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UPWELLING OFF THE NORTH WEST COAST OF AUSTRALIA

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Summary

A review of the information to date on the existence of upwelling off NW Australia has indicated that:-

(a) Contrary to previous belief upwelling cannot be conclusively demonstrated from the oceanographical data, although some limited surface nutrient enrichment (e.g. 0.30-0.35 μgat/l. in phosphates) does occur.

(b) Biological enrichment is a well documented feature of the coastal region north of 15°S and must be attributable to effects other than upwelling in the same area.

A number of possible causes of this biological enrichment has been examined but none can be conclusively proven from the data available.

1. *INTRODUCTION*

In many oceanographical atlases (Schott 1935 for example), upwelling is claimed as a feature off the NW coast of Australia, during the SE Trade Wind period of the year. However Rochford (1962), on the basis of data from 1959-1961, was unable to find any significant surface manifestation of large scale upwelling in that region. Wyrtki (1962) examined changes with time in the subsurface temperatures of the region between NW Australia and the south coast of Java. He concluded:

(a) "Only when the general wind pattern (i.e. from the SE) deviates considerably from average conditions might upwelling be possible along the NW coast of Australia for short periods but this would be the exception rather than the rule."

(b) "However it is questionable whether the enrichment (in zooplankton biomass) along the Australian coast is due to the stirring effects of the strong tidal currents there which bring matter from the bottom into the eutrophic layer or whether it is due to upwelling."

Tranter (in press) using zooplankton biomass values observed in the region off NW Australia up to 1964, was able to demonstrate much higher values in the region than further south. Moreover the values observed off NW Australia were of the same order as that from the well-known upwelling area south of Java. Tranter therefore concluded that some enrichment process occurred in the region off NW Australia.

The cruises of CSIRO in the eastern Indian Ocean, subsequent to 1964, did not systematically investigate the coastal waters off NW Australia throughout a full year. These cruises could not therefore provide any further significant information about the possible enrichment process responsible for the high zooplankton biomass. In August 1976, therefore, the Division carried out an oceanographical study of the dynamics, nutrient conditions, and zooplankton biomass of the region off NW Australia, to collect more information about this enrichment process. This report reviews the results of this cruise and of previous cruises in the area, to provide preliminary results for the planning of future oceanographical studies of the enrichment phenomenon.

2. *DATA AND METHODS*

Table 1 lists all relevant CSIRO cruises off the NW coast of Australia. Data from these cruises are available from World Data Centres A in Washington, D.C., USA, and B in Moscow, USSR. The most recent data from R.V. *Sprightly* can only be obtained at present from CSIRO Division of Fisheries and Oceanography. The methods used are described in Major *et al* (1972).

Wind regime

Between April and September of each year winds from the SE and S, which could generate upwelling are common (Table 2), particularly in the morning.

During the *Sprightly* cruise winds from the E and SE were most common (Fig. 2) with a median speed of around 7-10 knots (3.5-5 m/sec).

Bottom topography

The general features of the bottom topography off NW Australia are as shown in Figure 1.

3. *OCEANOGRAPHY OF THE NW AUSTRALIAN SHELF*

(a) *Sprightly* August 1976

The station positions for this cruise are shown in Figure 3.

(i) Dynamic topography

At the surface relative to 1100d.b. (Fig. 4), there was little evidence of current structure except in the north west of the region. Even there the maximum slope of some 10 d.cm in 50 nautical miles was indicative of a current to the north east of some 15-20 cm/sec. only.

Relative to 500 d.b. (Fig. 5) there was evidence of a flow to the west from the north east of the region possibly associated with the South Equatorial Current. Again however currents were weak, less than 25 cm/sec.

(ii) Surface temperatures (°C)

Temperatures increased from south to north in a more or less consistent relation with latitude (Fig. 6). In general temperatures were less near the coast at a particular latitude. In the north east of the region the east-west temperature difference was at a maximum with onshore temperatures some 0.5-1.0°C less than offshore.

This lowered temperature regime occurred in a region of lower salinity (Fig. 7). However further offshore the maximum temperature of 26°C also occurred in a pocket of lower salinity (Fig. 7).

Moreover the lowered temperature region was situated to the north of the nutrient enriched nearshore waters further south (Figs. 8 and 9).

(iii) Surface salinity(‰)

Salinities decreased from south to north with higher salinities near the coast at any particular latitude (Fig. 7). North of around 14°S however this pattern was disrupted by intrusions of higher and lower salinity water possibly caused by entrainment along the southern margin of the South Equatorial Current (Figs. 4 and 5).

(iv) Inorganic phosphate (μgat/l.)

Surface phosphate varied between 0.08 and 0.36 μgat/l. with the higher values (>0.30) occurring in two near shore regions (A and B Fig. 8) to the north of the region. These two regions of phosphate enrichment were off the mouth of King Sound and York Sound respectively (Fig. 1).

(v) Silicate silicon (μgat/l.)

Silicates (Fig. 9) whilst enriched along the coast in the same general area as for inorganic phosphates (off King Sound and York Sound) also were above 4 μgat/l. in isolated areas in the extreme southern and northern boundaries of the region.

(b) Previous CSIRO Cruises

(i) *Diamantina* 2/60 September.

Surface phosphates were similar in their distribution (A-B Fig.10) to those in August 1976 (Fig. 8) with maximum values around 0.3 μgat/l. near the coast in the north east of the region. There was no indication in the surface temperature of deeper water upwelling to the surface during the cruise (Fig. 11).

(ii) *Diamantina* 1/62 February - March.

Surface phosphates were overall lower than on other cruises later in the year. Again however the maximum value, 0.3 μgat/l., was found near the coast in the north east (A-B Fig. 12). There was no indication during this cruise of colder surface water indicative of upwelling (Fig. 13) as the cause of the slight phosphate enrichment near the coast.

(iii) Other cruises.

Other CSIRO cruises (Table 1) also showed no evidence of colder surface water or surface phosphate enrichment greater than around 0.20 μgat/l. within the region. The station coverage of these cruises however was inadequate to show upwelling events of dimensions less than 500 square miles in area. The previous cruise results (Sections 3(b)(i) and (ii)) indicate that the area of the enrichment could be of much smaller size than 500 square miles.

4. *EVIDENCE OF COASTAL ENRICHMENT*

(a) Seasonal changes in oceanographical conditions.

Utilizing data from earlier cruises as well as the 1976 *Sprightly* results, three positions (1-3 Fig. 1) were chosen at each of which stations from the same four cruises had been occupied throughout a year. These stations were occupied in summer (NW Monsoon) and winter-spring (early and late SE Trades).

Position 1.

In summer (Δ Fig. 14) and to a lesser extent in spring (■ Fig. 14) stratification in both temperatures and salinity was associated with a mid-depth increase in phosphates. However the salinity indicates that most of the seasonal changes were in the upper 40 m, with little seasonal change below that depth. It is most probable therefore that the increases in phosphate at mid depth are the result of *in situ* redistribution of phosphates during stratification and not of advection of offshore waters.

Position 2.

During the SE Trades (o X Fig. 15) these coastal waters were well mixed vertically to depths of around 60 m. Below this depth large increases in phosphates but little change in temperature or salinity suggest that *in situ* processes are responsible rather than any advection from offshore of phosphate-rich deeper waters. This possibility is also suggested as the cause of the increase in phosphates across the thermocline in summer (Δ Fig. 15).

Surface phosphate values (< 0.25 µgat/l.) during the period of observations (Fig. 15) indicate that some mixing of this deeper phosphate rich water with the surface layer did occur.

Position 3.

The seasonal variations in salinity were quite large but with only a small degree of stratification in spring (● Fig. 16). A thermocline was found in summer and spring (Δ ● Fig. 16). When the thermocline was present the bottom phosphates were at a maximum. In spring however phosphates varied between a maximum and minimum in profile values (⊙ Fig. 16). There are obviously insufficient data on the time changes to establish causes of this variability in phosphate, but there is no indication of surface enrichment to claim that upwelling had occurred.

(b) Zooplankton biomass and other relevant biological assessments of productivity.

On an earlier CSIRO cruise (*Dm* 3/61 September) sufficient stations were sampled off the NW Australian coast for zooplankton biomass, chlorophyll *a*, and C_{14} uptake to establish centres of biological enrichment. The results (Fig. 17) of measurements of zooplankton biomass, chlorophyll *a* and C_{14} uptake all show the most productive region to be off the region A-B when surface nutrient enrichment was most evident in August 1976 (Figs. 8 and 9). Unfortunately the zooplankton biomass values from this August cruise are not available for comparison.

It is noteworthy also that in region A-B (Figs. 8 and 9) during the *Dm* 3/61, the chlorophyll *a* maximum was at the surface while elsewhere it was found at depths down to 100 m.

Transparency measurements by Wyrtki (1962) also showed that the most turbid waters occurred in a coastal zone encompassing the region A-B (Figs. 8 and 9) of nutrient enrichment and of increased biological production.

There can be no doubt therefore that towards the end of the SE Trades period at least, a region of increased biological production does occur off NW Australia. It is difficult however to define the northern limit although the southern limit occurs most probably around 15°S.

5. *DISCUSSION*

The region of increased biological production north of 15°S (Fig. 17) was associated with surface phosphates and silicate values of 0.3-0.4 and 5-7 µgat/l. respectively (Figs. 8 and 9). Relative to the upwelling situation off the Somali-Arabian coast (Wyrtki 1971), the NW Australian enriched phosphate values were much lower (0.3-0.4 compared to 1.0-1.5 µgat/l.), although the silicates off NW Australia were only slightly less (5-7 compared to 10 µgat/l.). Nutrients in the upwelling region off SW Africa (Calvert *et al* 1971) were correspondingly higher also. However off Laurieton NSW surface phosphates during upwelling (Rochford 1975) were around the same concentration (0.3-0.4 µgat/l.) as the maximum values off NW Australia in August 1976.

Kabanova (1968) on the basis of surface primary production values claimed that the biological fertility off NW Australia was equal to, although less extensive than the richest upwelling region off Somali and Arabia. In view of the magnitude of the nutrient values observed off NW Australia during the year, it is difficult to accept equality in primary production between waters off NW Australia and Somali-Arabia, unless the stimulus to primary production occurs further north beyond the area investigated in detail by CSIRO cruises. Surprisingly also these maximum values of primary production off NW Australia occurred during the southern summer, contrary to the previous supposition that upwelling was associated with the winter SE Trade Wind system.

It must be accepted therefore that there is a discrepancy between the lack of upwelling discernible in the chemical characteristics and in the dynamic structure, and the very positive indications of enhanced biological production in coastal waters off NW Australia. A possible explanation of this could be a separation in space and perhaps in time of the region and events causing enrichment from those in which the maximum biological production is encountered, some distance downstream.

Upwelling certainly occurs in the Aroe Is. area further east in the Eastern Banda Sea (Wyrtki 1961) during the SE Trades. It is not impossible that biological effects of this upwelling could be encountered some 300 miles further west but this seems unlikely. Moreover Figure 17 if anything suggests a spreading to the north east away from a primary source of biological enrichment around A-B.

Averaged currents off NW Australia in July (Fig. 18) swing to the west around 15°S and join the South Equatorial Current, also flowing strongly to the west, at 10-12°S. A zone of divergence away from the coast might not be fully compensated by surface inflow, and upwelling on a slow generalized scale or on a more intense, but localized scale could also be generated.

However in summer (January) the current sets do not favour a similar divergence zone off NW Australia and the summer enrichment found by Kabanova (1968) off NW Australia seems unlikely to be associated with a local upwelling of this type. It is perhaps significant also that the two sites of maximum nutrient enrichment (A-B Figs. 8 and 9) are opposite large sounds. These could have very high production of organic matter over the extensive tidal flats and mangrove communities fringing them. In turn this organic matter could be the major stimulus to production at sites A and B (Figs. 8 and 9). During the SE Trades which blow seaward along the length of the sound or perhaps more frequently during the year by tidal movement alone, scouring of these sounds may contribute sufficient organic matter to the nearby coastal waters to stimulate their biological production.

6. *CONCLUSIONS*

The evidence so far available does not permit any conclusions about the oceanographical mechanism responsible for the biological enrichment in coastal waters off NW Australia. However a number of conclusions about the phenomena so far observed are important. These are:-

(a) Despite the clear evidence of biological enrichment off NW Australia, it is not possible to indicate its spatial and temporal extent.

(b) The nutrients (phosphates and silicates) and associated changes in vertical oceanographical structure during the year do not show any clear evidence of upwelling in this region.

(c) It is thought significant that the surface nutrients, consistently in all cruise data from the region, have exhibited maximum values in two coastal areas adjoining King Sound and York Sound to the north of 15°S.

7. *REFERENCES*

Calvert, S.E., and Price, N.B. (1971). Upwelling and nutrient regeneration in the Benguela Current October 1968. *Deep Sea Res.* **18**, 505-523.

Deutsches Hydrographisches Institut, Hamburg. (1960) Monatskarten für den Indischen Ocean. Deutsches Hydrographisches Institut Publ. Nr 242.

Great Britain. Admiralty. (1959) 'Australia Pilot'. Vol. 5. 5th edn. p.54. (Hydrographic Dep.: London).

Kabanova, G. (1968). Primary Production in the northern part of the Indian Ocean. *Oceanology* 8, 270.

Major, G.A., Dal Pont, G., Klye, J., and Newell, B. (1972). Laboratory techniques in marine chemistry; a manual. CSIRO Aust. Div. Fish. Oceanogr. Rep. 51.

Rochford, D.J. (1962). Hydrology of the Indian Ocean. II. The surface waters of the south east Indian Ocean and Arafura Sea in the spring and summer. *Aust. J. Mar. Freshwater Res.* 13, 227-251.

Rochford, D.J. (1975). Nutrient enrichment of East Australian coastal waters. II. Laurieton upwelling. *Aust. J. Mar. Freshwater Res.* 26, 233-243.

Schott, G. (1935). 'Geographie des Indischen und Stiller Ozeans.' (C. Boysin: Hamburg.)

Tranter, D.J., Kerr, J.C. (in press). Further studies of plankton ecosystems in the eastern Indian Ocean. III. Numerical abundance and biomass. *Aust. J. Mar. Freshwater Res.*

Wyrtki, K. (1961). Scientific results of marine investigations of the South China Sea and the Gulf of Thailand 1959-1961. NAGA Report Vol. 2.

Wyrtki, K. (1962). The upwelling in the region between Java and Australia during the south-east monsoon. *Aust. J. Mar. Freshwater Res.* 13, 217-225.

Wyrtki, K. (1971). 'Oceanographical Atlas of the International Indian Ocean Expedition.' (Nat. Sci. Foundation : Washington.)

TABLE 1

CSIRO Oceanographical cruises off NW Australia

Month	Cruise	Temp.	S‰	O_2	P	N
10	*Dm* 2/59	✓	✓	✓	✓	✓
9	*Dm* 2/60	✓	✓	✓	✓	✓
5	*Dm* 2/61	✓	✓	✓	✓	✓
7-8	*Dm* 3/61	✓	✓	✓	✓	✓
2-3	*Dm* 1/62	✓	✓	✓	✓	✓

TABLE 2

Average wind direction (1911-'57)

BROOME

	0900			1500		
	%SE	%S	%SW	%SE	%S	%SW
Jan.	8	10	26	3	3	18
Feb.	11	15	31	1	3	25
Mar.	25	10	13	7	7	18
April	39	10	2	20	16	17
May	42	11	1	22	21	16
June	42	7	6	32	21	14
July	44	10	3	23	22	20
Aug.	37	18	4	10	18	31
Sept.	36	21	11	5	15	33
Oct.	20	24	24	3	6	29
Nov.	14	16	23	1	6	19
Dec.	12	13	26	3	4	15

Underlined are percentages >30%

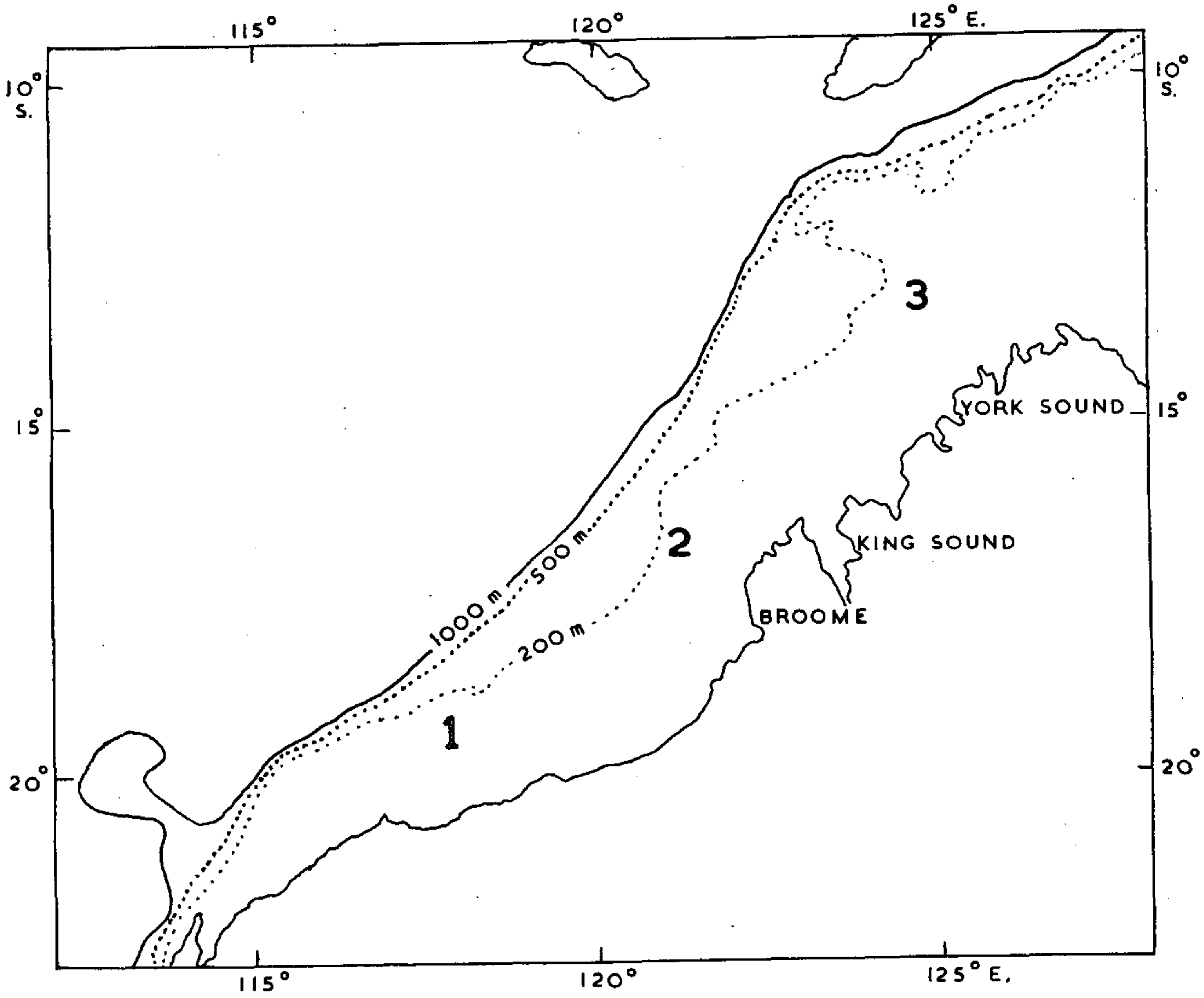

Fig. 1 Chart of the major features of the bottom topography of the Eastern Indian Ocean between NW Australia and Indonesia. (1), (2) and 3 indicate station location. Section 4(a).

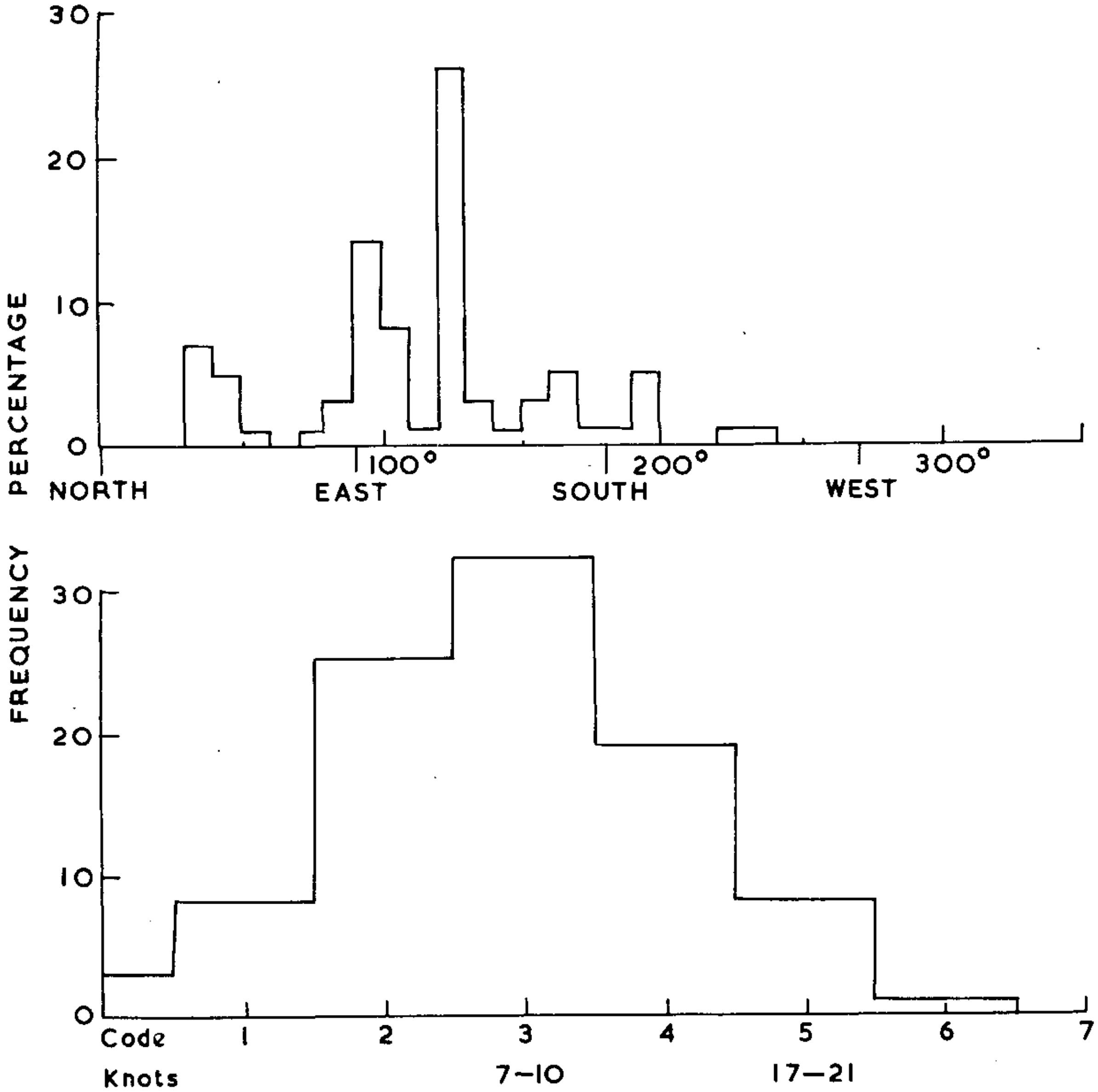

Fig. 2. Histograms of the percentage frequencies of wind directions and speeds during *Sprightly* cruise in August 1976.

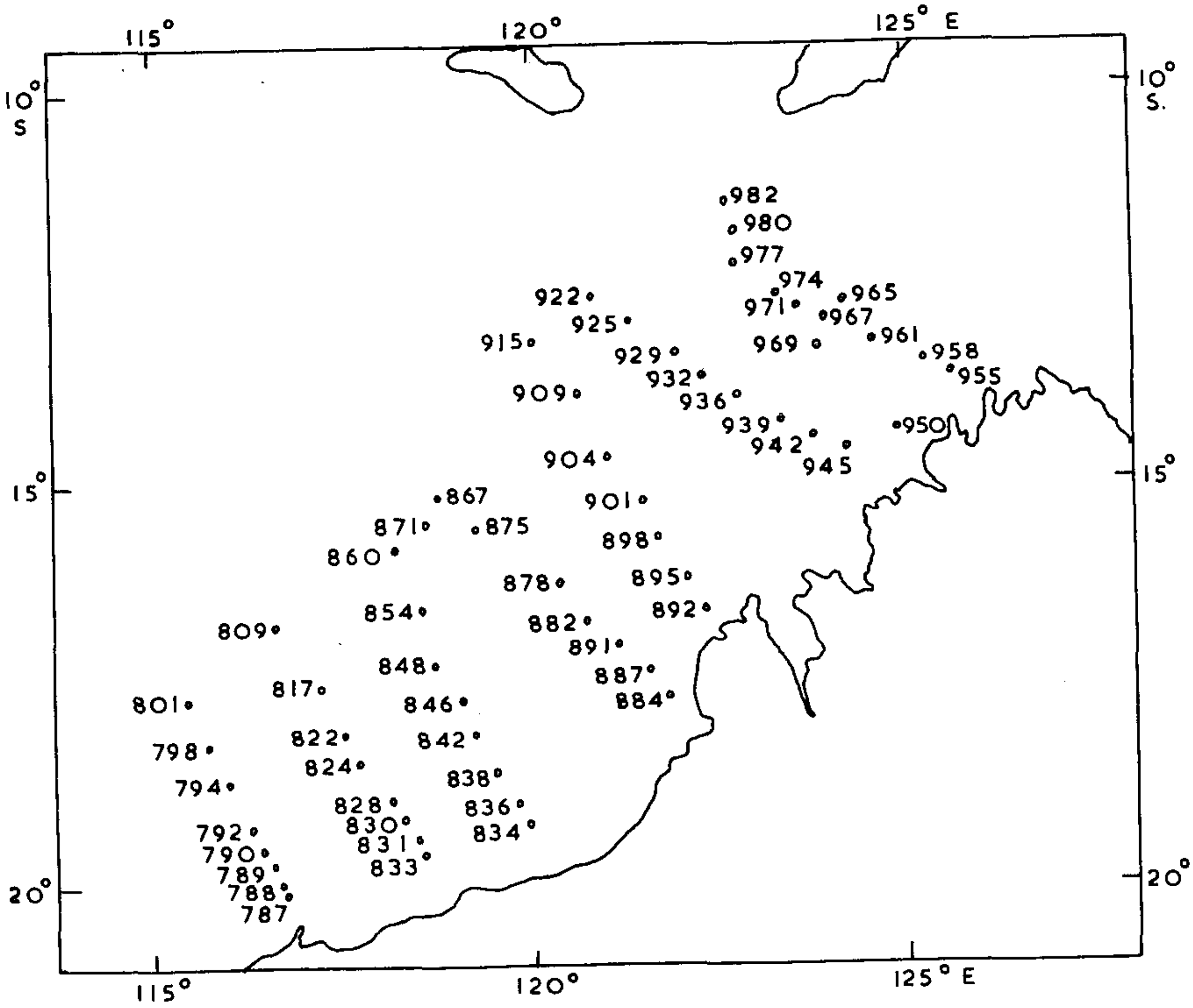

Fig. 3 Chart of station positions *Sprightly* cruise August 1976.

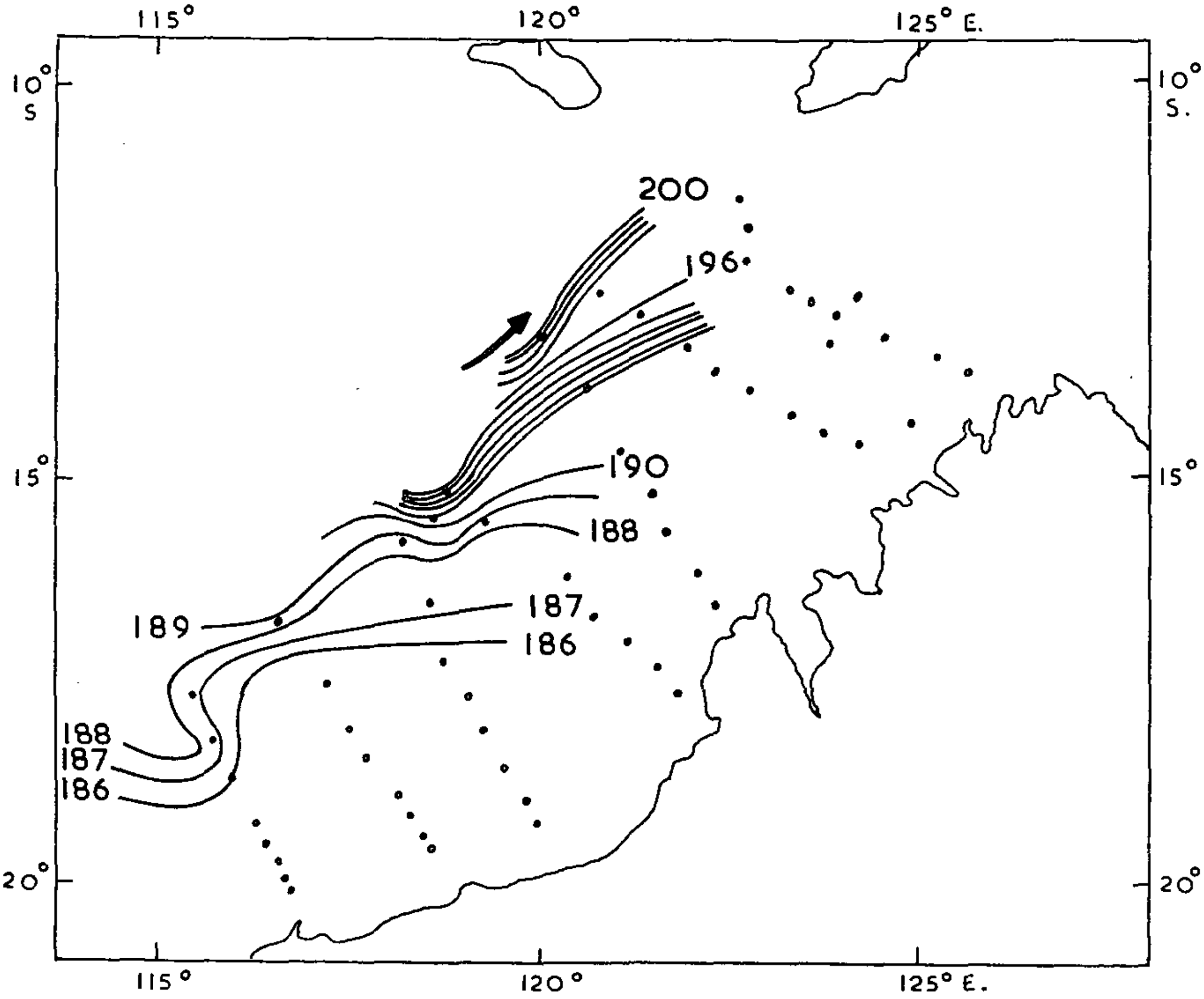

Fig. 4 Dynamic topography (dyn cm) of the sea surface relative to 1000 d.b. *Sprightly* cruise August 1976.

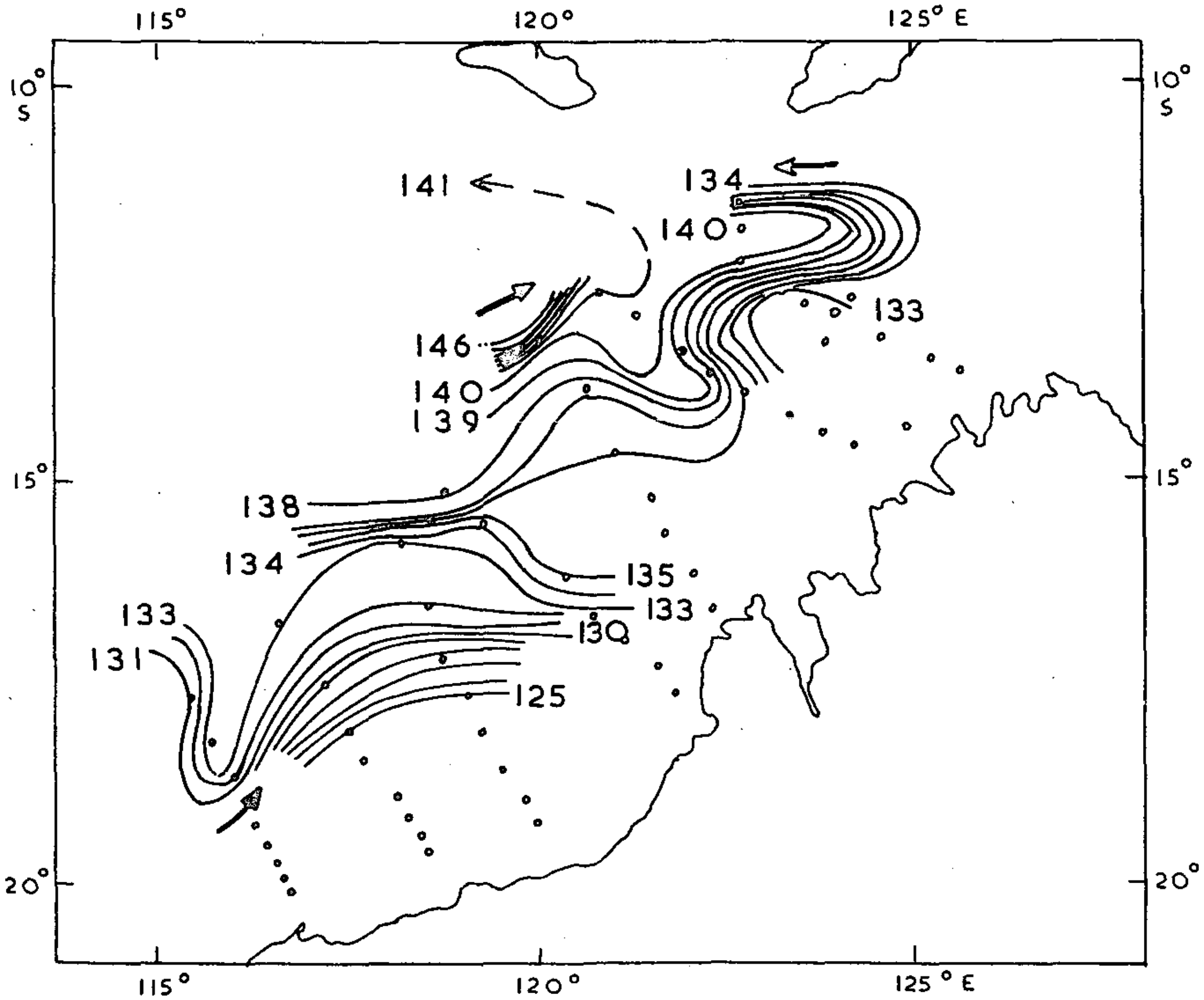

Fig. 5 Dynamic topography (dyn cm) of the sea surface relative to 500 d.b. *Sprightly* cruise August 1977.

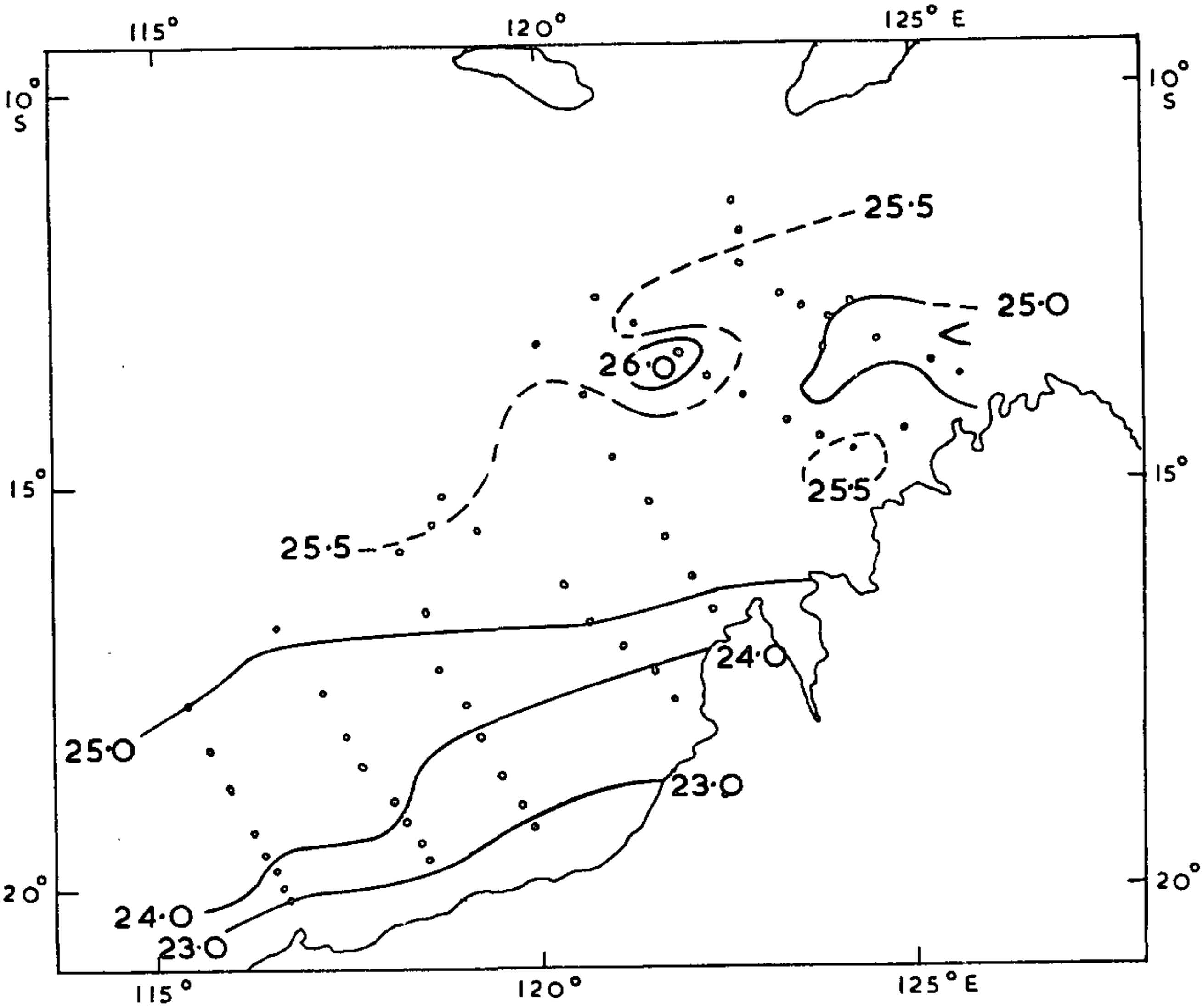

Fig. 6 Temperature (°C) of the sea surface *Sprightly* cruise August 1976.

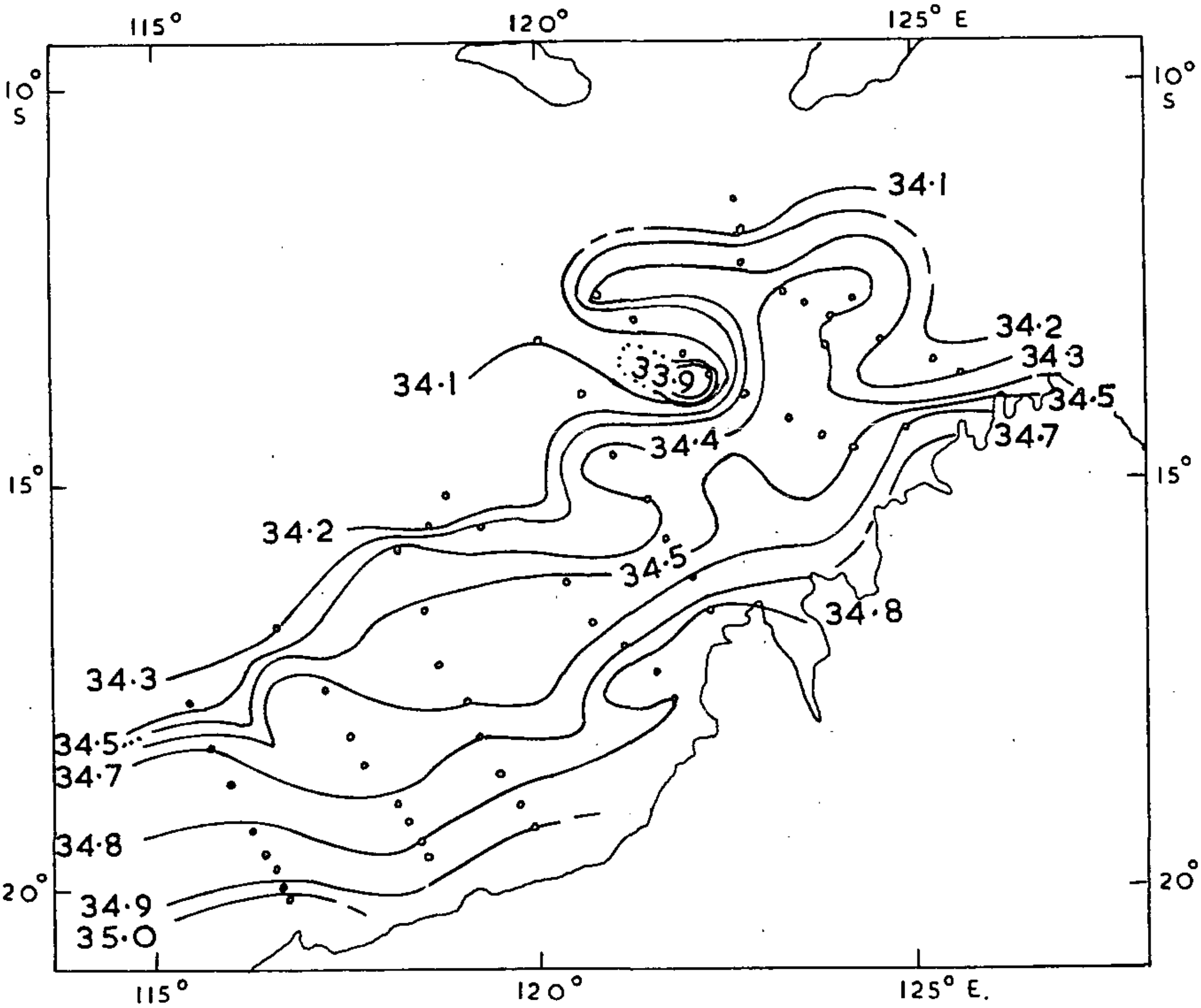

Fig. 7 Salinity (‰) of the sea surface *Sprightly* cruise August 1976.

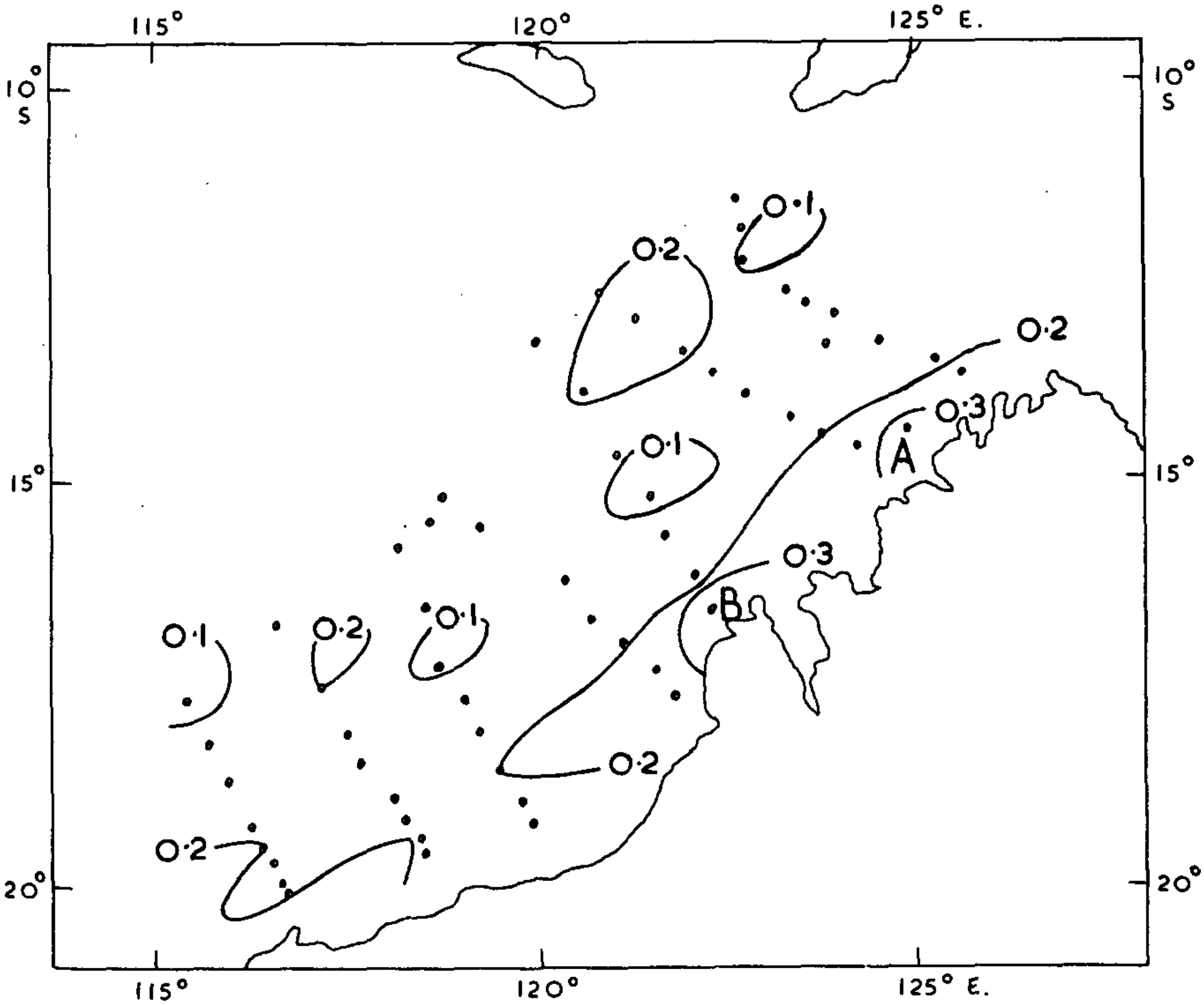

Fig. 8. Inorganic phosphate concentration (μgat/l.) at the sea surface *Sprightly* cruise August 1976.

A - B Coastal regions of maximum phosphate.

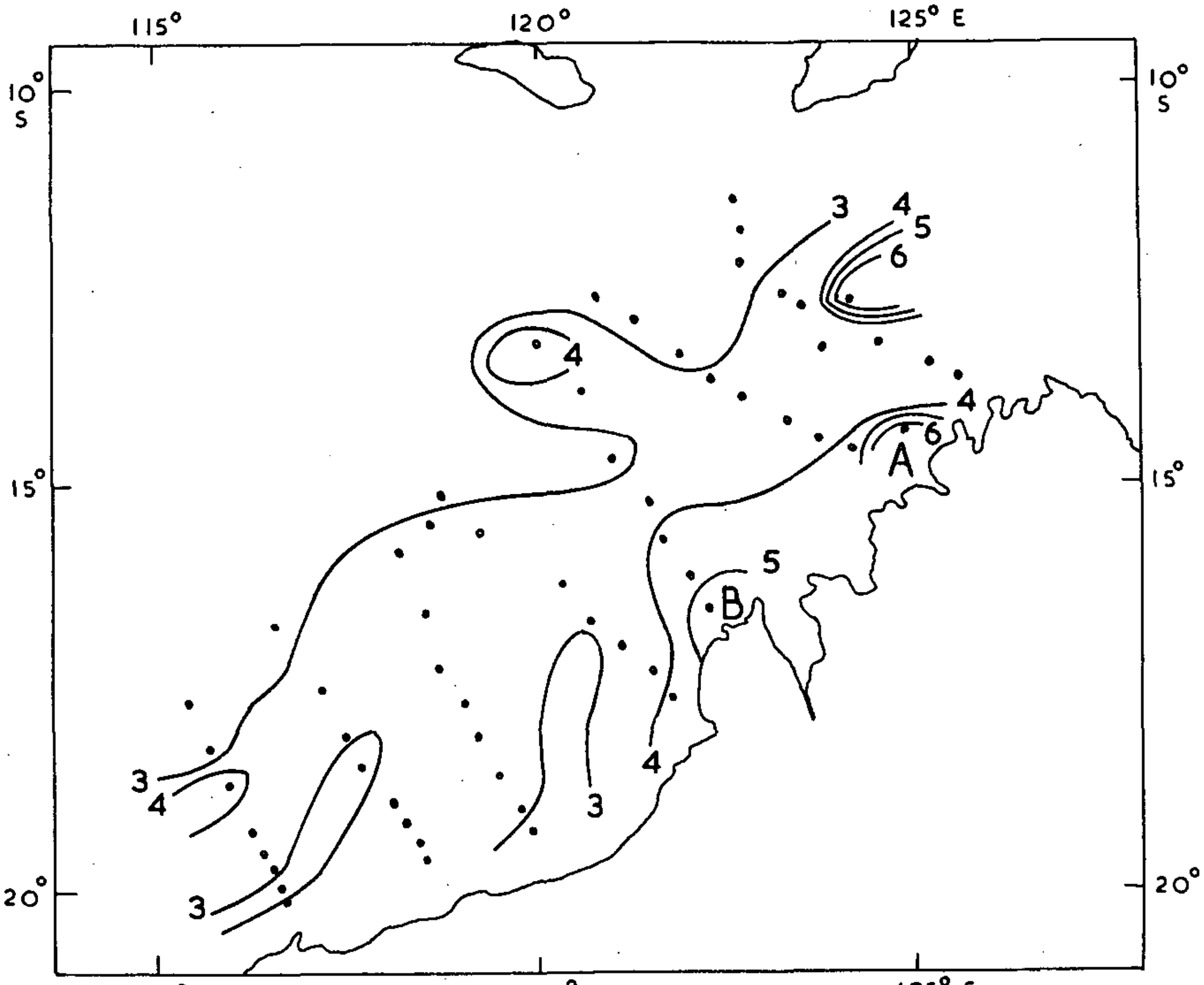

Fig. 9 Silicate silicon concentration (μgat/l.) at the sea surface *Sprightly* cruise August 1976.

A - B Coastal regions of maximum silicate.

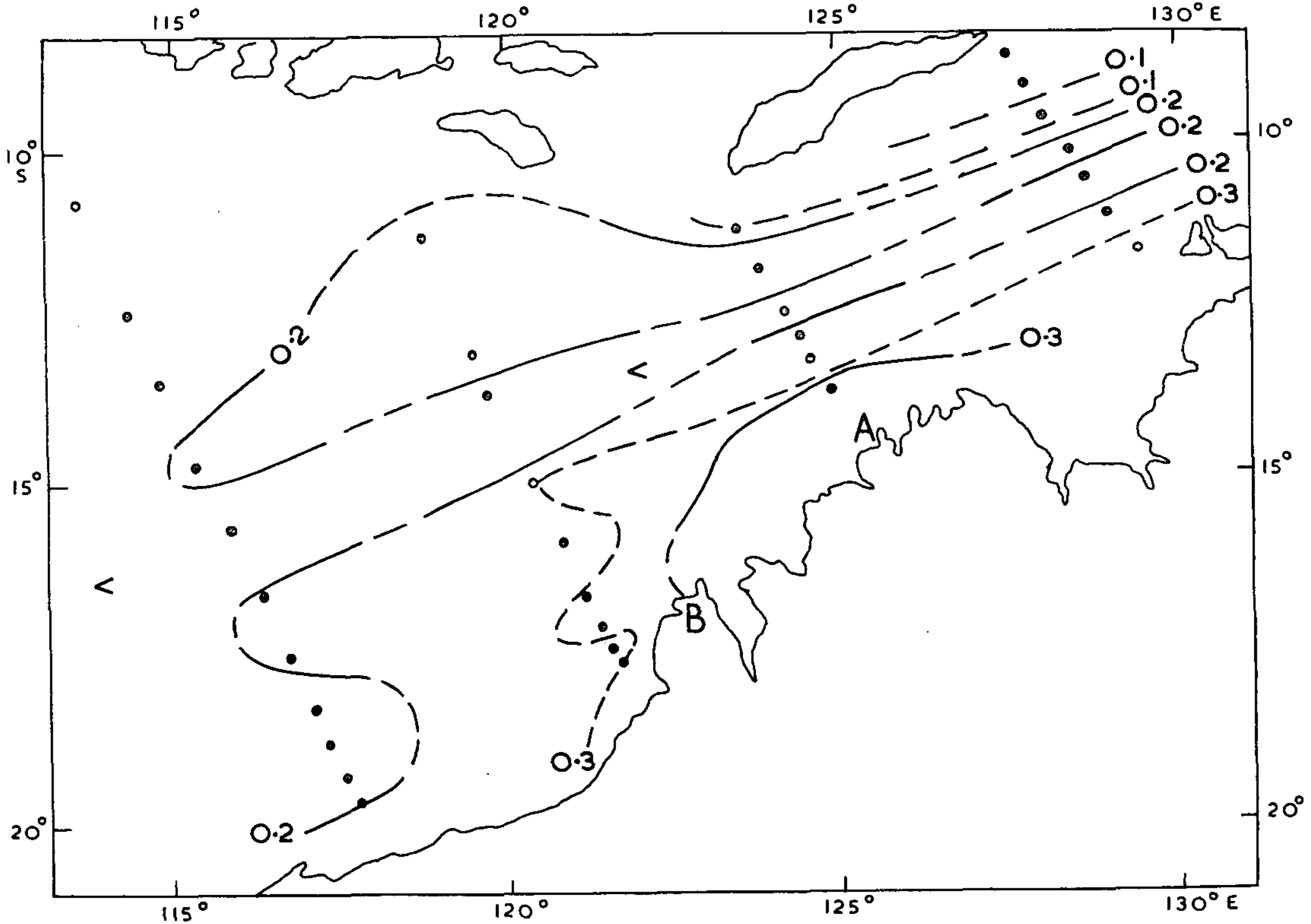

Fig. 10 Inorganic phosphate concentration (μgat/1.) at the sea surface *Diamantina* cruise 2/60 September 1960.

A - B Taken from Fig. 8.

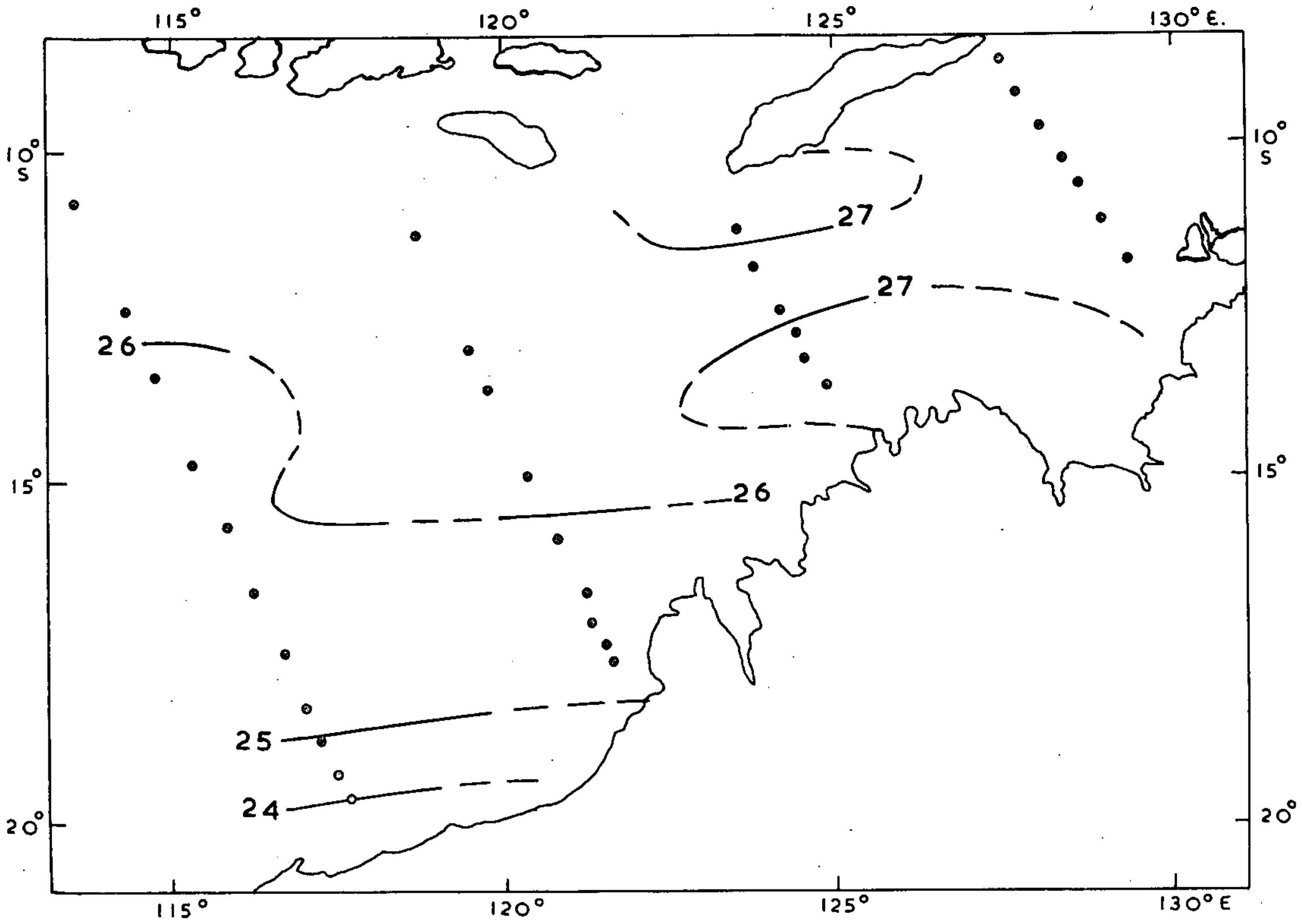

Fig. 11 Temperature (°C) of the sea surface *Diamantina* cruise 2/60, September 1960.

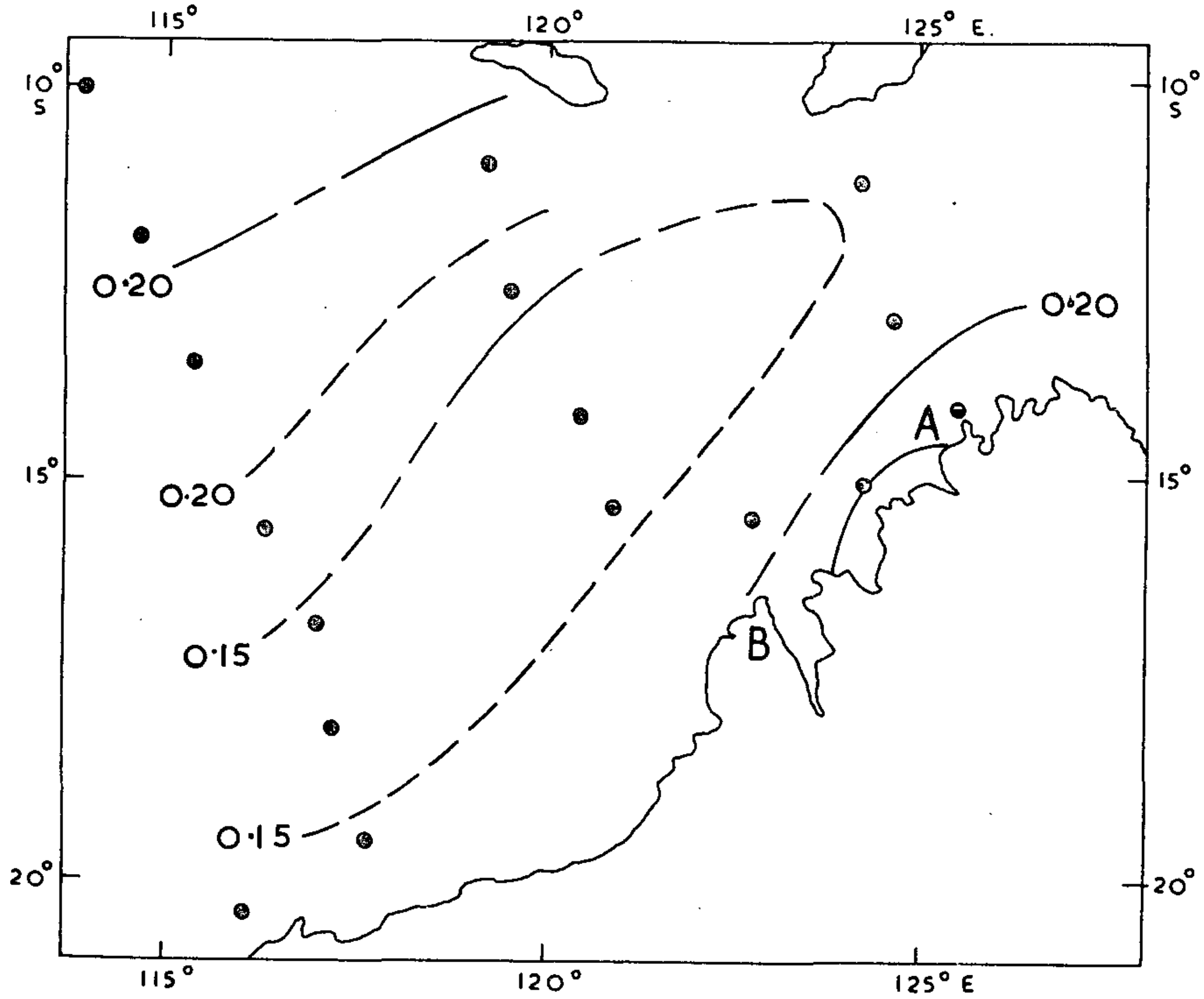

Fig. 12 Inorganic phosphate concentration (µgat/1.) at the sea surface *Diamantina* cruise 1/62 February - March 1962.

A - T Taken from Fig. 8.

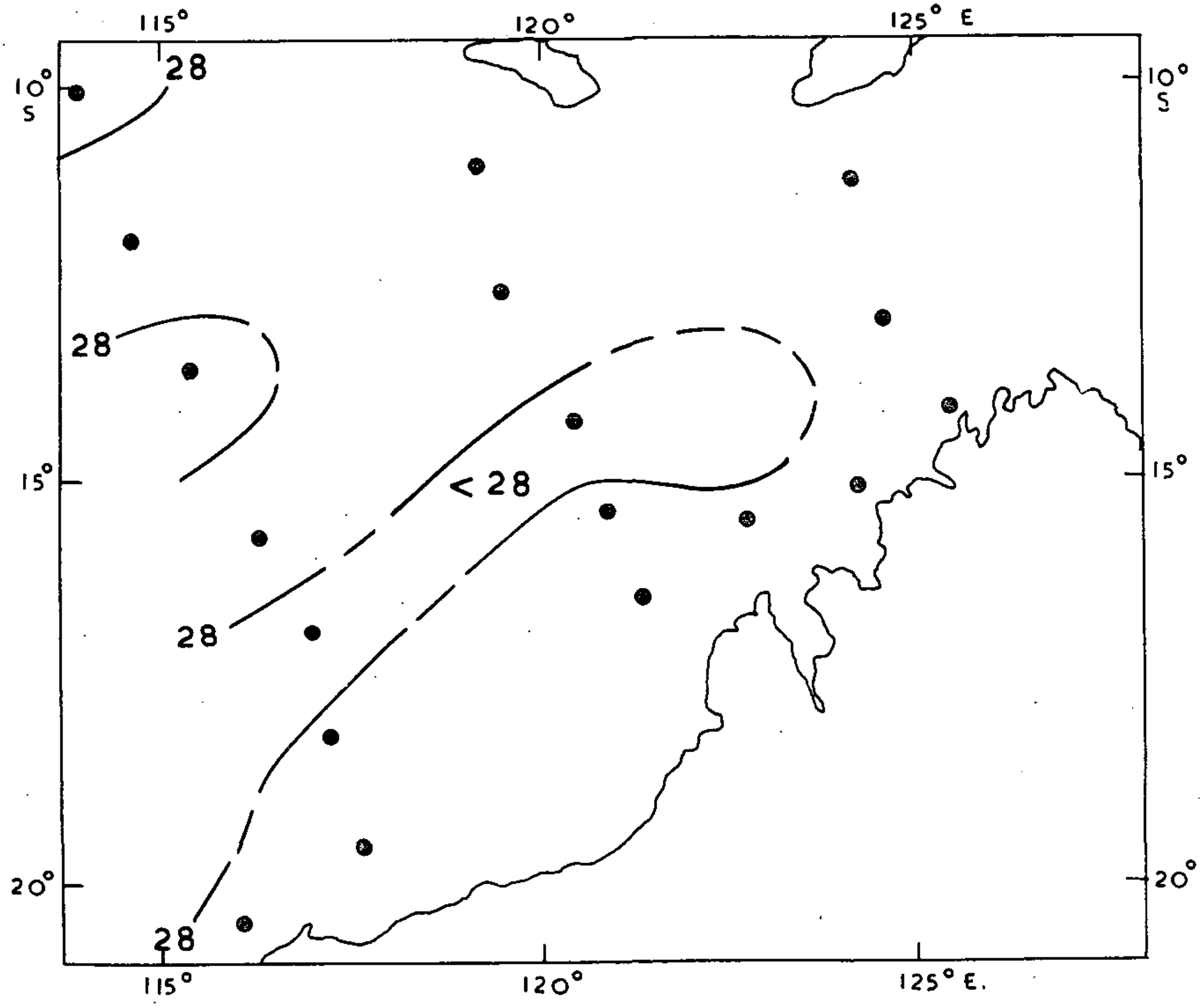

Fig. 13 Temperature (°C) of the sea surface *Diamantina* cruise 1/62 February-March 1962.

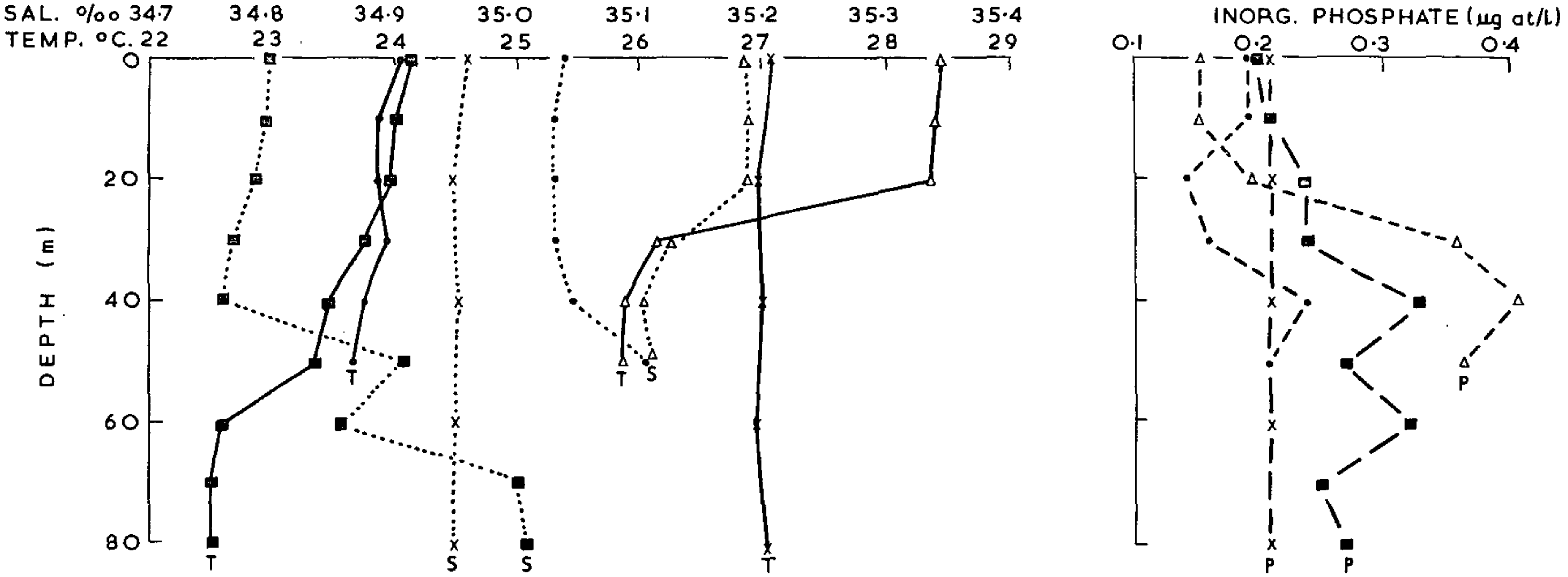

Fig. 14 Vertical profits of Temperature C, (T), Salinity ‰ (S), • Inorganic phosphate µgat/1. (P) at Position 1 (Fig. 1)

• Dm 312/60
x Dm 76/61
Δ Dm 3/62
Spr.830/76

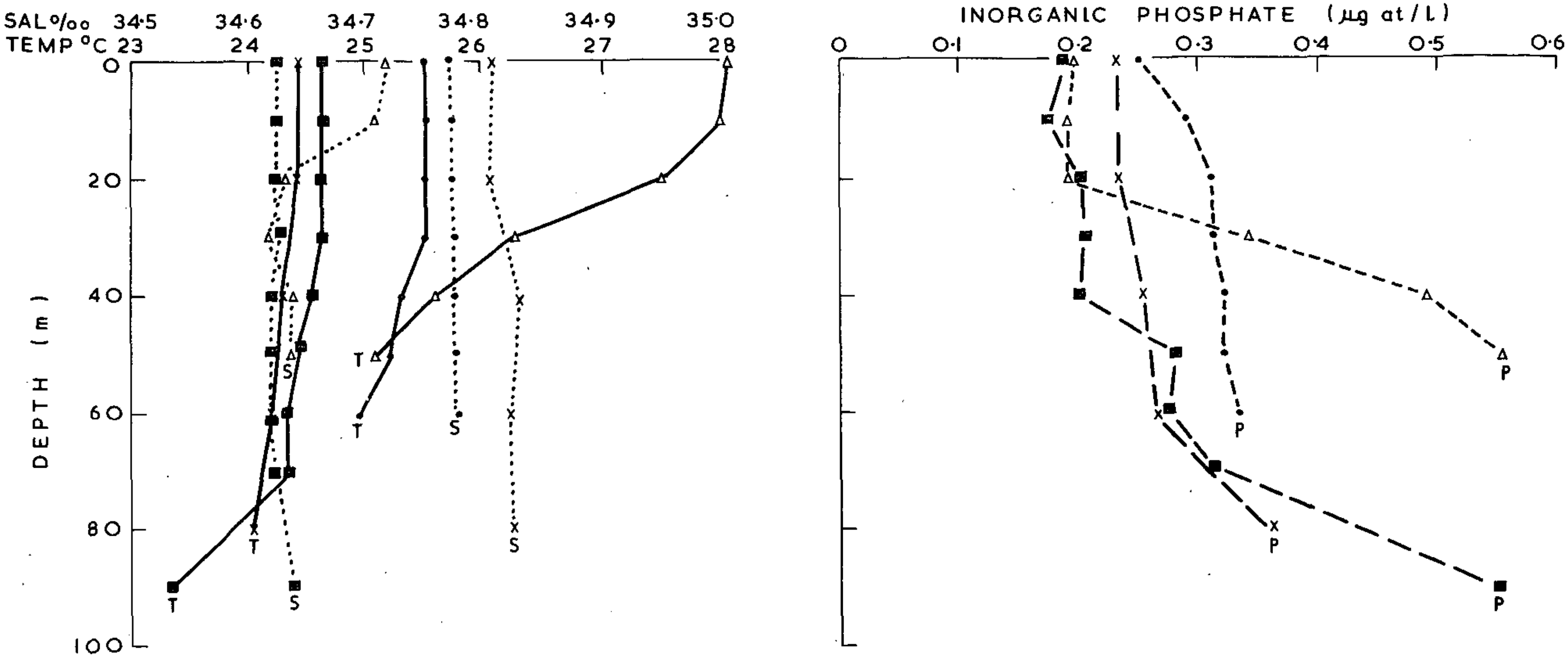

Fig. 15 Vertical profiles of Temperature °C (T), Salinity ‰ (S), inorganic phosphate µgat/1 (P) at Position 2 (Fig. 1)

o Dm 303/60
x Dm 175/61

Δ Dm 14/62
Spr 891/76

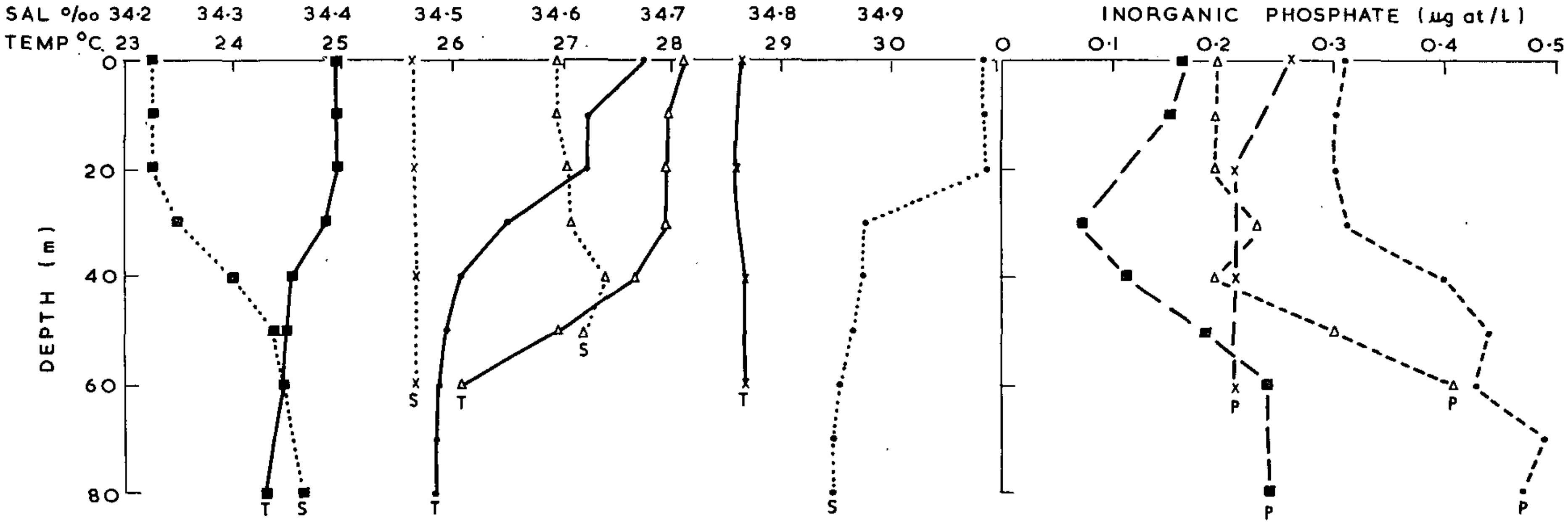

Fig. 16 Vertical profiles of Temperature °C (T), Salinity ‰ (S), inorganic phosphate µgat/l. (P) at Position 3 (Fig. 1)

o Dm 281/60
x Dm 64/61

Δ Dm 18/62
Spr 958/76

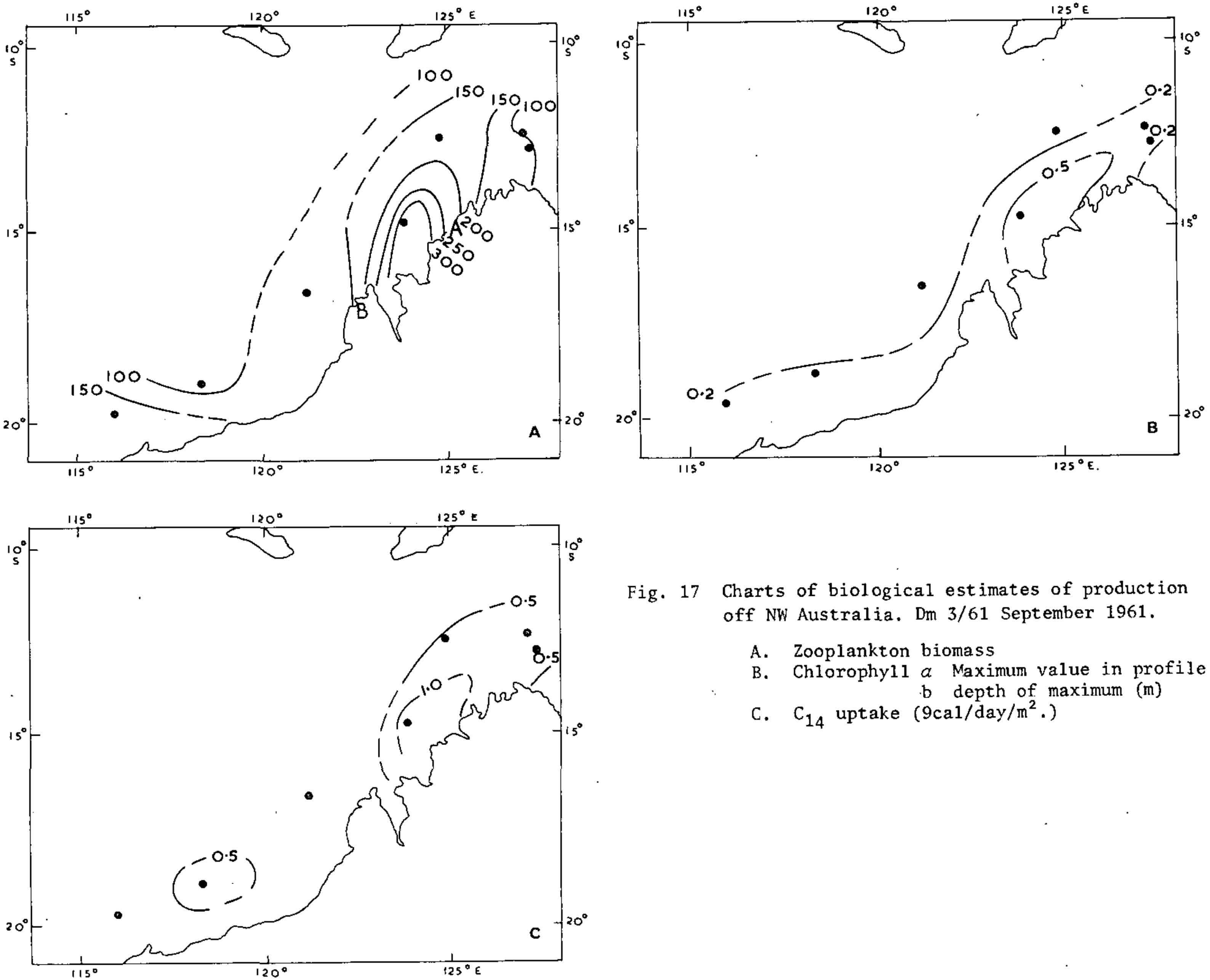

Fig. 17 Charts of biological estimates of production off NW Australia. Dm 3/61 September 1961.

A. Zooplankton biomass
B. Chlorophyll *a* Maximum value in profile
b depth of maximum (m)
C. C_{14} uptake (9cal/day/m^2.)