures was related to a similar drop in Sydney air temperature. The plots indicate a general reduction in both air and water temperature over the period 9-24 June 1995..

3.1.8. Summary

In general, Berowra Creek seems to behave like a typical estuary. Some particular points of interest in this short-term data investigation are:

- The deep hole at Cunio point can become highly stratified, and this generally involves a decoupling of top and bottom velocities.
- The nearby shallows can be a source of cold salty water for the deep hole at Cunio Point.
- Strong winds can affect flows. However, changes in tidal elevations often coincide with strong winds. This makes it difficult to separate the local and broader scale effects of the wind.

The circulation during what we can refer to as a high stratification regime (say greater than 2 kg m^{-3} density difference between Cunio top and bottom) can be hypothesised as having the following semi-diurnal characteristics:

- The upper layer moves in response to tidal forcing.
- The lower layer is relatively decoupled from the upper layer with some degree of tidally induced mixing occurring between the two layers, particularly on the ebb tide.
- The mixing between the two layers causes a transfer of momentum which drives a relatively closed circulation cell within the deeper area at Cunio Point.
- The velocity readings at Cunio Point are within the lower half of this circulation cell and hence have velocities in the opposite direction to those in the upper layer.
- More effective mixing on the ebb flow results in the lower half of the circulation cell being driven in the upstream direction for more than half of the time. This explains the behaviour exhibited on the progressive vector plots.
- The mixing between the upper and lower layers increases with tidal range and seems to be higher for ebb than flood flows.

While the above hypothesis is not completely proven, it offers a consistent explanation for the behaviour observed in the data. The circulation described above is depicted in Figure 17.

3.2. Long-Term Investigation

After looking at the short-term period of 9-22 June, the next step is to widen the investigation to cover the entire 14 weeks. In this period, from 26 May to 1 September 1995, the investigation will be concerned with general long-term trends.

3.2.1. Filtering the Data

It is useful to view the entire span of time-series data on one plot if the long-term characteristics are to be studied. This, however, causes problems as seen in Figures 18 and 19, which show data sampled hourly. These five time-series plots are identical in style to the earlier time-series plots (Figures 9 to 12), but they are very difficult to read because there is too much data on one plot.

One solution to this problem is to filter the data. It can be seen in Figures 18 and 19 that all of the data sets follow an oscillating pattern due to tidal effects. Filtering can remove these semi-diurnal tidal effects, thereby revealing longer term trends.

Tides in the Sydney region follow a cycle having a period of approximately 12.2 hours, which is a frequency of 0.082 cycles per hour. In these circumstances that is a relatively high frequency and must be removed. In this case the frequency cut-off was chosen, after some trial-and-error, at 0.025 cycles per hour, or 40 hours per cycle.

The difference the filter makes can be seen by comparing Figures 18 and 19 to Figures 20 and 21. The latter time-series plots show how all of the relatively high frequency oscillations have been cut out, leaving only the longer term fluctuations. Note that the filter has the effect of shortening the data set at both ends. The period covered in the plots is thus approximately 29 May - 29 August.

The filtered data was used to produce the plots listed in Table 3. A discussion of these follows.

Table 3: Figures Covering Long-Term Data

Figure Title	Fig.	Locations plotted *	Period plotted	Parameters in each plot
Five Time-Series Plots – unfiltered	18,19	Cunio Pt + Oaky Pt + Sydney Hbr; Berowra Fy + Oaky Pt	27 May - 1 Sep	*Time series for*: Salinity (psu), Water temperature (°C), Density (kg/m^3), Water level (m), Longitudinal velocity (m.s^{-1}).
Five Time-Series Plots - filtered but uncorrected	20,21	"	29 May - 30 Aug	"
Five Time-Series Plots – filtered and corrected	22,23	"	"	"
Longitudinal displacement versus time – filtered	24	Cunio Pt + Berowra Fy	"	Longitudinal distance from origin (km) vs. Time (days)
Velocity Correlation – Stratification Plot – unfiltered	25	Cunio Pt + Berowra Fy	"	Top-Bottom density difference (kg.m^{-3}) vs. Top-bottom long. velocity correlation coefficient. (10 day moving average)
" – filtered	26	"	"	"

3.2.2. 5 Time-Series Plots – Filtered

As in Section 3.1.1, a short discussion of each of the five plot windows shown in Figures 22 and 23 will follow. Note that the two changeover points for the S4 gauges are marked by asterisks.

Pressure

The Cunio Point data shows a set of spurious data at the top gauge between the first and second changeover points. This is not a significant problem because it can be assumed that the true data would follow the same pattern as the bottom gauge.

Of more significance is the fact that the pressures at Berowra Ferry and Cunio Point are almost identical. Furthermore, the pressure at these locations are differs in behaviour from the pressure at Oaky Point. When comparing pressures, it should be noted that offsets can exist between different sites. Hence it is the trend of the pressure difference between sites that is significant. A change in the pressure difference indicates that the water surface is

* Cunio Pt and Berowra Fy data includes top and bottom data unless otherwise stated.

tilted. This may be due to changes in: inflow Berowra Creek of the Hawkesbury River); strong winds; and low frequency tidal components. For example, the increase and decrease in water level at Oaky Point and Berowra Ferry in early July respectively, coincided with a strong southerly wind event.

Salinity, Temperature and Density

As before it can be said that generally Oaky Point has the highest salinity, Berowra Ferry the lowest, and that the top salinities are lower than bottom salinities. Note that the high stratification evident at the Cunio Point deep hole in the short term investigation does not occur in following months shown in the long term record.

Several phases of behaviour are evident in the salinity and density records shown in Figure 23. In chronological order, at Cunio Point, these are:

- A high stratification period in late may to early June
- A reduction from high stratification to moderate stratification, due mainly to a reduction in salinity, in early June
- A moderate stratification period with relatively constant salinity and density period from early to late June
- A low stratification period with increasing salinity and decreasing temperature from late June onwards.

In contrast, at Berowra Ferry, Figure 22 shows that there is a low stratification that persists over the full monitoring period (May to August). In general, the salinity increases over this period at Berowra Ferry and Oaky Point with higher salinities occurring at Oaky Point – this is most likely due to a net upstream transport of salt.

Longitudinal velocity

The filtered velocity record reveals that top and bottom velocities at Berowra Ferry are not as well correlated as they appear in the short-term unfiltered set. Figure 22 shows a net upstream transport at the bed and a net downstream transport at the surface. This is consistent with a baroclinic circulation driven by a longitudinal density gradient with less dense lower salinity water at the upstream end.

The longitudinal velocity record at Cunio Point (Figure 23) clearly shows a net upstream transport at the bed and a net downstream transport at the surface. For much of the record where stratification is low (ie from early July onwards), the surface and bottom longitudinal velocities are out of phase. Further, the large upstream bottom flows coincide with the density at Oaky Point exceeding that at Cunio Point bottom. This suggests that a baroclinic flow dominates transport into the deeper part of Cunio Point. A return flow then occurs in order to satisfy continuity of fluid, explaining why the top and bottom longitudinal velocities are out of phase from early July onwards.

The fact that bottom velocities are higher than top velocities at Cunio Point may be due to the baroclinic flow into the hole at Cunio Point occurring via a gravity current. If the relevant S4 current meter were within this gravity current, relatively high velocities could be recorded. On the other hand, the return flow could be spread over a considerably greater depth resulting in lower velocities.

3.2.3. Longitudinal Displacement Plots – Filtered

Figure 24 shows a plot of longitudinal displacement versus time. It can be seen that velocities at the top are significantly less than bottom velocities. This plot is consistent with the comments made above that there is a net upstream displacement of fluid at the bed.

3.2.4. Velocity Correlation – Stratification Plot

Velocity correlation plots (Figures 25 and 26) show that Cunio Point top and bottom are decoupled (ie flowing in opposite directions) during periods of high stratification and coupled (ie flowing in the same direction) during periods of low stratification. The plots showed that Berowra Ferry top and bottom were strongly coupled during most of this period.

It should be noted that these velocity correlation plots are representative of the dominant forcing mechanism – tides.

3.2.5. Summary

Inflows into the Cunio Point hole during low stratification periods are dominated by baroclinic flows, possibly behaving as gravity currents. A return flow occurs in response to the gravity current. This resulting circulation is shown sketched in Figure 27.

4. CONCLUSIONS

Longitudinal circulation patterns are dominated by tidal forcing and the degree of stratification. These ebb and flood tide patterns are asymmetric with respect to each other (ie not mirror images). The net (ie long term) longitudinal circulation depends upon baroclinic forcing where the deep hole at Cunio Point gradually fills with salty water. The system is reset when a flood event flushes the deep water from the Cunio Point hole. Lateral circulation also plays a role in the exchange of water in the Cunio Point hole.

Given the above circulation patterns, Berowra Creek can be modelled by a 5 box model consisting of four reaches along the length of the Creek; each reach would comprise a box except at Cunio Point where it is appropriate to have an upper and lower box. This is depicted in Figure 28. The exchange between boxes 2 and 3 would depend upon the tidally induced velocities (ie tidal range), the direction of the flow and the degree of stratification. Superimposed upon this would be a baroclinic flow from Box 4 to 3 when the density in Box 4 exceeds that in Box 3. In turn, this will drive an equivalent flow from Box 3 to 2. Finally, provision must be made for scouring of fluid from the Cunio Point hole for large flow events.

In technical terms, the tidally driven exchange between Boxes 2 and 3 could be represented by a function of the bulk Richardson number while the long term baroclinic flow from Box 4 to 3 could be evaluated using a gravity current type formulation. Given the number of processes operating, the use of inverse techniques to solve for the exchanges between the boxes with the available data would at best provide qualitative results. Rather, it may be more appropriate to construct a physically based box model.

5. REFERENCES

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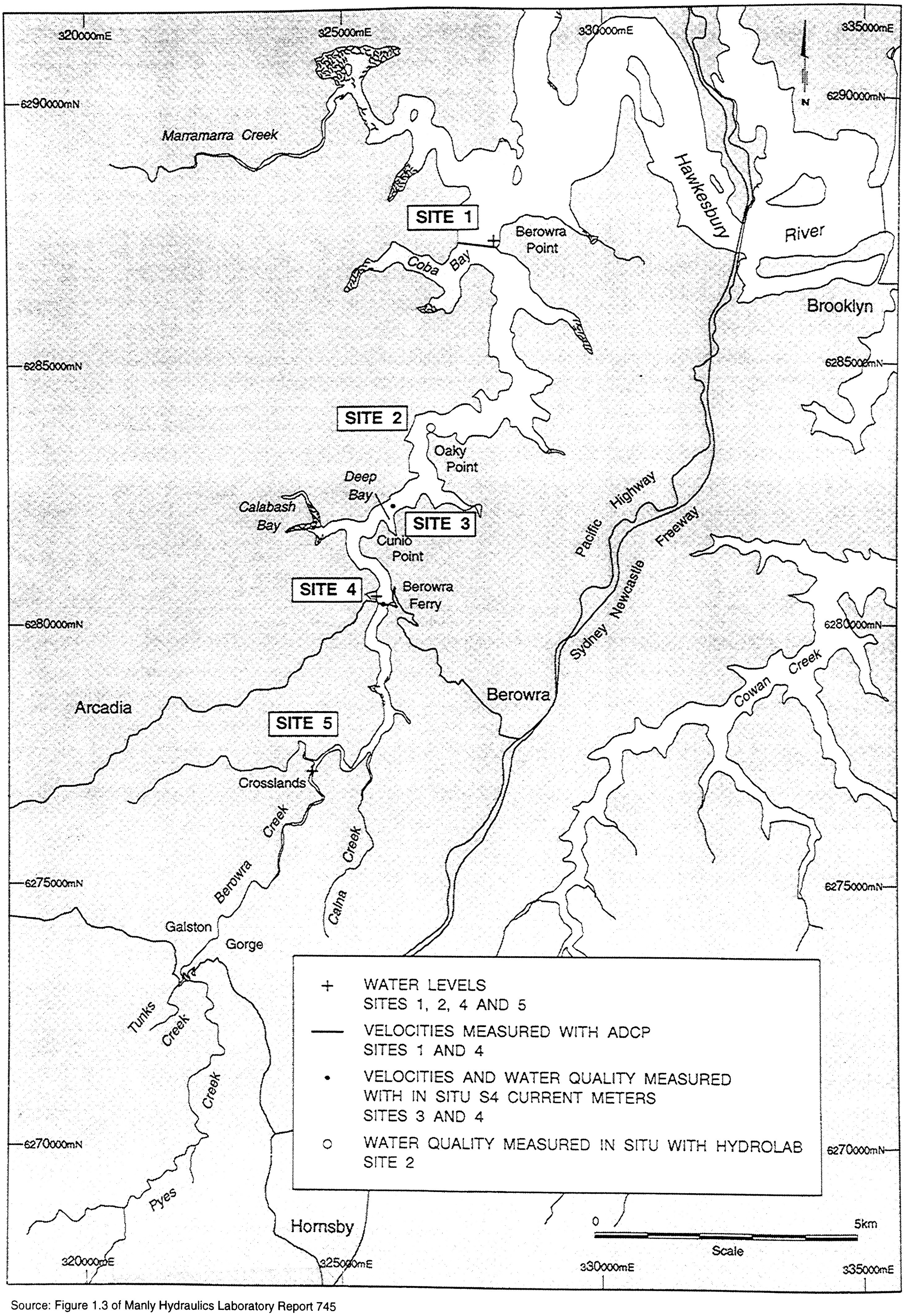


Source: Figure 1.3 of Manly Hydraulics Laboratory Report 745

FIGURE 1 MAP OF BEROWRA CREEK SHOWING STUDY SITES

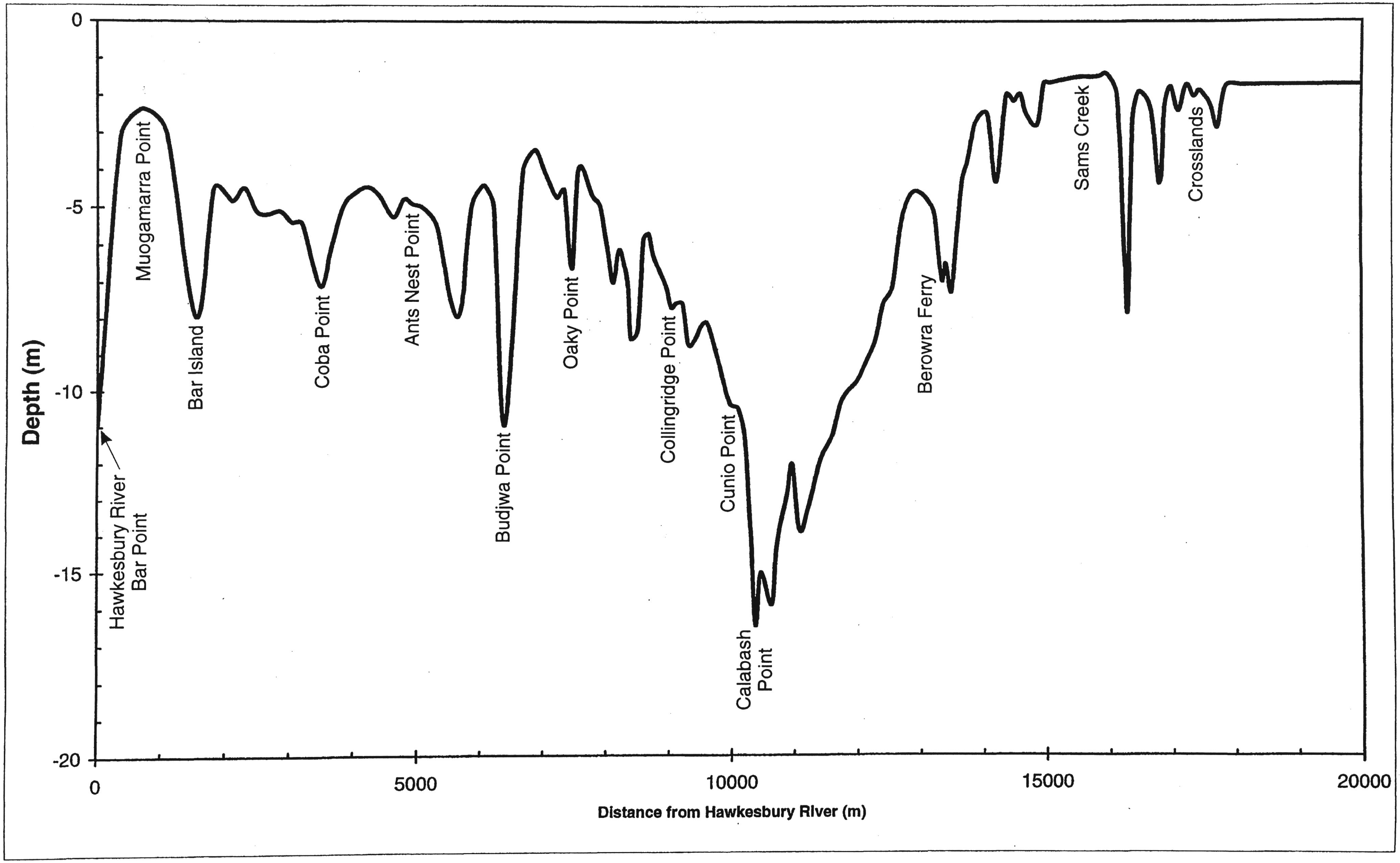


FIGURE 2 BATHYMETRY MAP OF BEROWRA CREEK

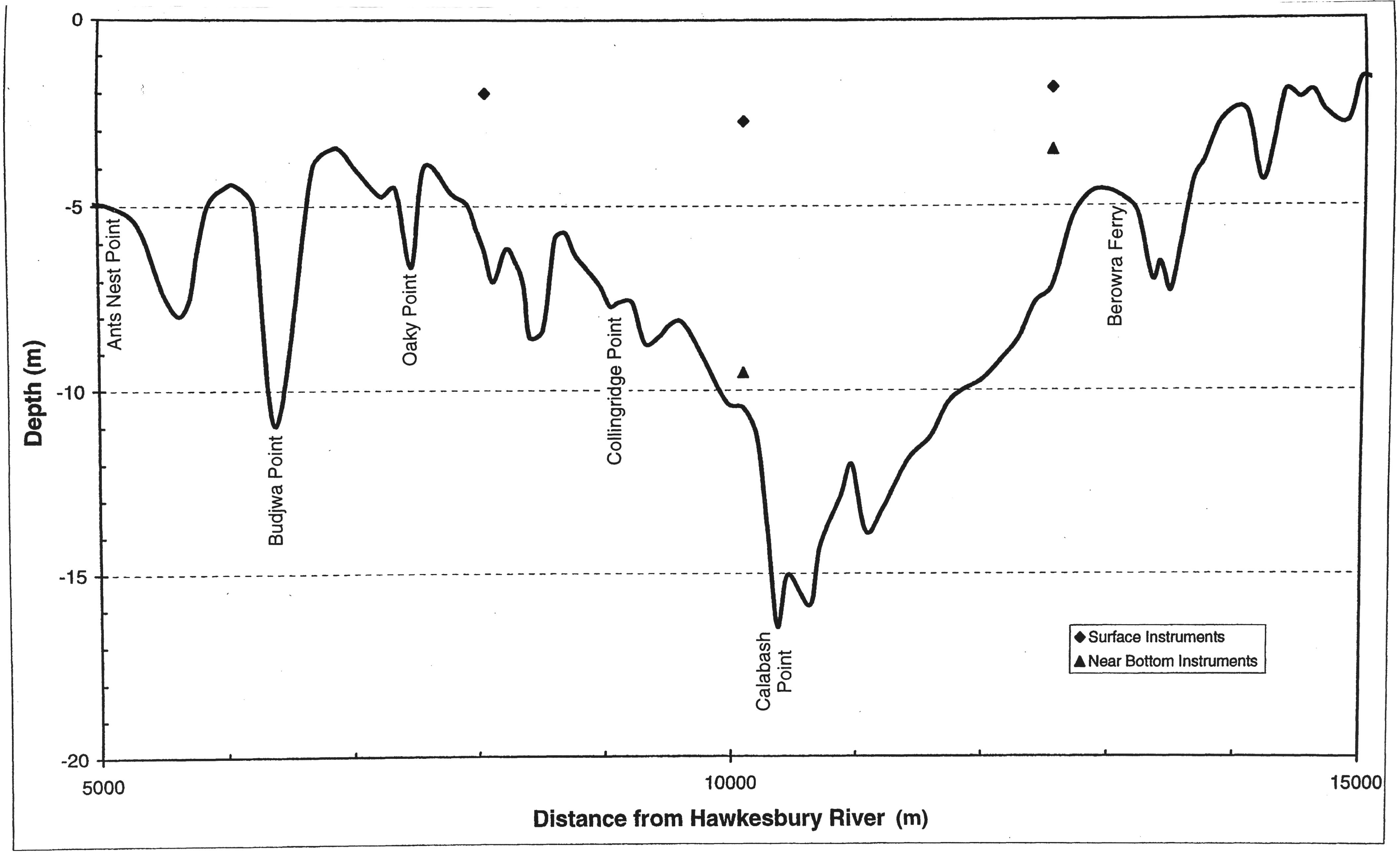
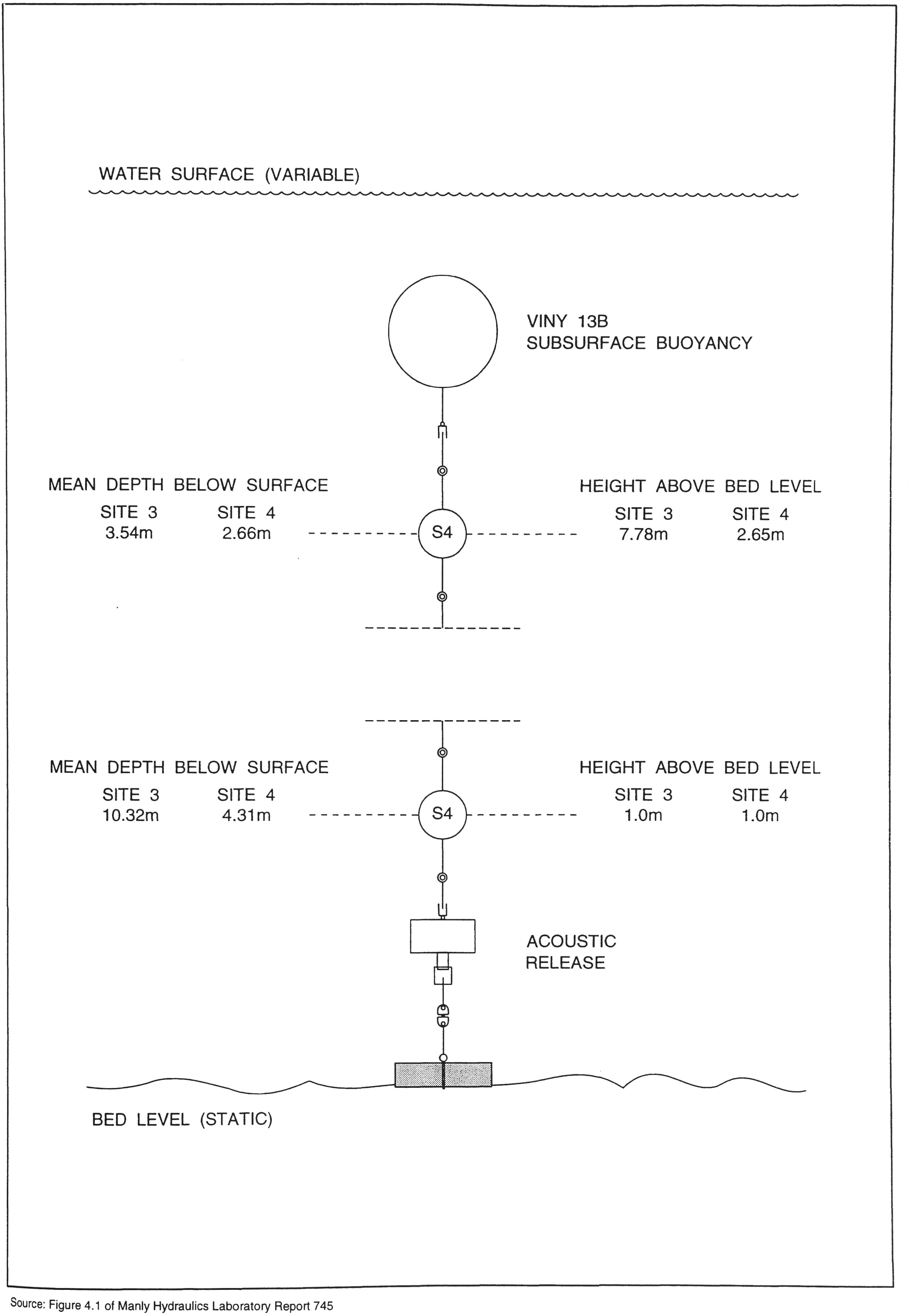


FIGURE 3 DETAILED BATHYMETRY MAP OF BEROWRA CREEK



Source: Figure 4.1 of Manly Hydraulics Laboratory Report 745

FIGURE 4 CONFIGURATION OF S4 GAUGES

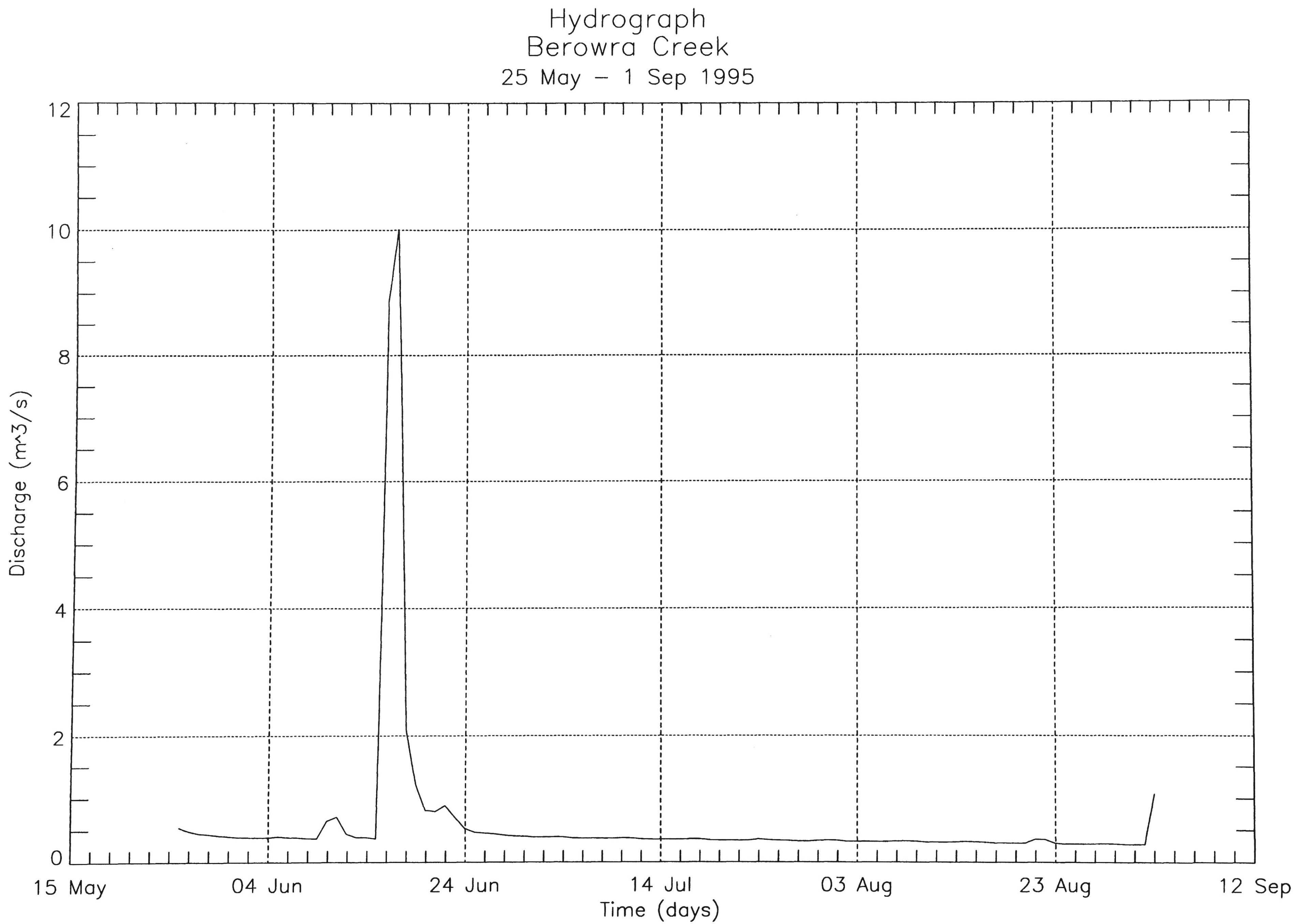


FIGURE 5 BEROWRA CREEK HYDROGRAPH

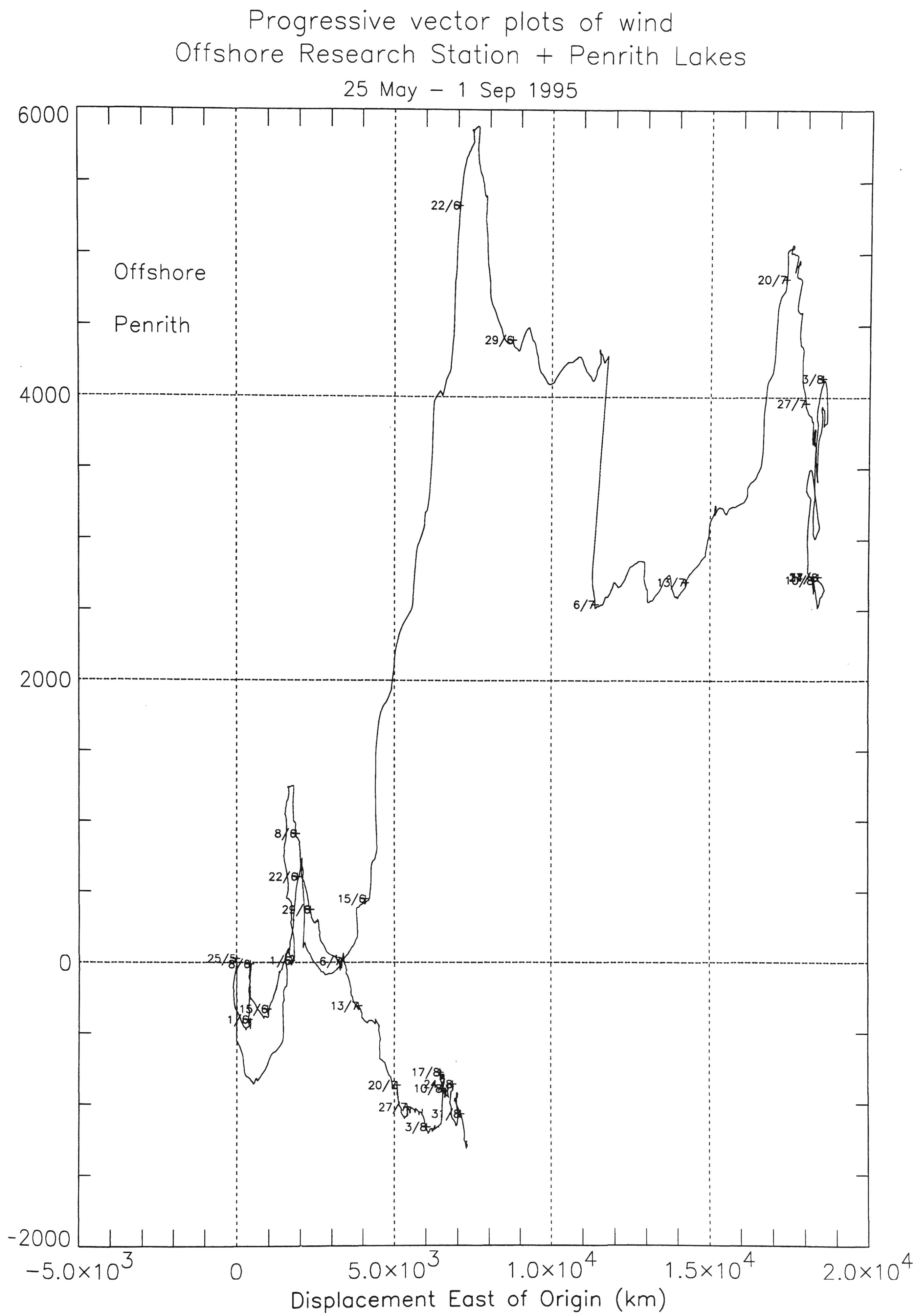


FIGURE 6 PROGRESSIVE WIND VECTOR PLOT - OFFSHORE REFERENCE STATION AND PENRITH LAKES

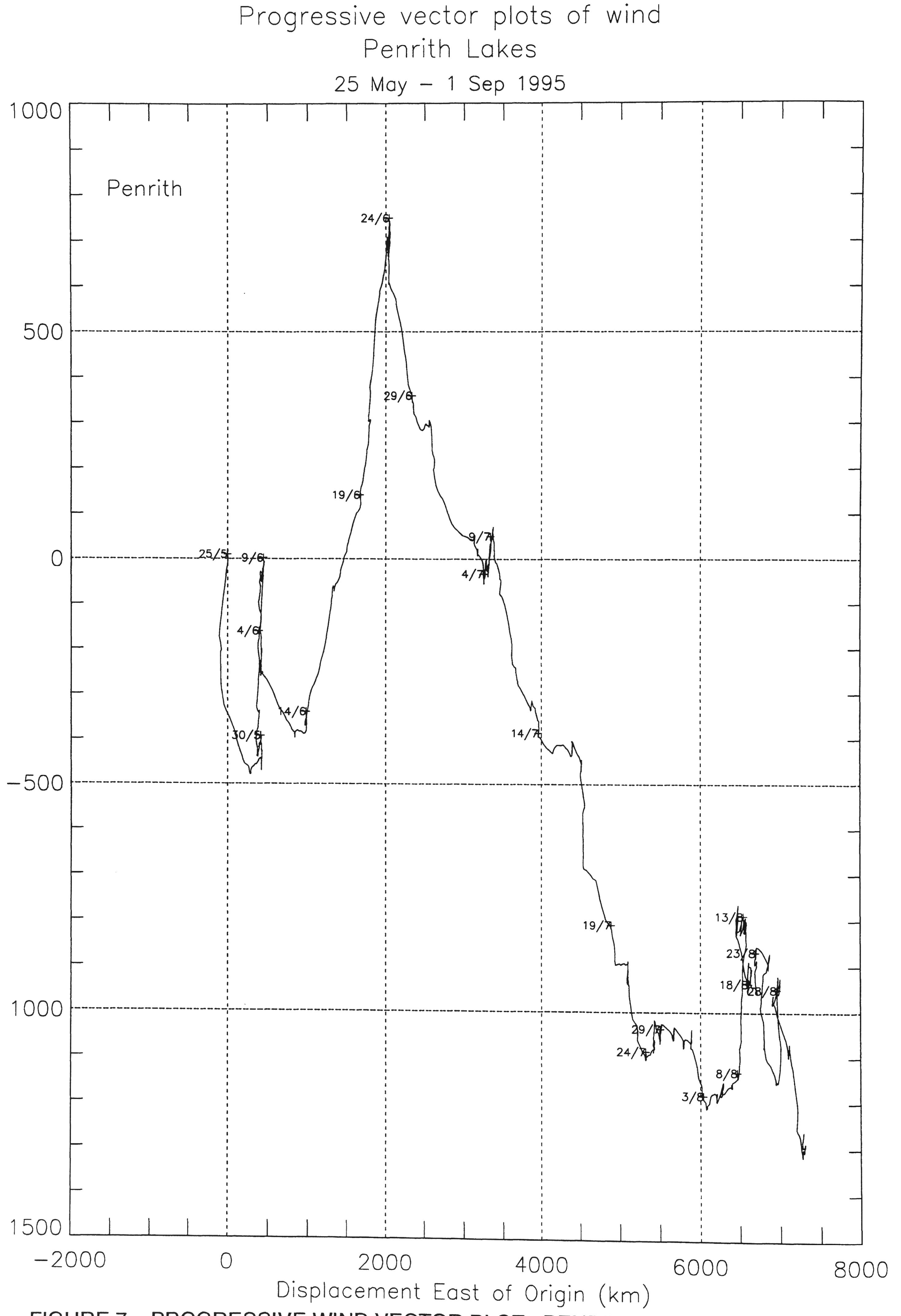


FIGURE 7 PROGRESSIVE WIND VECTOR PLOT - PENRITH LAKES

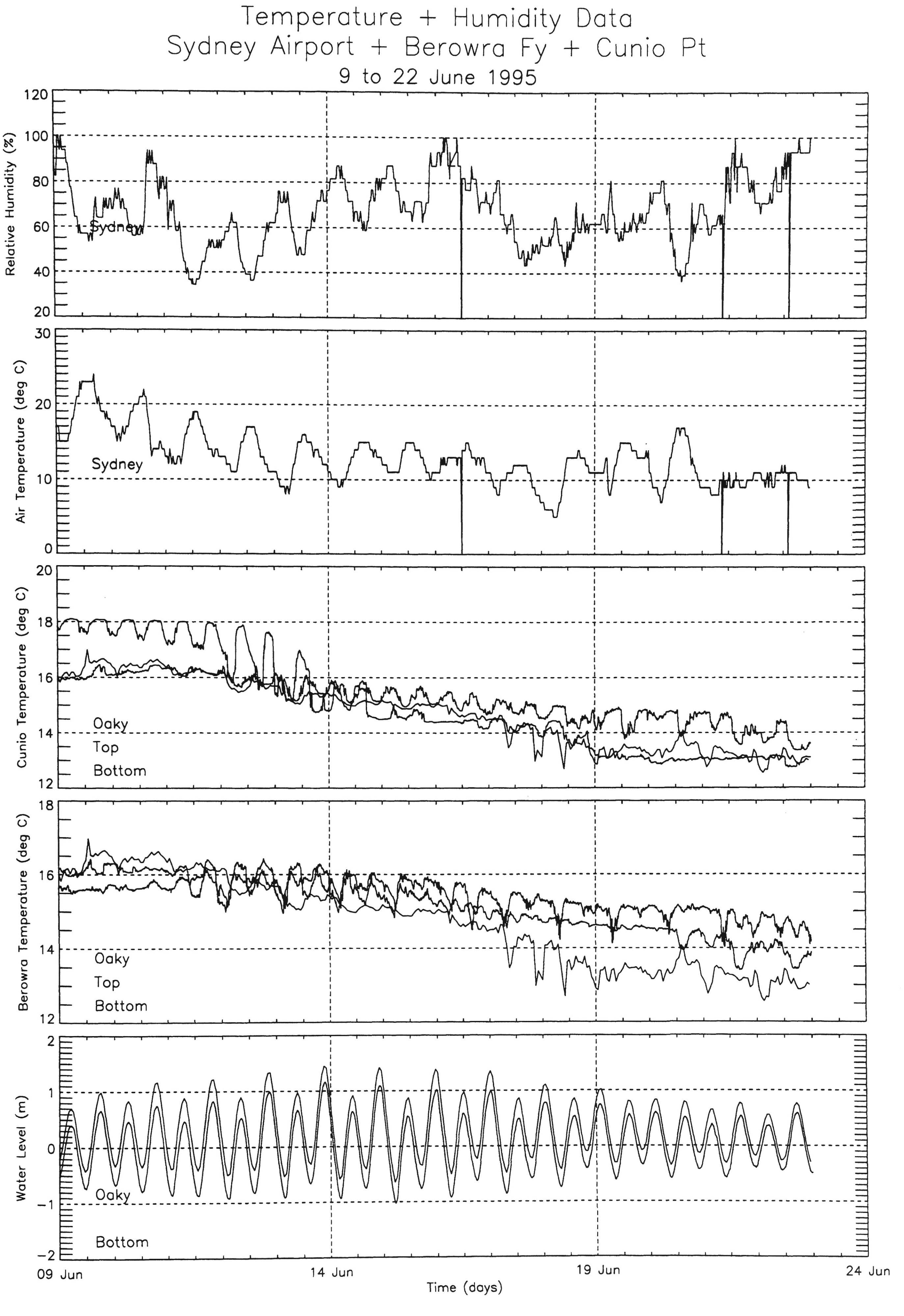


FIGURE 8 TEMPERATURE AND HUMIDITY DATA

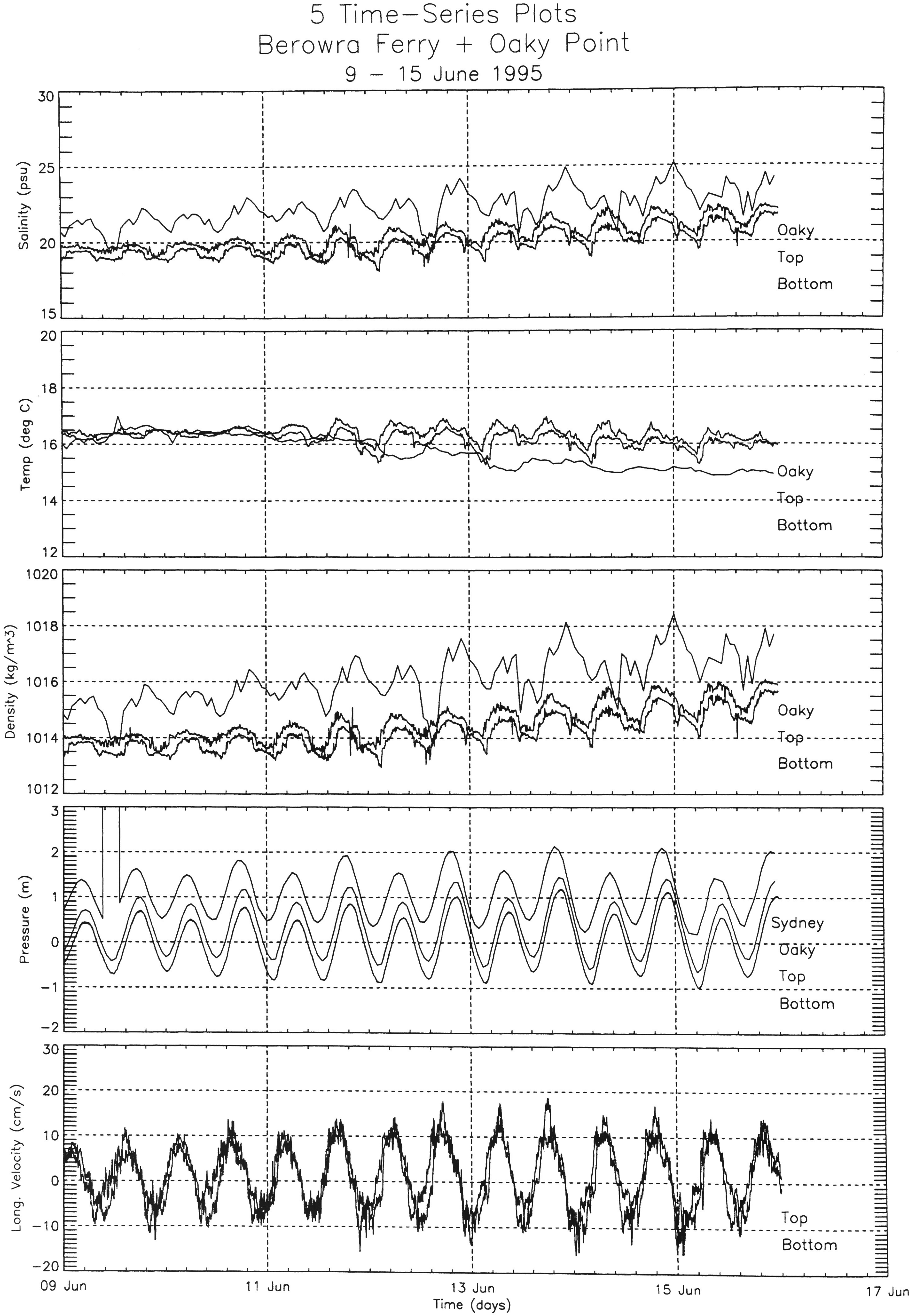


FIGURE 9 BEROWRA FERRY TIME SERIES PLOTS, 9-15 JUNE 1995

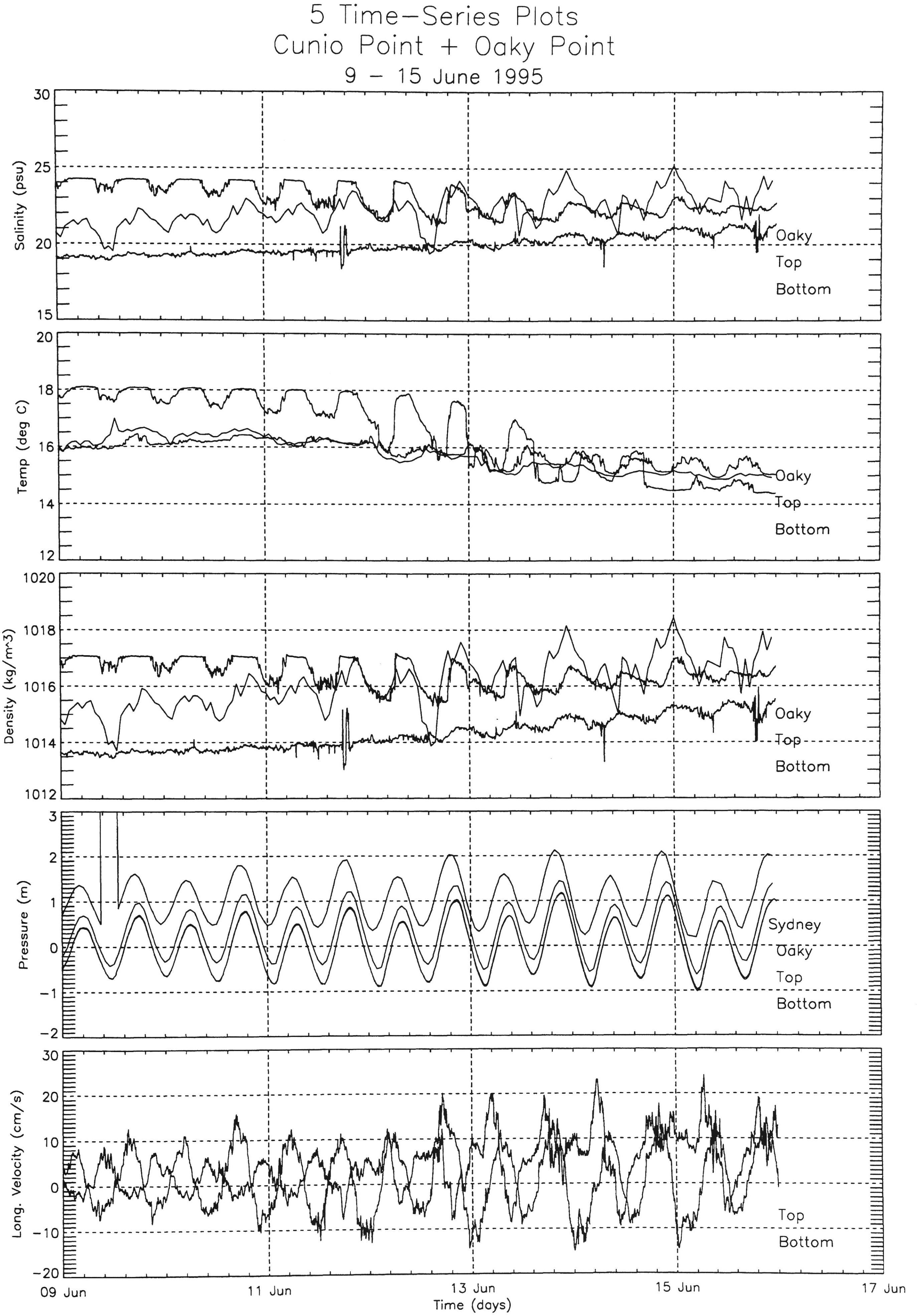


FIGURE 10 CUNIO POINT TIME SERIES PLOTS, 9-15 JUNE 1995

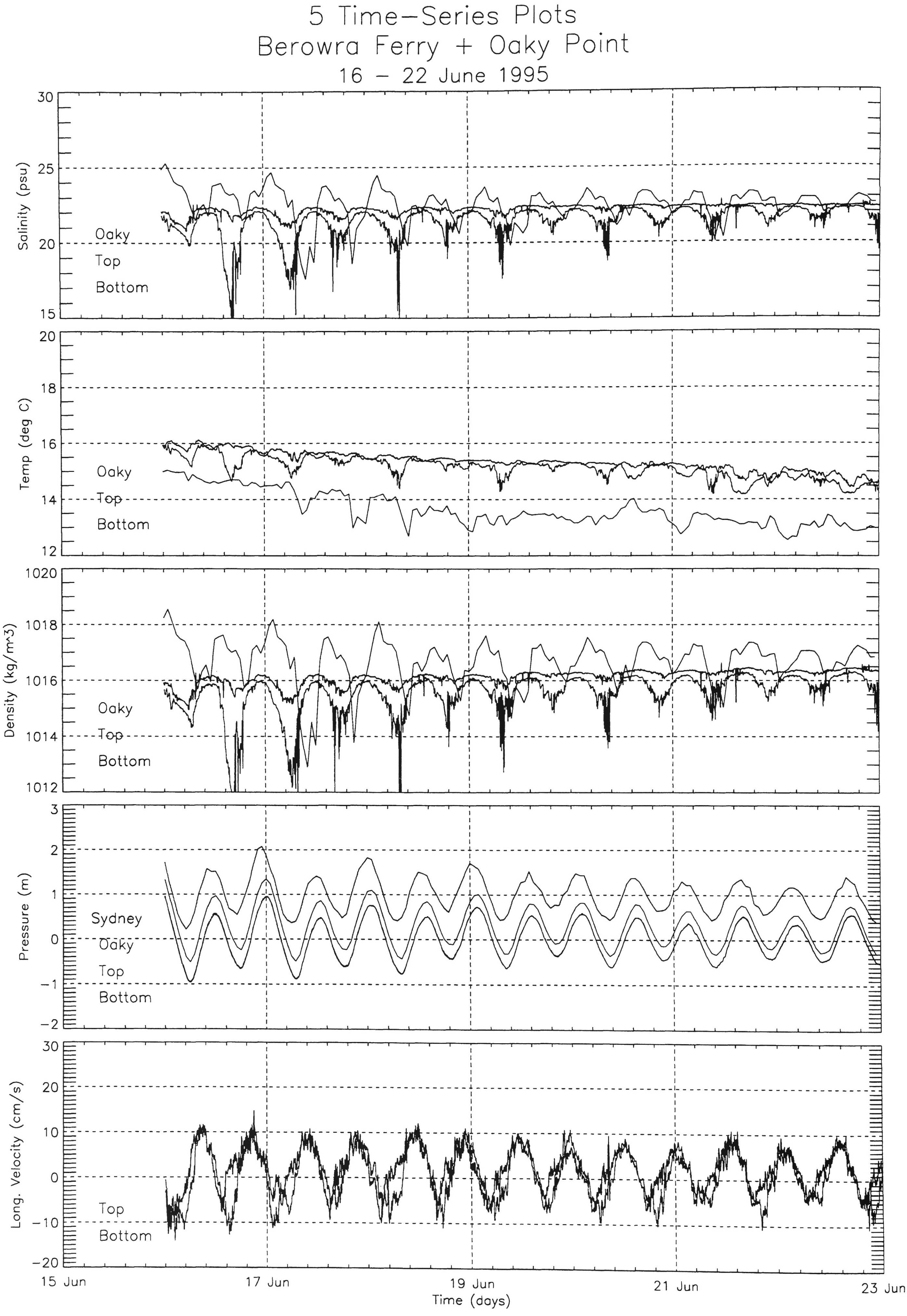


FIGURE 11 BEROWRA FERRY TIME SERIES PLOTS, 16-22 JUNE 1995

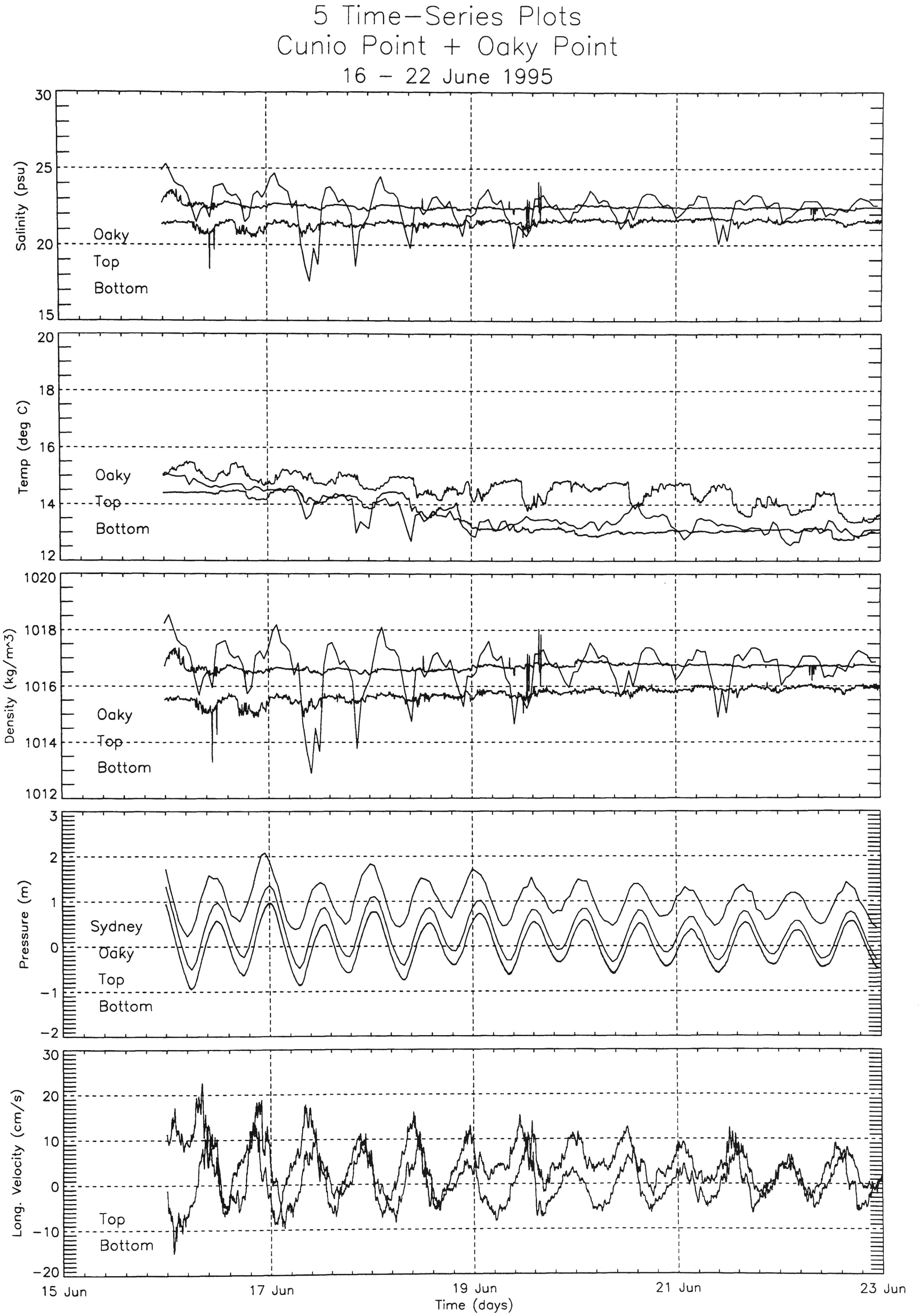


FIGURE 12 CUNIO POINT TIME SERIES PLOTS, 16-22 JUNE 1995

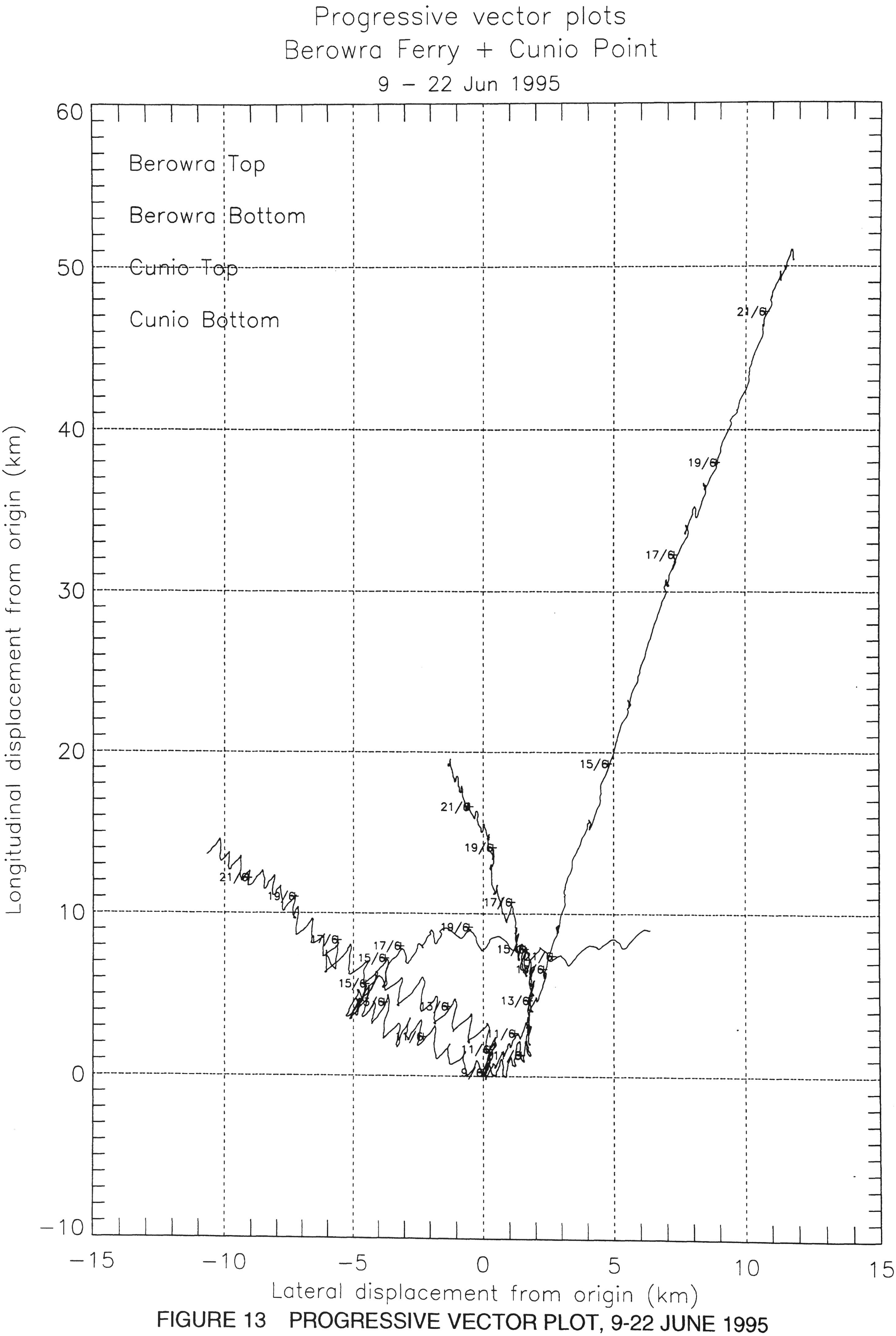


FIGURE 13 PROGRESSIVE VECTOR PLOT, 9-22 JUNE 1995

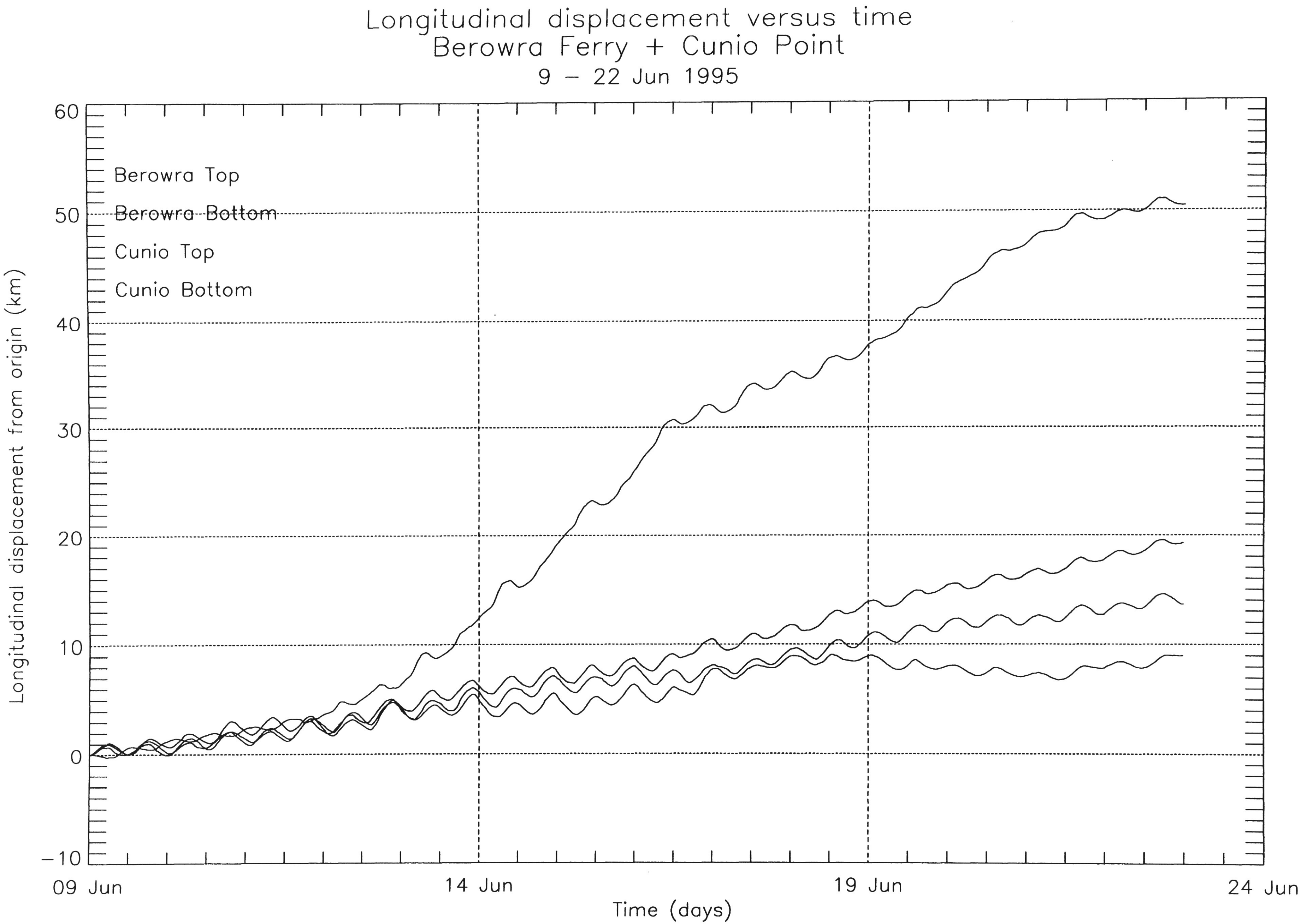


FIGURE 14 LONGITUDINAL DISPLACEMENT PLOT, 9-22 JUNE 1995

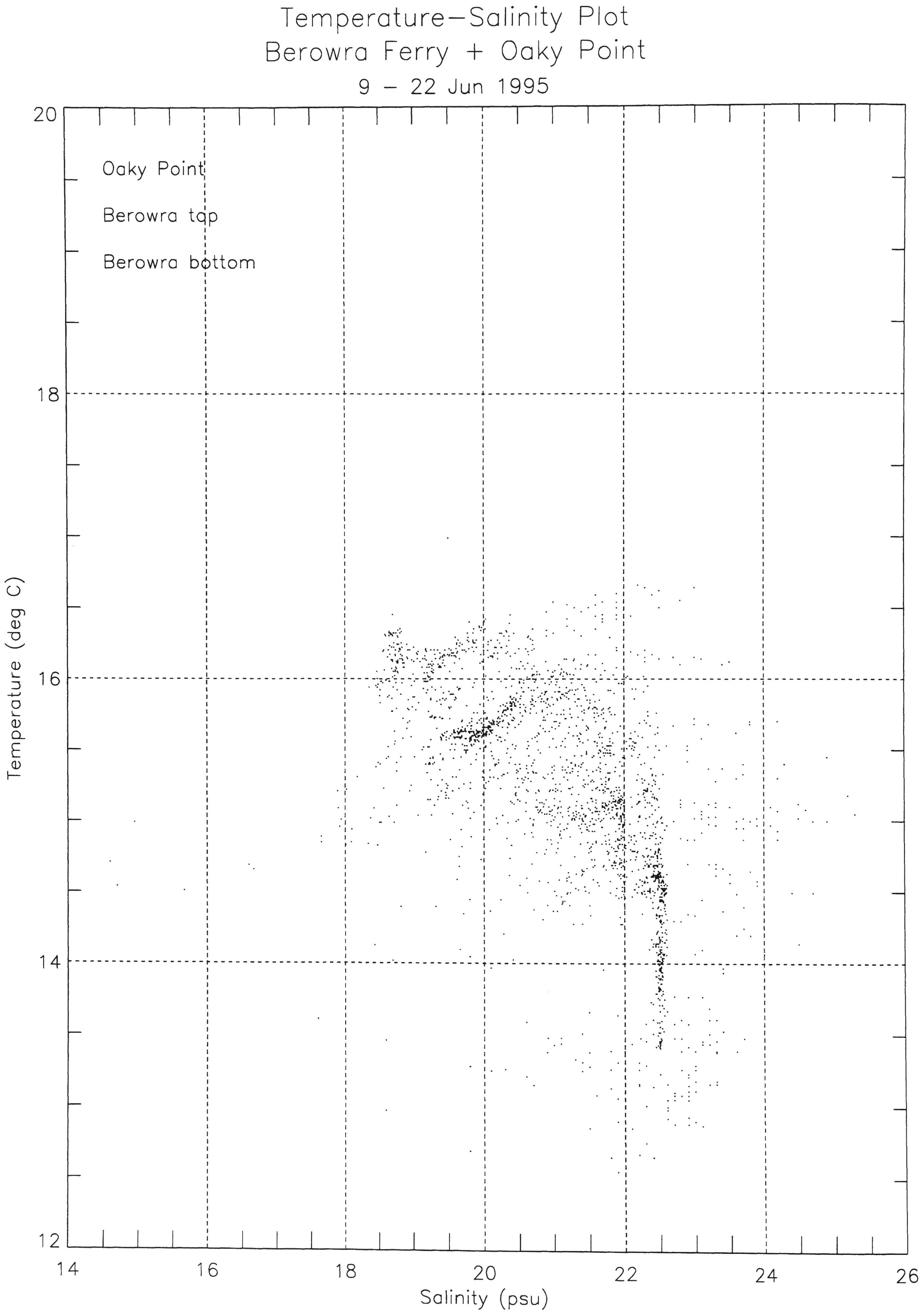


FIGURE 15 BEROWRA FERRY TEMPERATURE-SALINITY PLOT, 9 -22 JUNE 1995

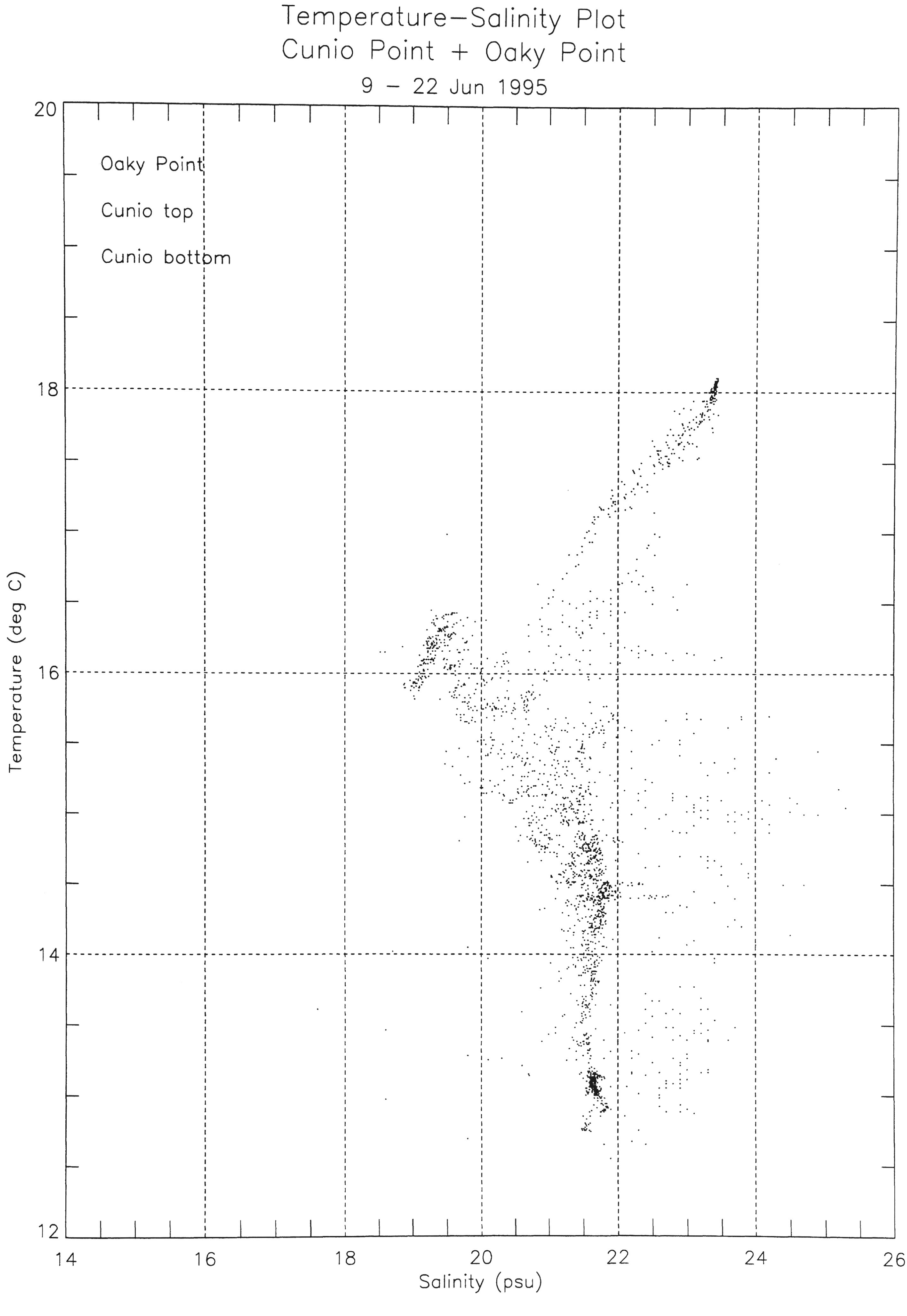


FIGURE 16 CUNIO POINT TEMPERATURE-SALINITY PLOT, 9 -22 JUNE 1995

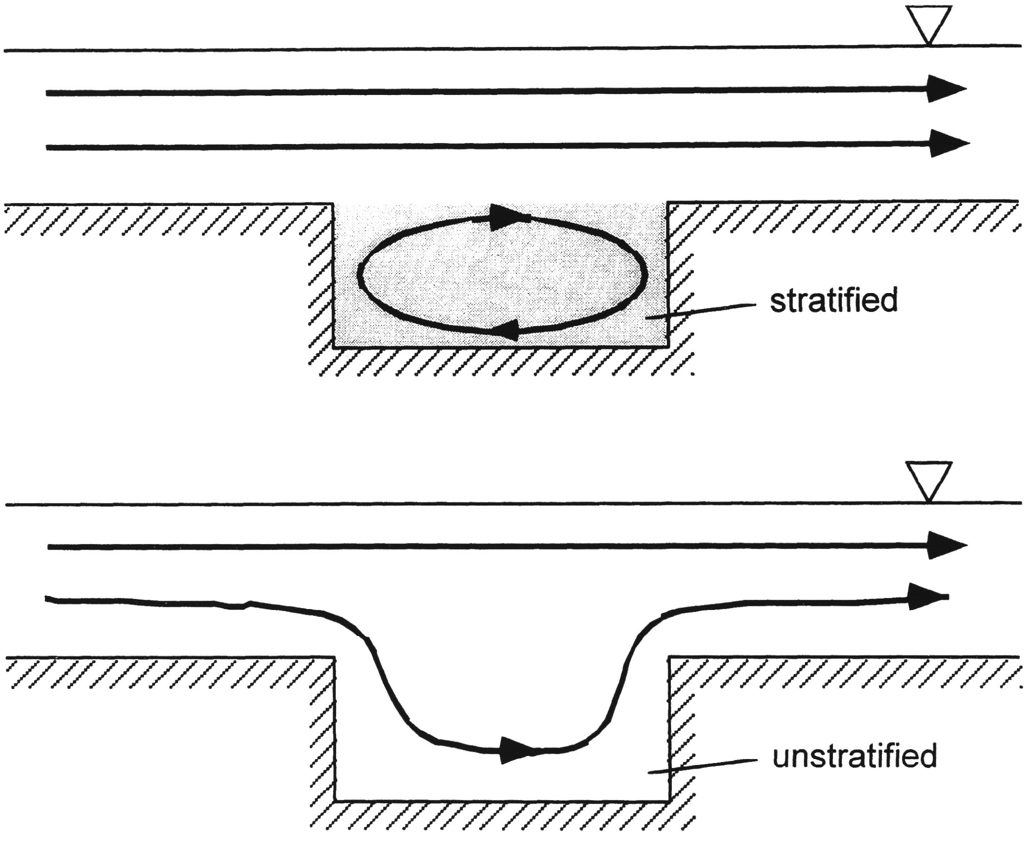


FIGURE 17 HIGH AND LOW STRATIFICATION CIRCULATION SCHEMATIC

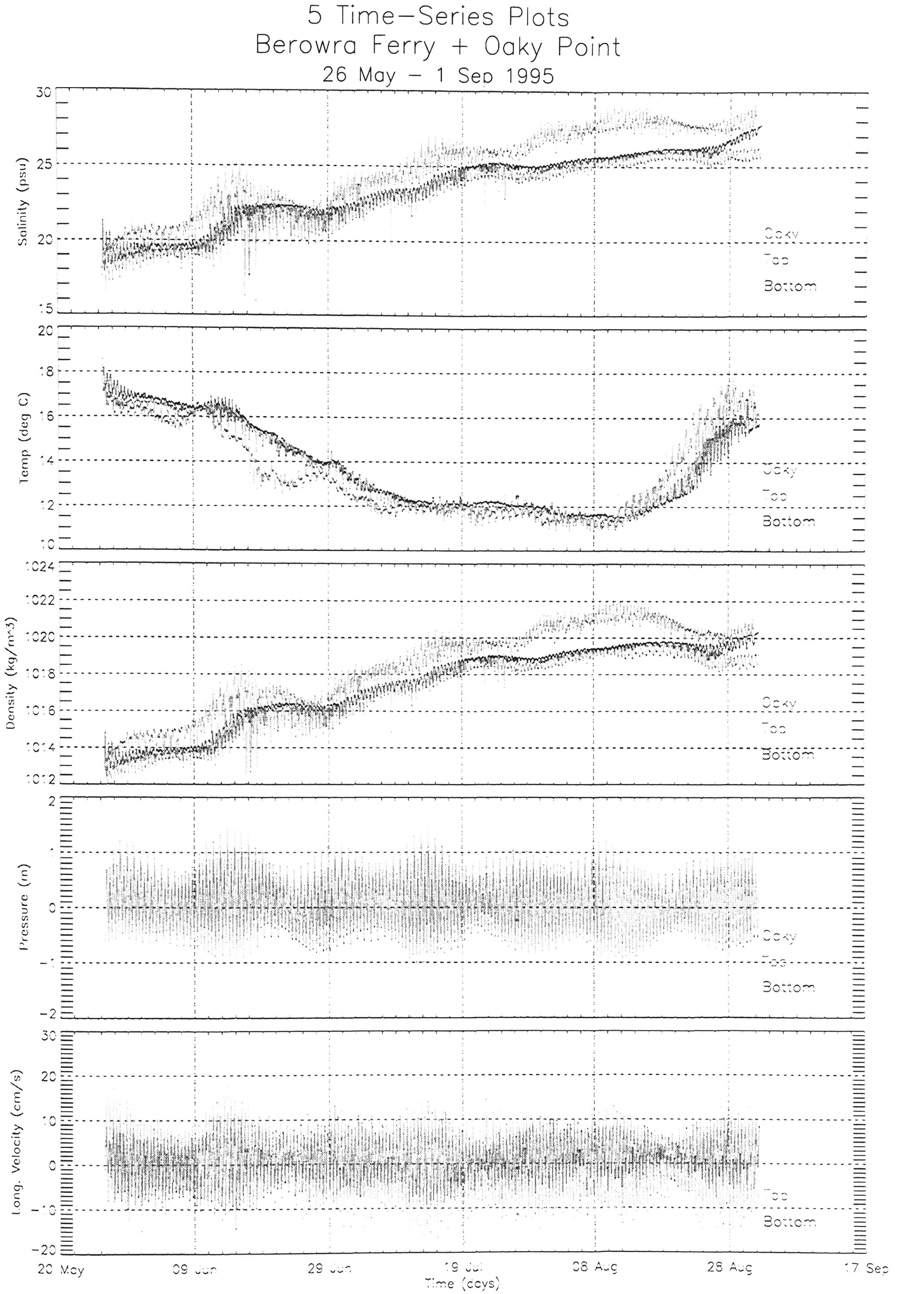


FIGURE 18 UNFILTERED BEROWRA FERRY TIME SERIES PLOTS, MAY-SEPTEMBER 1995

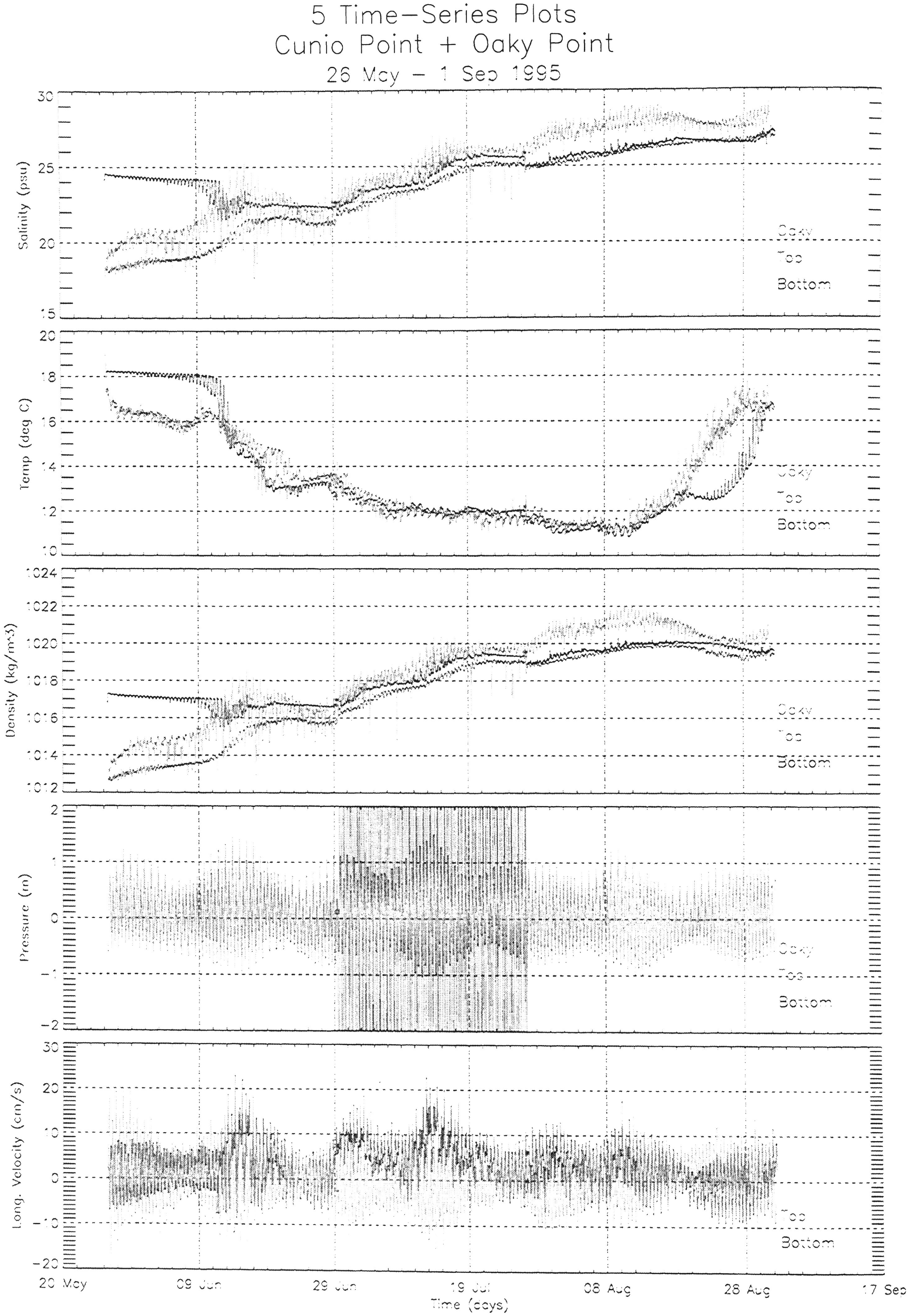


FIGURE 19 UNFILTERED CUNIO POINT TIME SERIES PLOTS, MAY-SEPTEMBER 1995

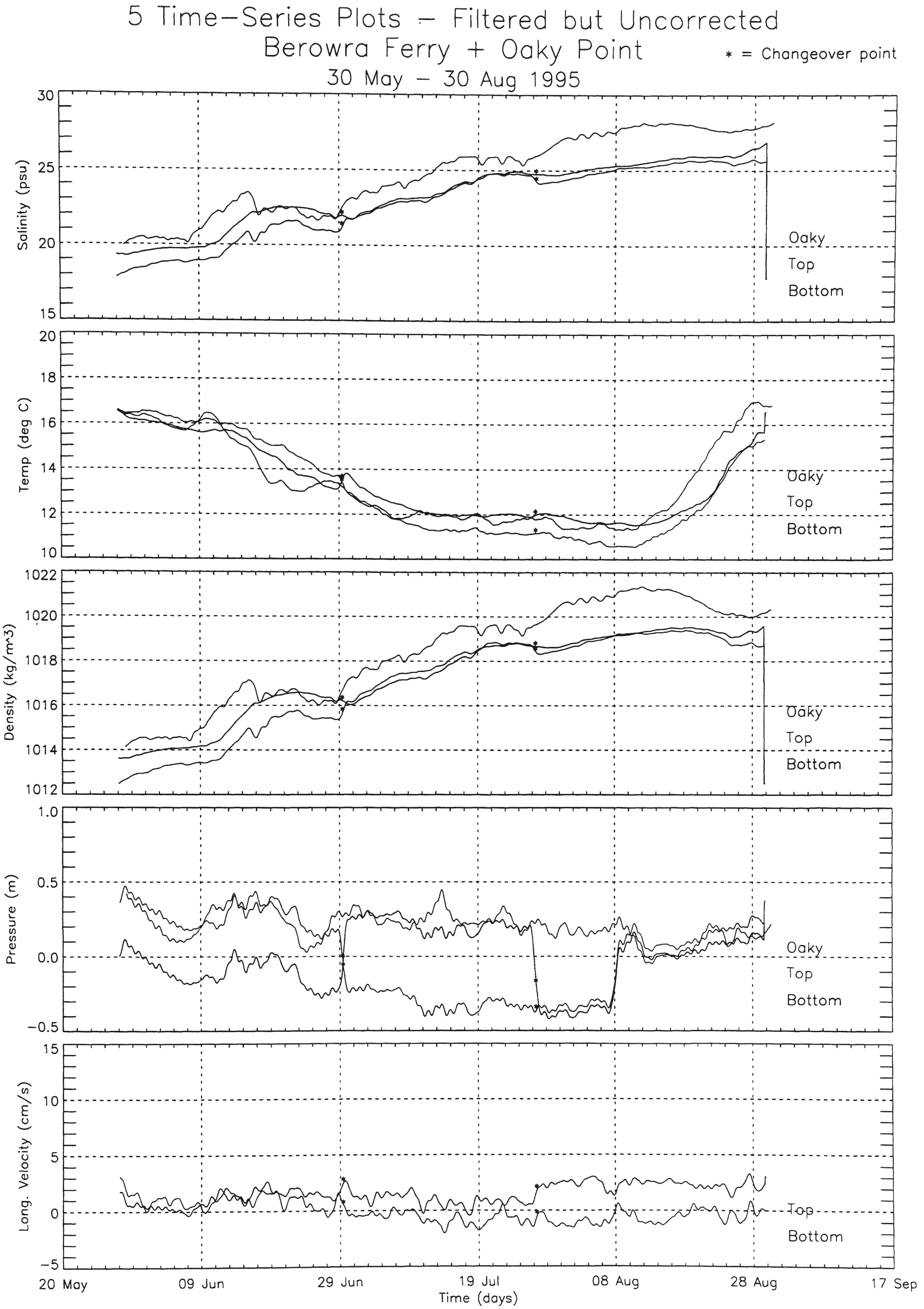


FIGURE 20 FILTERED BEROWRA FERRY TIME SERIES PLOTS, MAY-SEPTEMBER 1995

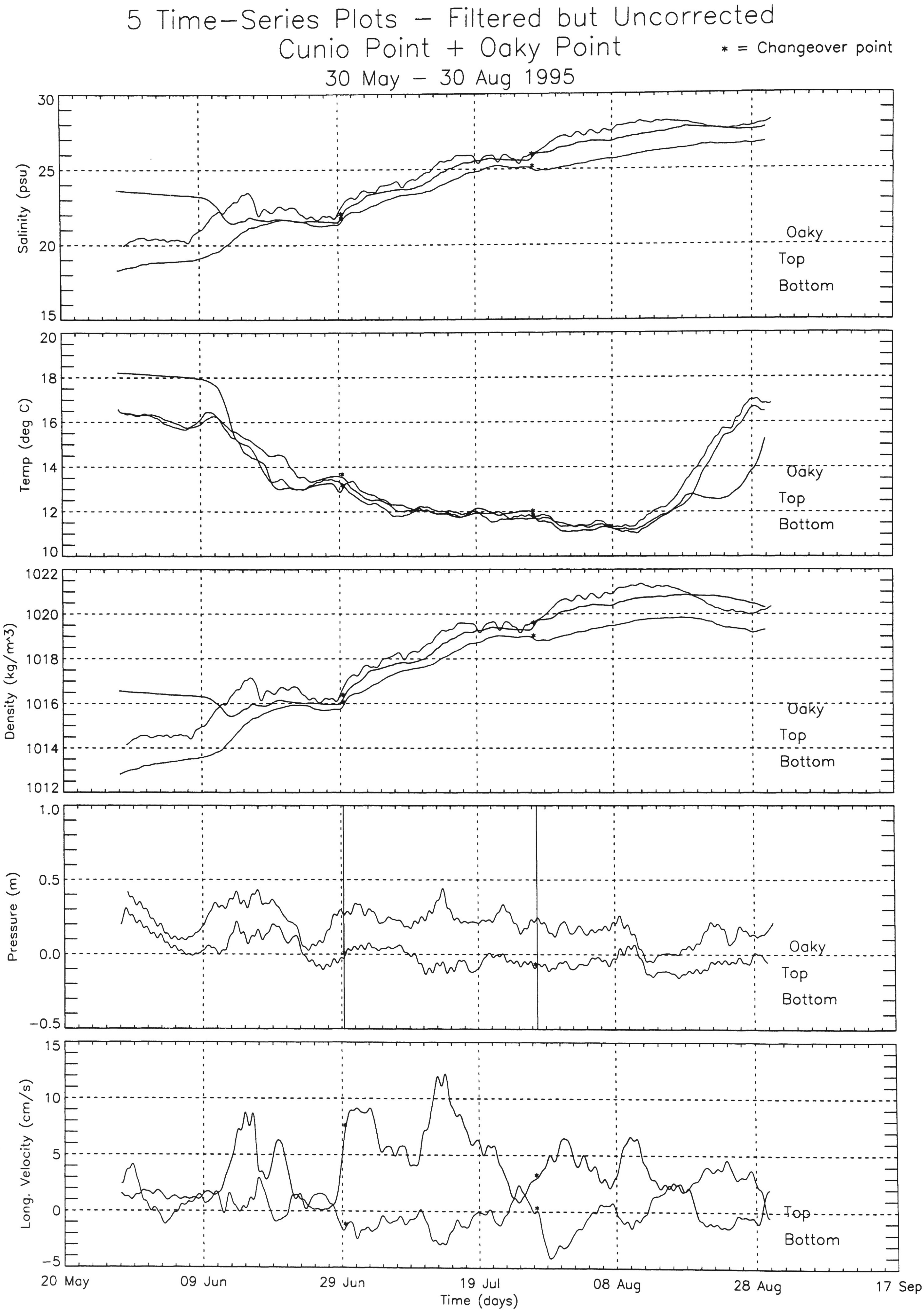


FIGURE 21 FILTERED CUNIO POINT TIME SERIES PLOTS, MAY-SEPTEMBER 1995

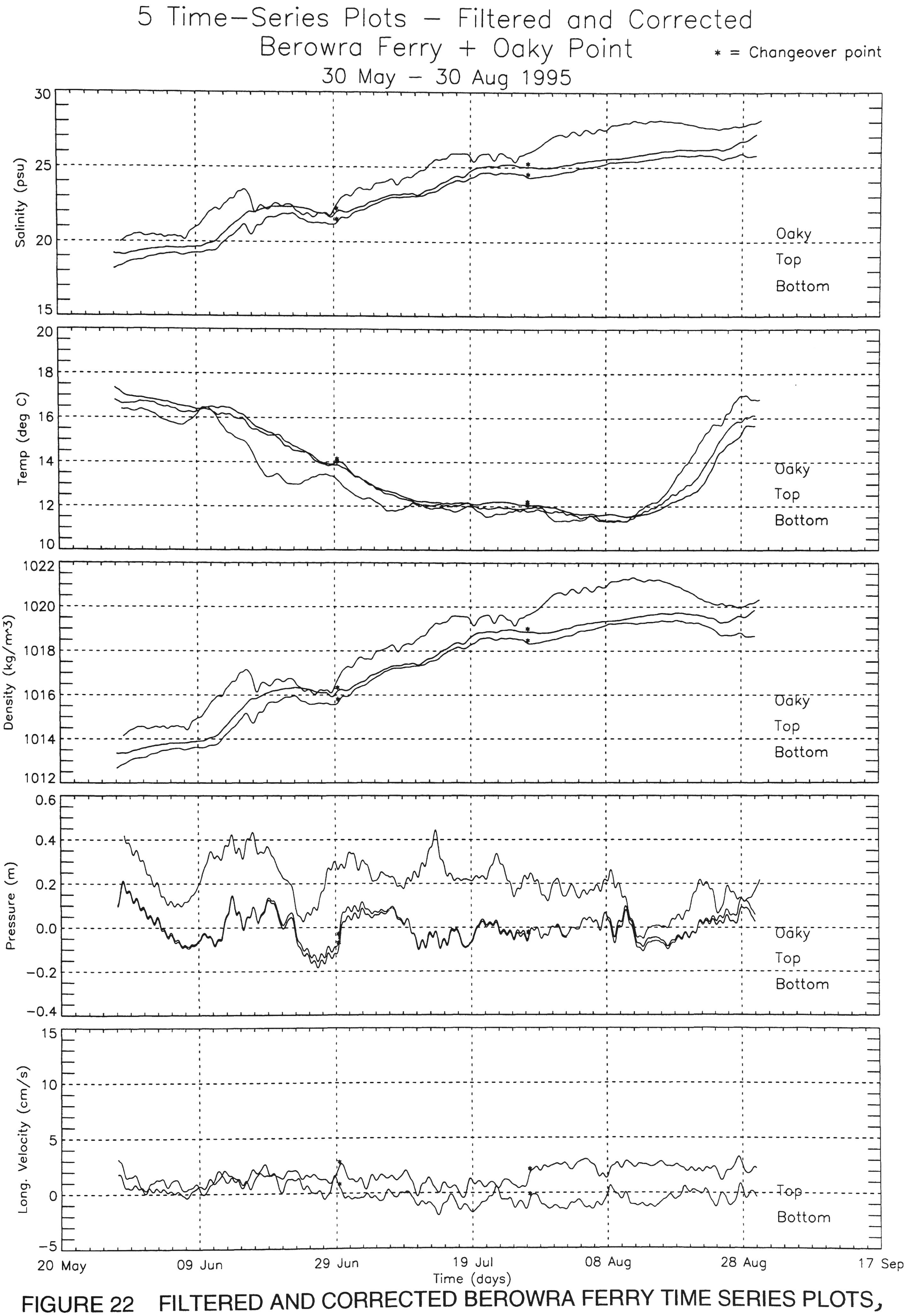


FIGURE 22 FILTERED AND CORRECTED BEROWRA FERRY TIME SERIES PLOTS, MAY-SEPTEMBER 1995

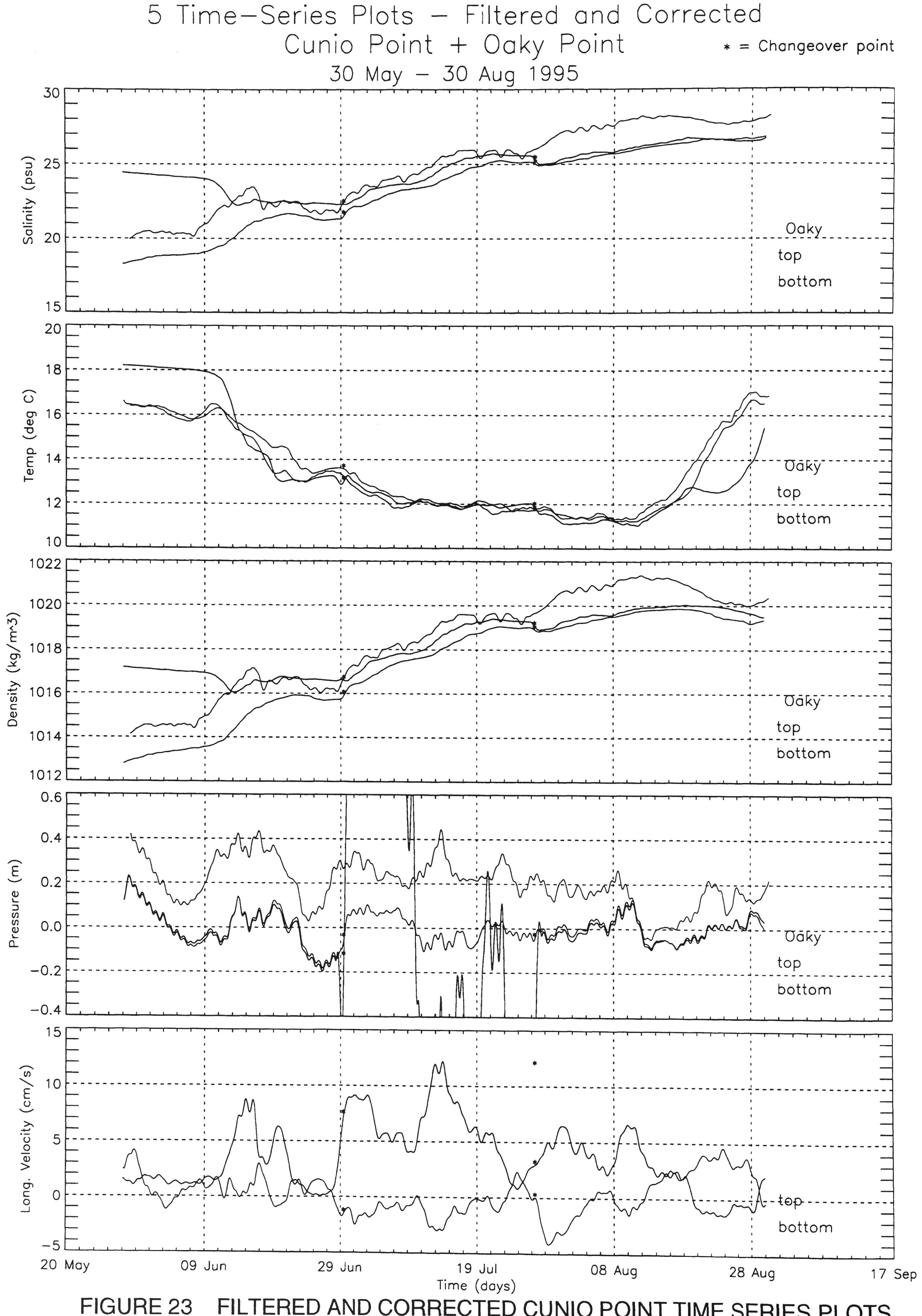


FIGURE 23 FILTERED AND CORRECTED CUNIO POINT TIME SERIES PLOTS, MAY-SEPTEMBER 1995

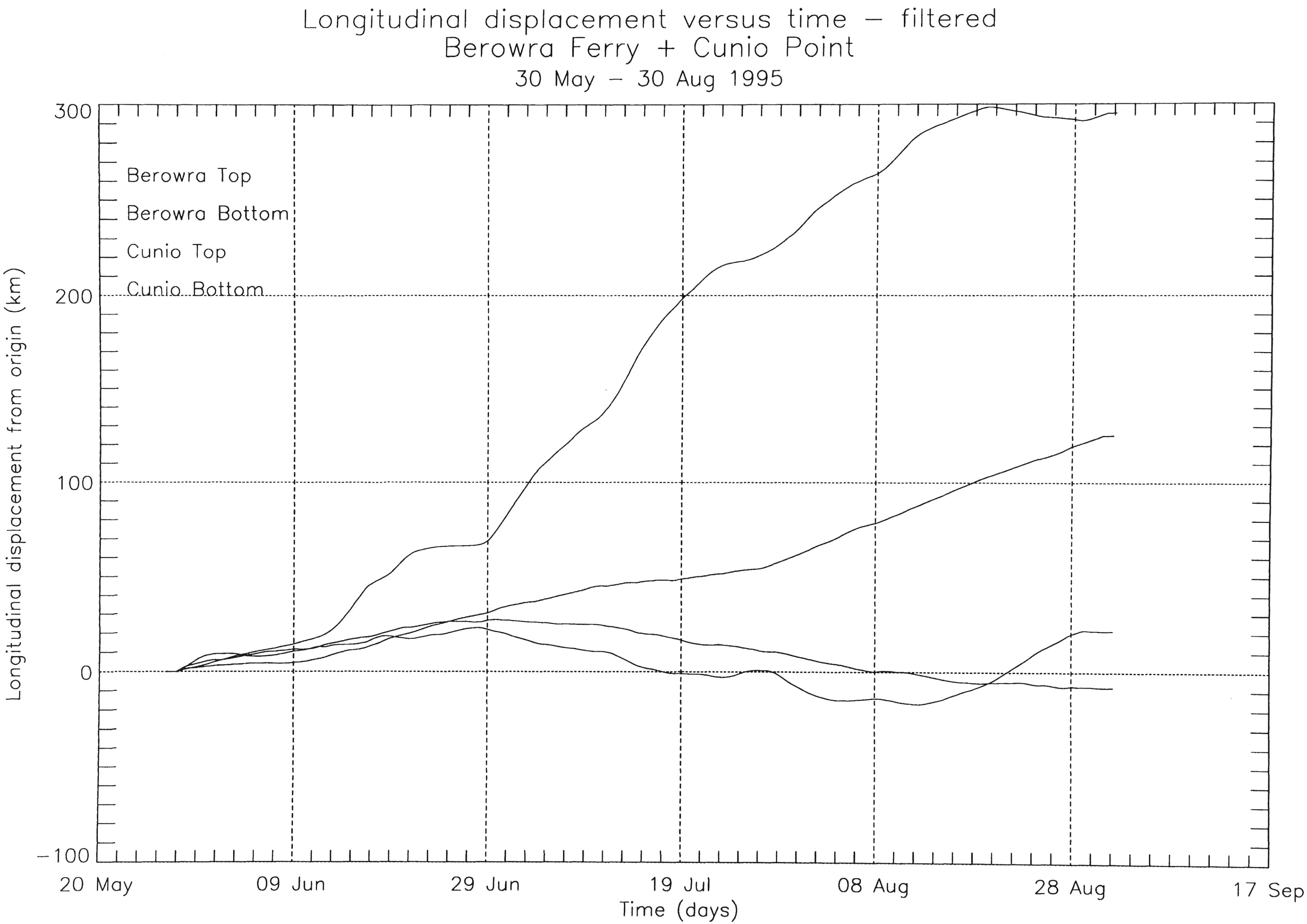


FIGURE 24 LONGITUDINAL DISPLACEMENT PLOT, MAY-SEPTEMBER 1995

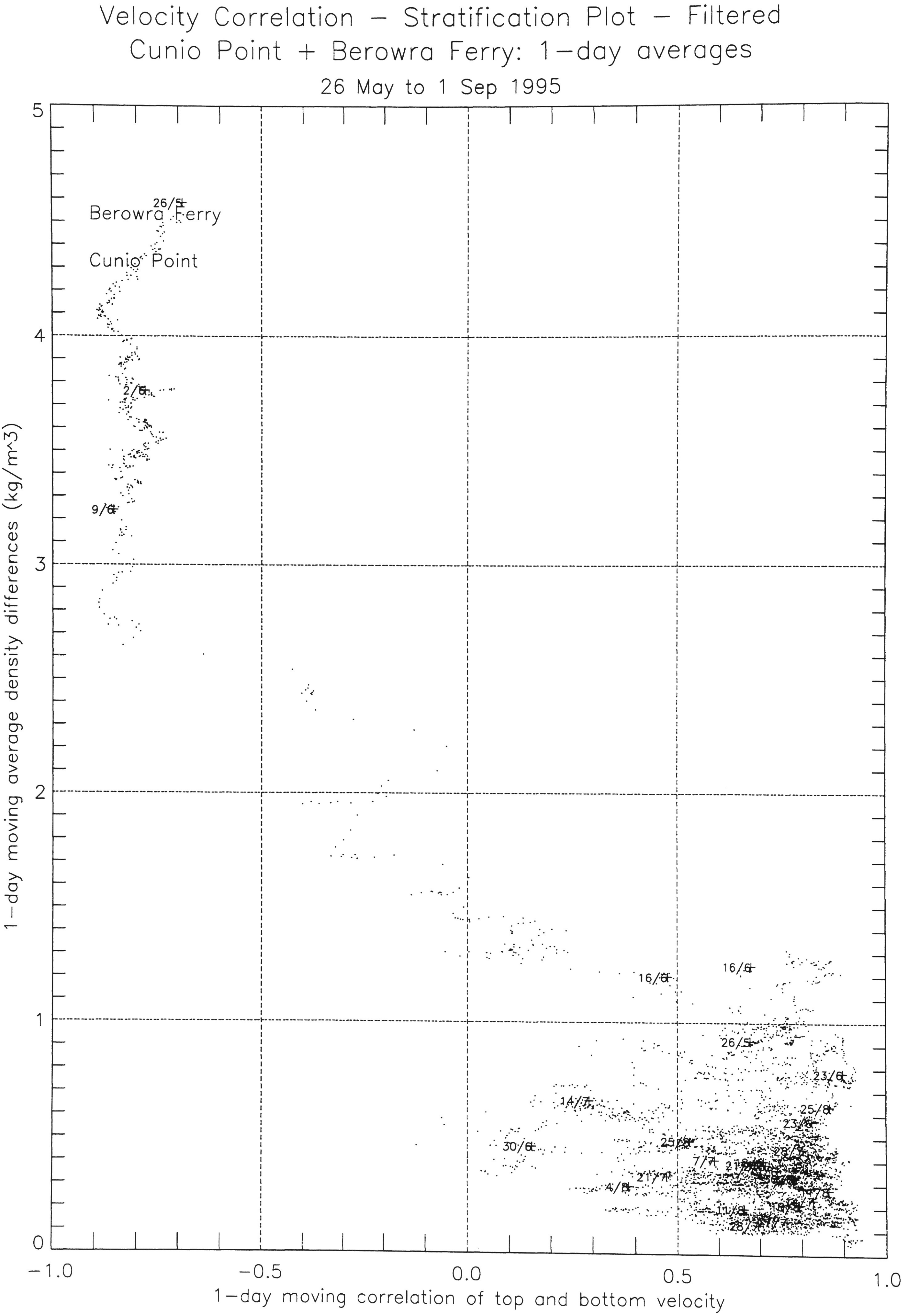


FIGURE 25 VELOCITY CORRELATION-STRATIFICATION PLOT - 1 DAY AVERAGE

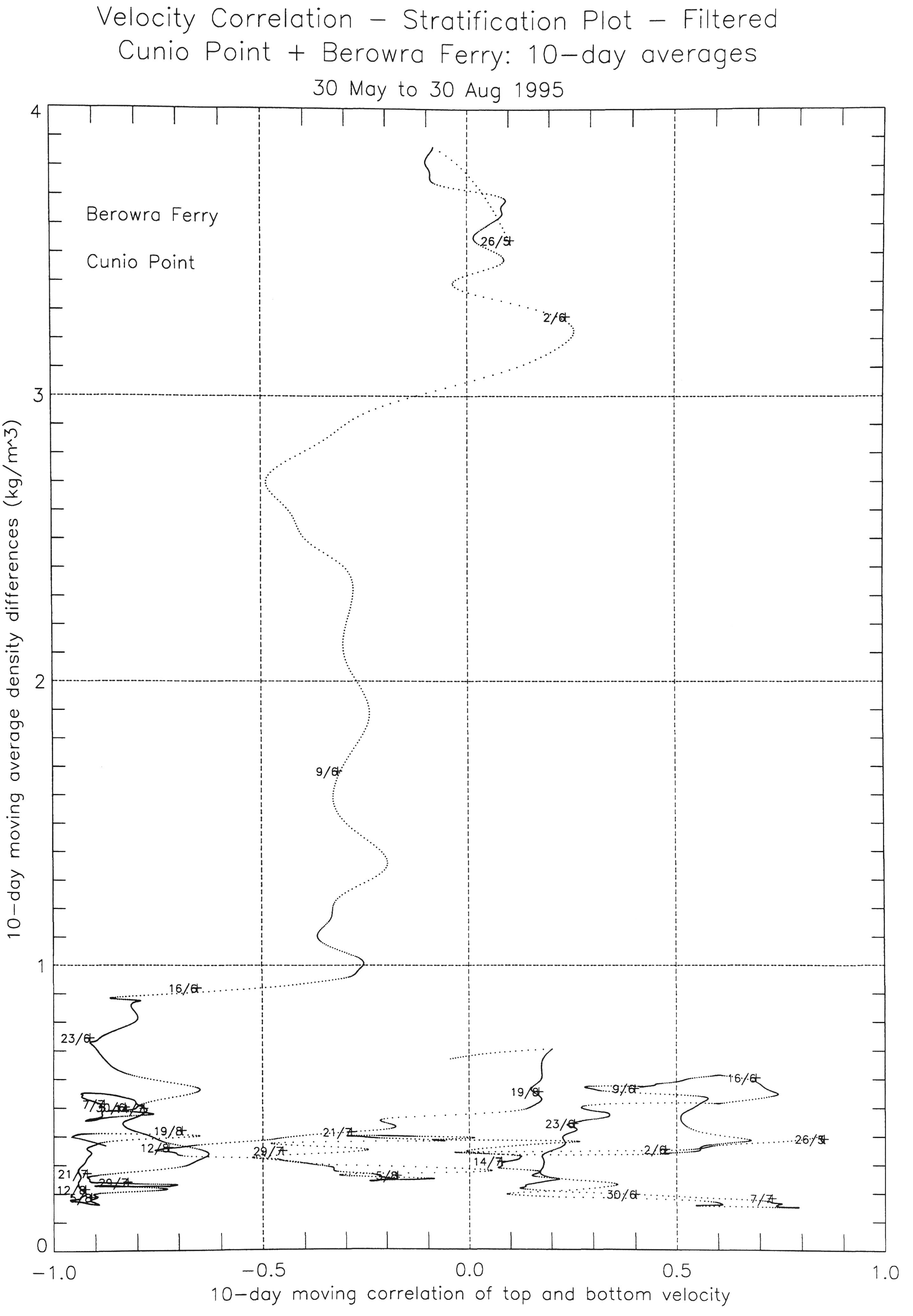


FIGURE 26 VELOCITY CORRELATION-STRATIFICATION PLOT - 10 DAY AVERAGE

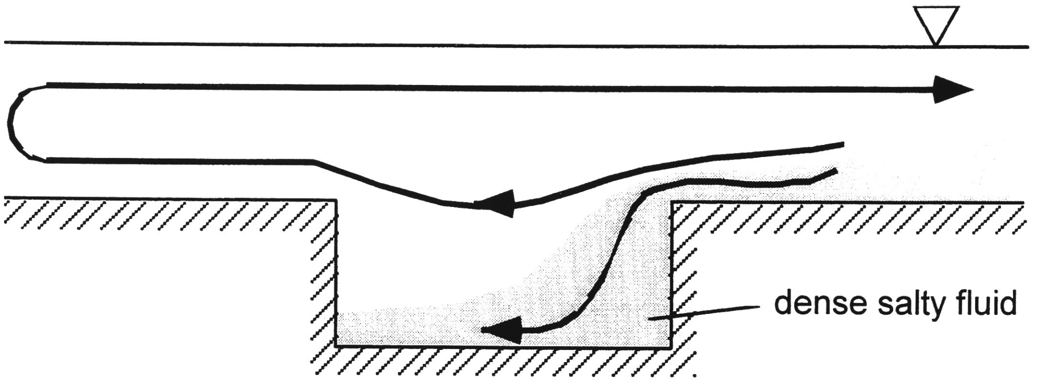


FIGURE 27 LONG TERM BAROCLINIC CIRCULATION SCHEMATIC

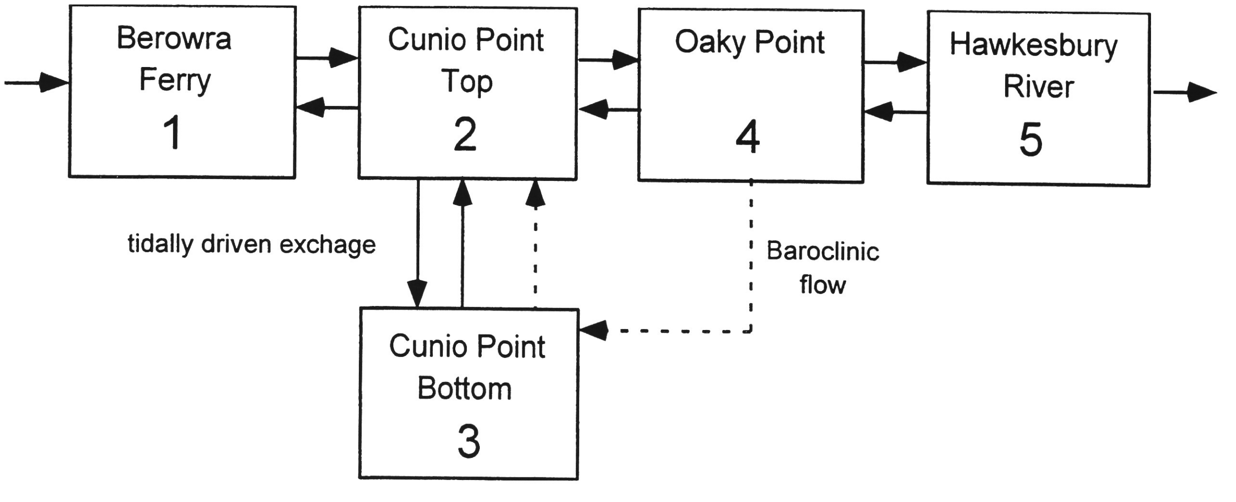


FIGURE 28 FIVE BOX MODEL

Appendix A

Corrections to S4 Data

CORRECTIONS TO S4 DATA

There were a number of problems that arose in the S4 data sets referred to in this report. This data was corrected before the data was interpreted. These corrections are described in the following

Pressure Data

In the plot of pressure about the mean value, a number of serious discontinuities and jumps are evident in the top and bottom readings. These occur at 29 June, 27 July, and 8 August. The large jumps at 29 June and 27 July coincide with redeployment of the S4 gauges and occur because the gauges cannot be replaced in exactly the same positions. For example, the recorded pressure will increase if a gauge is deployed lower in the water, and vice versa.

The large jump at 8 August is not due to gauge redeployment, though it is due to some other unnatural cause. The large increase in pressure seems to indicate that both the top and bottom gauges were dragged deeper into the water column. It is speculated that this probably occurred due to interference from some water craft.

Pressure records for each deployment period were corrected by shifting the records so that their mean values coincided. Note that the top gauge data at Cunio Point in the second deployment period is spurious, but the bottom gauge gives a reliable reading for this period.

Salinity and Temperature

At the time of collection, all data in addition to current readings from the S4s was considered superfluous, and thus the salinity and temperature equipment were not properly calibrated. The inaccuracies in these data sets are more serious than those in the pressure data, and more difficult to correct.

The uncorrected salinity, temperature and density records show discontinuities at the two changeover points. The inaccuracy of the data is also seen in the fact that the salinity and density at the top is sometimes measured as higher than salinity at the bottom. This is physically impossible at anything longer than very short periods, for higher densities at the top of the water column result in a highly unstable situation.

The following describes the correction process used.

Correcting the Cunio Point Data

The first step in the attempt to correct the data was to go back to the original instrument logs for the S4 gauges. These logs, kept at the time of instrument deployment, include the serial numbers of deployed instruments and the results of checks performed. Each gauge was 'checked' by placing it in a bath of saline solution. The main aim of this was to calibrate the current meter, but salinities and temperature were also recorded as a by-product. Unfortunately, the actual salinity and temperature of the bath was never recorded. A summary of the available information of interest from the log book can be found in Table A.1.

Table A.1 Information from Checks Performed on S4 Current Meters.

Deployment Date	Check Date	Location	Instrument No.	Salinity Reading	Temperature Reading
Cunio Point					
26/5/95	24/5/95	Top	0878 2044	31.20	17.47
"	24/5/95	Bottom	0545 1401	30.39	16.50
29/6/95	-	Top	0545 1282	-	-
"	-	Bottom	0816 1762	-	-
27/7/95	25/7/95	Top	0878 2044	31.64	13.54
"	24/7/95	Bottom	0545 1267	32.69	12.69
Berowra Ferry					
26/5/95	23/5/95	Top	0878 2043	33.59	16.94
"	25/5/95	Bottom	0545 1283	31.92	16.65
29/6/95	-	Top	-	-	-
"	-	Bottom	-	-	-
27/7/95	27/7/95	Top	0545 1401	30.53	11.82
"	24/7/95	Bottom	0545 1267	32.69	12.69

The Cunio Point data in Table A.1 tells us that two checks were performed on 24 May, two days before the gauges (nos. 08782044 and 05451401) were deployed. The difference in the salinity and temperature readings shows that the two gauges are not reading the same values. We do not know the actual salinity and temperature and so cannot correct the gauges to an absolute standard, but we can correct them relative to each other. The top gauge salinity reading is 0.81 psu higher than the lower gauge reading. Thus, to make the top and bottom gauges comparable, we can subtract 0.81 from the top or add 0.81 to the bottom. It was decided to increase the Cunio Point bottom data by 0.81 psu throughout the first deployment period. A similar exercise can be performed with the temperature readings.

No checks were performed before the start of the second deployment period, so no corrections were made. The checks performed before the start of the third deployment period were one day apart, but it was decided they were comparable, and so the procedure applied to the first deployment period was repeated. For example, the 1.05 psu difference between bottom and top salinities was removed by shifting the top gauge data down by 1.05 psu.

The final results of the corrections at Cunio Point are seen in Table A.2.

Correcting the Berowra Ferry Data: First and Second Deployments

The correction procedure used at Cunio Point was not repeated on the Berowra Ferry data. This is because the checks recorded in the log books were performed at least two days apart, and so it was judged that comparison between top and bottom gauges could not be safely made. Furthermore, if a procedure similar to that described above had been applied, it would have shifted the top and bottom values further apart, not closer together as they should be. The log book, however, still gave some important information; the top gauge in the first deployment period became the bottom gauge in the second deployment and vice versa.

On the 10 and 11 June 1995, some depth profiles were obtained at various locations in Berowra Creek. These profiles came from the Seacat CTD device, which instantaneously measures various parameters, including salinity and temperature, over the entire depth of the water column. The profiles taken in this period can be seen in an appendix to 'Berowra Creek Tidal Data Collection' (MHL, 1997). One of these locations was very close to the S4 gauges at Berowra Ferry.

The data from the S4 gauges was compared with data from the Seacat depth profiler and corrected according to it because the CTD is more accurate. To do the comparison, the corresponding times in the S4 data and the CTD data must be chosen. Then the corresponding depths must be chosen. The depth profile data is classed into 0.2 metre bins. Thus, if the water is 1.8 metres deep then there will be 9 sets of data in the vertical profile. Once the corresponding times and positions in the water column are selected, the data can be compared. On average, the S4 top reading was about 0.17°C below the corresponding

CTD reading, while the S4 bottom reading was 0.78°C below. Salinity data showed that, on average, the S4 top reading was 0.26 psu below the corresponding CTD reading, while the S4 bottom reading was 0.14 psu above. The S4 data was then corrected to correspond more closely to the CTD data. Thus, for example, 0.17 was subtracted from the top temperature data.

These corrections are applied to the first deployment period only. Recall that in the second data period the top and bottom gauges were swapped around. Thus, the corrections made to the top gauge in the first deployment become the corrections made to the bottom gauge in the second deployment, and vice versa. The corrections are shown in Table A.2.

Corrections to the Berowra Point Data: Third Deployment Period

There is no CTD data for comparison for the third deployment, so it was assumed that the end of one deployment and the start of another should match up reasonably closely. It was decided keep the top gauge temperature data fixed and to shift the bottom gauge data down by 0.17. The top gauge salinity data was shifted upward by 0.32 psu, and the bottom gauge was left unchanged. These shifts were relative to the corrected second deployment data, so the actual shifts were found by adding on the second deployment corrections. Thus, for example, 0.78 was be added to the top temperature data (the same correction as for the second deployment) and no correction was made to the bottom temperature data (0.17–0.17 = 0). The actual corrections are shown in Table A.2.

Table A.2 Summary of corrections performed on S4 data.

Deployment Period	Top Salinity Correction	Bottom Salinity Correction	Top Temperature Correction	Bottom Temperature Correction
Cunio Point				
1	-	+0.81	-	-
2	-	-	-	-
3	-	–1.05	-	-
Berowra Ferry				
1	+0.26	–0.14	+0.17	+0.78
2	-0.14	+0.26	+0.78	+0.17
3	+0.18	+0.26	+0.78	-

Comments

The use of the term 'correction' should not be misunderstood. The corrections applied to the S4 data are not exact, but do bring the data closer to the true values. The corrections are valuable mainly because they make top and bottom values comparable. The different methods of correction used at Cunio Point and Berowra Ferry mean that the corrected data is not necessarily comparable between the two sites. That is, the two sites have not been corrected relative to the same absolute values.

Despite the shortcomings procedures described above, the corrections are valuable because they make the data more sensible. That is, top salinities and densities are now consistently less that the bottom salinities and densities, there are no inversions of top and bottom readings, and the 'jumps' at the (instrument) changeover points were reduced.