

A DESCRIPTIVE PHYSICAL ANALYSIS OF WATER
MOVEMENT IN THE SOUTH WEST INDIAN OCEAN
DURING THE NORTHEAST MONSOON SEASON

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A DESCRIPTIVE PHYSICAL ANALYSIS OF WATER
MOVEMENT IN THE SOUTH WEST INDIAN OCEAN
DURING THE NORTHEAST MONSOON SEASON

A thesis submitted in partial fulfilment of the
requirements for the degree of Master of Science in
Oceanography at the University of Cape Town

Signed by candidate

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ABSTRACT

The Agulhas Current is unique as a western boundary current in having as its source of surface water currents that are linked to the variable current regions of the North Indian Ocean. In which way the Agulhas Current derives its supply from these currents and how these currents interrelate, is very poorly understood. In an attempt to make a contribution to the understanding of this flow an isentropic analysis in depth on seven σ_t -surfaces for the whole South West Indian Ocean during the Northeast Monsoon season was carried out. This analysis was augmented by the calculation of the velocities according to the Witte-Margules equation on each σ_t -surface at ten selected vertical sections. In addition the detailed volume transport and the velocity structure for each vertical section were calculated. The results pointed to a significant variation in transport and velocity structure from year to year. The large scale circulation in depth of the ocean is described. It is found that the Agulhas Current derives its supply of water from different sources at different depths and that at depth a large measure of recirculation of Agulhas Current Water takes place. It is not thought that this has been reported before and these findings might be of importance to the understanding of the current system as a whole. A few innovations in the standard oceanographic methods are described and two computer programs to aid analyses are presented.

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CHAPTER I

INTRODUCTION

The water movement in the South West Indian Ocean is dominated by the anti-cyclonic sweep of the Agulhas System. The Agulhas Current itself is a western boundary current flowing close to the South African coast and has its surface origins in the waters of the South Equatorial Current from which a seasonally varying flow branches south to eventually become the Agulhas Current. The mechanism by which this occurs is only partially understood depending as it does on the interrelation between the East Madagascar, South Madagascar, West Madagascar, East African Coastal and Mozambique Currents. This interrelation is also subject to seasonal variation due to direction changes in the Monsoon Winds. The movement of subsurface and intermediate waters in this ocean has been shown to be related to the surface flow, but the extent of this relation is only partially understood.

For a long time scientific research on the problems of the Indian Ocean was hampered by the severe lack of physical observations. The International Indian Ocean Expedition has done much to improve this situation insofar as many more oceanographic stations are now available and the distribution of stations is more homogeneous, covering areas in which previously the deficiency was greatest.

The object of this thesis was to bring the full weight of all the newly accumulated data to bear on the unsolved problem of the relation between the different current branches that

constitute the Agulhas System, especially those parts that can be described as the source waters of the Agulhas Current. As mentioned above the deep flowing Agulhas Current is not only a surface phenomenon and the research thus had to be one that dealt with water flow in depth. Since the current systems are subject to variations of a seasonal and of a year-to-year nature which may determine the validity of using non-synoptic data, a further object of the research was to investigate this problem in so far as this is possible.

To this end one Monsoon Season was chosen as being most likely to produce intelligible results. A careful selection was made of the most suitable aspects of the currently accepted methods for large scale analysis and these were combined to investigate the water movements of this particular area. Eight σ_t -surfaces were chosen on which the parameters of depth, salinity, temperature, oxygen and phosphate content were plotted. To facilitate the interpretation of the contours the geostrophic velocity on these σ_t -surfaces at ten vertical sections was calculated. To increase the quantitative aspect of the investigation, the volume transport for each 0.20 σ_t -layer across the ten sections was calculated as well as the transport between each pair of stations constituting the lines of oceanographic stations used as vertical sections. To make possible the description of the probable flow of water without total reliance on combinations of non-synoptic data and to add some measure of three-dimensionality to the method, the distribution of σ_t , oxygen and velocity on the ten vertical sections was shown. The results obtained in this way were contrasted with and discussed in the light of previous and concurrent research.

During this investigation it was brought to my attention that the work being done by Prof. Wyrski and Mr. Duncan at the University of Hawaii was of a closely similar nature, but on closer examination it seemed clear that although there was a large measure of overlapping, most of the work would be of a complementary nature towards the same end.

CHAPTER II

REVIEW OF PREVIOUS RESEARCH

2.1 INTRODUCTION

The Indian Oceans uniqueness as a world ocean is due to two interrelated facts, namely the enclosure of the ocean in the north by a land mass, preventing exchange of water masses with the Arctic Ocean, and a wind regime which reverses twice a year. The resulting change in the surface current system was already known by the ninth century (Aleem 1967). As knowledge of the oceans increased, these changing current systems became better known, so that by 1862 with the publication of Mühry's *Klimatologische Übersicht der Erde* the current systems of the Indian Ocean were as well known as those of other oceans. At the end of the nineteenth century and the beginning of the twentieth century science started taking an interest in the exploration of the seas (Wüst 1964) and some of the first deep ocean cruises visited the Indian Ocean. Before World War II admirable use was made of the data available from these cruises and numerous publications appeared (Michaelis 1923, Paech 1926, Möller 1929, Schott 1935; to name but a few) in which the gross physical structure of the ocean was described. After the war research was spasmodic and largely uncorrelated. In 1960 the International Indian Ocean Expedition was launched (Wüst 1960, Highley 1968, - 1965) to increase substantially the knowledge and understanding of this ocean and to this end encouraged a large number of oceanographic vessels to make synoptic observations over a large area.

The research on the Indian Ocean thus falls into three phases: a time of exploration with the resulting gain in knowledge of the large scale structure of currents and water masses with an occasional attempt to justify their behaviour by physical laws; a time of limited and piecemeal studies of smaller areas and current systems and lastly a time in which an attempt is being made to correlate the available data and to relate the various currents and wind systems to one another.

2.2 REVIEW OF EARLY WORK

The South West Indian Ocean received its first modern scientific attention when ships on the now famous exploratory cruises occupied oceanographic stations in it. Amongst these were the Challenger 1873-6, the Gazelle 1874-6, the Enterprize 1883-5, the Egeria 1887-99, the Valdivia 1898-9, the Gauss 1902-3, the Sealark 1905 and the Planet 1906. These cruises (- 1884, - 1888, - 1888, — 1902, — 1926, — 1926, - 1898, - 1909) hoped to extend the existing knowledge from the surface layers to the deeper waters and to correlate the accepted surface currents with the existing fields of temperature, salinity and density.

In reality the knowledge of the surface currents at this time was fairly good depending as it did on analysis of ships' drift. The first publication of this sort was Rennell's Chart of the Bank and Current of Cape Lagullas (Rennell 1778), a remarkable work for its time later to be included in the book "An investigation of the Currents of the Atlantic Ocean and of those which prevail between the Indian Ocean and the

Atlantic" (Rennell 1832). In this work the overall current structure from Madagascar to Cape Agulhas is quite clear. The Mozambique Current and the South Equatorial Current form the sources of the Agulhas Current and the Agulhas Return Flow is given as the dominant continuity flow south of the Agulhas Bank.

Publication of this type with quite variable significance followed, but the painstaking work by the Koninklijk Nederlandsch Meteorologisch Instituut at de Bilt (- 1911, - 1913, - 1914, - 1915) round about the turn of the century established the current patterns quite clearly. Further work on the drift of ships up to the present has refined, but not significantly altered, our conception of the surface currents in the South West Indian Ocean.

The first of the big exploratory cruises to extend this knowledge scientifically was that of the Novara in 1857-9 which touched at Cape Town and from there sailed more or less along the latitude 40°S to touch at St. Paul and sail north to Ceylon. The world cruise of the Challenger followed in 1872, covering the Indian Ocean south of 40°S only. A wide variety of oceanographic parameters were measured and pioneering biological research done. The German ship Gazelle working at the same time, did not do any biological work, but covered the Indian Ocean more extensively, going from Cape Town to Kerguelen, from there to Mauritius and circling back via 38°S to Australia. She was followed in 1899 by the German steamship the Valdivia which covered large parts of the North Indian Ocean, to be followed in turn by the Planet in 1906 and the Möwe in 1913.

The Planet cruise was the first in this ocean during which

Comore Islands stretching to nearly 20°S and south of this a cyclonic circulation of water from the West Madagascar Current flowing across the Channel and joining the Mozambique Current. This, in detail, was the general circulation pattern for the southern summer as understood at this time, most of which is still relevant today (see fig. 3.1).

Trying to relate the surface isotherms with his current analysis, Michaelis (1923) found that the warm Agulhas Current was clearly supported by the displacement of the isotherms to the south. In the Mozambique Channel no correlation at all was found. This he assumed was due to lack of data.

This was work of a rather fundamental nature and other research at this time on surface currents added little to it. The painstaking analysis of Barlow for instance (1931, 1933, 1935) at the Marine Division of the British Meteorological Office made only a few small, but important, additions to our knowledge. He found, using the accumulated ships' drift from 1910-34, that the South Equatorial Current flows between latitudes 8°S and 15°S which carries it straight past Cape d'Ambre. Of a dividing of the current at Mauritius he found no sign and in fact states that there is no evidence of a continuous current throughout the year from Mauritius to Durban, past the south of Madagascar. A most interesting analysis by Barlow of the annual variation in velocity of North and South components of the Agulhas Current, the Mozambique Current and the East African Coastal Current, shows the seasonal variations of the Agulhas Current and the nearly direct correlation between it and the Mozambique Current. It also shows an inverse relationship between the strength of the Agulhas

Current and the East African Coastal Current. The combined results of Barlow's work were published in 1939 in the Meteorological Office's Indian Ocean Currents. He did not attempt to make deductions on the scale of Michaelis although much of his work is of an interpretive nature. Keeton (1935) also of the Marine Division, attempted to supplement the work of Barlow by an interpretation of the surface isotherms but was only able to confirm the larger warm currents such as the Mozambique and the Agulhas.

The use made of isotherms to support the work on surface currents was carried out much more successfully by Paech (1926). He attempted to show the variation in surface currents from month to month for the whole year in the area bounded by 0°S to 30°S and 30°E to 62°E . He also made an attempt to correlate the bathymetry of the ocean bed and the currents. In both of these he showed some success. He believed that during January the South Equatorial Current would start to disintegrate, part of it flowing north, after it had passed the shallow ridge south of the Seychelles. Only in passing Cape d'Ambre would it intensify again. For the current flow southwards along the east coast of Madagascar and past Cape St. Marie he showed a very definite set of warm tongues for January which seem to support this flow, but in contrast to Michaelis he did not find any continuous flow from here northwards along the west coast of Madagascar during this month. The Mozambique current is however, well supported by the interpretation of the isotherms at all times. In the Mozambique Channel he found two circulation patterns the border between them lying at a latitude of about 20°S . The penetration of

the East Madagascar Current into the Mozambique Channel thus seems to vary greatly from month to month.

The results of the Gauss expedition in the Indian Ocean were used by Schott (1926) to investigate the deeper water movement. He dealt extensively with the probable trustworthiness of the data, the areas of formation of the various water masses and the depths at which they are to be expected. He found that, certain factors of secondary importance being omitted, the deep water circulation in the Indian and Atlantic Oceans show great similarities and, drawing a section along 60° E found the core of a salinity maximum (North Indian) at 2500 m.

These studies were followed in 1929 by the all-embracing work of Möller on *Die Zirkulation des Indischen Ozeans*, the first major work making use of all the exploratory cruises that had gone before. Making use of T/S diagrams, Möller divided the Indian Ocean into sixteen areas with characteristic water masses. Six vertical sections crossing the Indian Ocean were used to investigate the water masses and their probable movement. The first section running from the Gulf of Aden to the latitude of Port Elizabeth along the African Coast and through the Mozambique Channel shows in a quite unambiguous way the formation and resulting flow of the Antarctic Intermediate Water and the Red Sea Water lying between 500 and 1000 m. The low salinity Antarctic Intermediate Water shows a tendency to override the high salinity Red Sea Water but on the whole the limit of their individual influence is at the northern end of the Mozambique Channel. A second section running from Ceylon in a south-southwest direction shows a much limited flow of

Red Sea Water and although its influence at 2500 m may be traced to 45°S ; at 1000 m its influence is restricted to north of 8°S . Warm, saline water in both cases form a covering layer of approximately 500 m. Interpreting the T/S diagrams and the isotherms and isohalines on her sections, Möller attempted to deduce the circulation patterns for the two monsoon seasons.

The meridional circulation of the surface and intermediate layers in the western part of the ocean she considered as consisting of the following: in the surface layers (0 to 800 m) there are a series of convergences and divergences including a "Subpolar Convergence" at 50°S coinciding with the West Wind Drift, "Subtropical Convergence" nearly coinciding with the South Equatorial Current and a "Tropical Convergence" which coincides with the Equatorial Counter Current. Between these are divergences. The flow of the Antarctic Intermediate and Red Sea Water lies below this and flows in the way described before. But Möller avoided a clear distinction between surface and intermediate flow since, due to the convergences, these are so interrelated. Since the surface water movements are influenced by the wind regimes she dealt with these extensively and found that they are closely correlated. The surface currents she found dominated by the set of convergences and divergences, the main currents lying on lines of convergence of water.

The movement of the deeper currents she found to be meridional except near the equator where a flow from east to west is to be expected. This is true for "Subtropical Undercurrent" as well as the Antarctic Intermediate Current. The

North Indian Deep Current flows southeast. The variation due to changing wind regimes does not have any influence except in the subtropical covering layer. Due to variations in temperature and salinity she expected an intenser flow in the Intermediate Waters in May and September than in November to May.

This comprehensive work of Möller's has been described thoroughly because it lies as foundation, consciously or unconsciously, to much of the piece-meal work that has been done at a much later stage.

After World War I another series of deep-ocean cruises were undertaken including those of the Meteor 1925-6, Discovery 1926-7, William Scoresby 1929, Dana 1928-30 and Discovery II in 1930. These threw some new light on some of the problems especially since new measuring techniques for salinity and temperature had considerably increased the accuracy the need for which was felt particularly in deeper water. Thomson (1933) showed that Möller's (1929) description of the North Indian Deep Water continuing at a depth of 2000 m. to 3000 m. to the southern Subtropics could not be supported by the new salinity and temperature data from the Dana cruise and that the influence of this water terminates altogether at the equator.

In 1935 Thomsen carried his research even further and discussed at length the origins and movements of some of the major characteristic water-masses of the Indian Ocean. Red-Sea Water originates in the Red Sea where it has a salinity of 40‰ and a temperature of 23°C and flows into the Indian Ocean at about 800 m. It mixes with surrounding water and very soon forms only about 10% of the watermass that continues

as the salinity maximum ($35.35^{\circ}/\text{oo}$) and oxygen minimum (0.62 ml/l) at 9.8°C . The influence of this water is restricted to the western side of the ocean and does not extend further south than the northern part of the Mozambique Channel. Thomsen again disclaims any analogy to the southflowing deep current of the Atlantic in the Indian Ocean. Antarctic Intermediate Water ($34.20^{\circ}/\text{oo}$ and 5.0°C) is formed in the antarctic and subantarctic zones and forms a salinity minimum at about 1000 m. He traces this water in its northern movement across the ocean and finds that it is being diluted rapidly as it passes through the Mozambique Channel, more so than the water passing east of Madagascar. The depth of the salinity minimum decreases swiftly after it has passed Madagascar showing its rising up over the Red Sea Water. Other water types are the Southern Subtropical Water ($35.70^{\circ}/\text{oo}$ and 16°C) found in the Southwestern Indian Ocean and the Northern Subtropical Water ($35.90^{\circ}/\text{oo}$ and 28.5°C) in the Northwestern Indian Ocean.

In this connection, namely the source regions of the water types, Deacon (1937) brought the weight of two Discovery cruises as well as other accumulated data to bear on the question of the formation of water masses in the Southern Ocean. He does find evidence for a warm deep current between 2000 and 3000 m. flowing south, contradicting Thomsen (1935), although this current does not necessarily coincide with the salinity maximum.

This first period of oceanwide analysis of the data available for the first two sets of exploratory cruises was culminated by the exhaustive work of Schott (1935), *Geografie des Indischen und Stillen Ozeans*. It would be impossible to

deal here with his complete exposition of the meteorological, oceanographic and historical knowledge up to that date. His surface temperatures show the main features of the Agulhas and Somali Currents. Although the surface salinities show up the low salinity band of the South Equatorial Current and the Mozambique Current it does not show any direct connection between them. The general surface current picture does not present any radical change in the conception of the currents. The currents passing Cape St. Marie and Cape de'Ambre are depicted as narrow and intense and no continuous northward flow off West Madagascar is shown. Parts of the Equatorial Counter Current turn south and impinge on the South Equatorial Current. Isotherms at 200 m show very little except the Agulhas Current at 35°S latitude. At 400 m the same holds true except for the clear cold tongue of the South Equatorial Current. Furthermore a clear and comprehensive summary of previous work is given.

Sverdrup et al. (1942) summarised the knowledge up to that time stating that the annual variations in the anti-cyclonic systems is greater than in the North and South Atlantic. He decided that subsurface currents below the tropical discontinuity in the Northern Indian Ocean are probably sluggish, resulting in the low oxygen values obtained. The Antarctic Intermediate Water loses its characteristics sooner than in any of the other oceans.

Latterly fewer researchers have attempted to deal with the Indian Ocean in this way, treating it as a whole. Lacombe (1951) used the geostrophic interpretation to deal with the ocean-wide circulation finding a few new and interesting

phenomena. He found that the bottom topography had a marked effect on the currents and was struck by the great northward extent of the return flow of the Agulhas Current. These conclusions were supported by Le Pichon (1960).

2.3 RESEARCH ON WATER MASSES AND DEEP WATER MOVEMENT

When the large scale phenomena of the Indian Ocean were once described, various problems appeared which were now dealt with on their own. One of these was the formation of the deeper water masses and their spreading through the ocean. In reply to Thomsen (1933), Möller (1933) defended her conception of the flow of the North Indian Subtropical Water below the Antarctic Intermediate Water reaching to nearly 20°S as put forward by her in 1929. She found that new information that had come to light shows that the North Indian Water, including the Red Sea Water, is restricted to the western side of the ocean but otherwise felt that her basic model remained intact. Schott (1935) was not able to contribute to this argument since he made use of mostly the same data as Möller.

A line of Discovery stations stretching from latitude 40°S to 10°N running parallel to the African coast and passing through the Mozambique Channel was used by Clowes & Deacon (1935) to throw new light on this question. They decided that the flow as represented by their data is a compromise between Möller's and Thomsen's. The high salinity water found below 2000 m south of 25°S is due to Atlantic Deep Water circling eastwards around Cape Agulhas and not due to North Indian Deep Water. The influence of the North Indian Deep

Water does not terminate suddenly at latitude 20°S , but the oxygen distribution showed quite clearly that the North Indian Deep Water does reach latitudes of 35°S , where it is sandwiched between the Antarctic Intermediate and the Atlantic Deep Water. They point out very strongly that, due to changes in conditions at its origin, the volume and salinity of the North Indian Deep Current are subject to large variation.

Dietrich (1935) analysed the velocity structure, temperature and salinity structure of the southern part of the Agulhas Current to a depth of 2000 m. He showed the effects of the Agulhas Current to these depths and pointed out that, due to the dissipation of the Agulhas into large scale semi-stationary eddies, the influence of the Agulhas Current Return Flow is of minor importance in the South West Indian Ocean.

By this time Deacon (1937,1945) established the origin and probable mode of formation of the Antarctic Intermediate Water and Wüst (1935,1938) had dealt with the deeper currents and given the first comprehensive description of the water-masses at depth in all oceans.

Sverdrup et al. combined most of the existing knowledge (1942) defining the water masses in the Indian Ocean as consisting of a thin surface layer, the subsurface layers (geographically determined) of the Indian Ocean Central Water and the Indian Ocean Equatorial Water, the intermediate waters of the Antarctic Intermediate Water and the Red Sea Water and below this the Deep Water. The boundary between the Central and Equatorial Water was not defined. He felt that the out-flow of Red Sea Water is intermittent with a seasonal and probable a year-to-year variation. The data used by Möller (1929) he feels is subject to systematic error.

Some very interesting features were described by Tchernia (1951) as a result of the cruises of the Charcot through ocean areas in which very few stations had been occupied up to that time. In a large measure he was able to substantiate Schott's (1935) sections. He also found that in the eastern Indian Ocean there exists a definite vertical limit to the Antarctic Intermediate Water whereas in the western Indian Ocean the water shows a slow and progressive rising to the surface. In another publication in 1951 Tchernia, considering the influence of Arabian Sea Water, stated that it is felt no further than 20°S in the Mozambique Channel. In 1958 Tchernia et al. decided that a new deep water mass might be formed as the hydrological barrier between Antarctic Intermediate Water and Arabian Sea Water which would then flow southwards.

Ishino (1958) described the section done from Mauritius to Durban by the Umitaka Maru in which there is an indication of the Agulhas and its return flow but the large distance between stations prevents distinct features from being evident.

The flow at depth was dealt with in detail by Muromtsev (1959). His scale, however, is of such a nature that no new details emerge. According to his current directions the north-east component of the Agulhas Return Flow only appears below 300 m. Any northerly flow only occurs at 2000 m and has disappeared by 2500 m when most of the meridional flow is southward.

Using meridional sections Menaché (1961) showed a region of tremendous upwelling of water reaching from 1000 to 200 m at the location where the Mozambique Current, bending back on itself, and the flow south of Cape St. Marie pass one another,

but in similar sections of the ORSOM I campaign further east no such upwelling is noticeable above 1000 m. The Lacerda Cruise (— 1964) shows nothing of this nature either.

Latterly, as more data and, in particular, deep stations data has become available, more work has been done on the deeper layers and their movement. Le Pichon (1960) dealt extensively with the deep water circulation in the Southwest Indian Ocean. He found that water above 2000 m is always influenced by the deep currents like the Agulhas. For instance, he found that Arabian Sea Water is entrained by the Agulhas Gyre and that the minimum oxygen layer at this depth shows clearly the path of the Agulhas Current. He attached much importance to the bottom topography and found a northward flowing "western boundary current" below 2000, 2500m and a southward flowing below this, forming a level of no motion between 2000 m and 2500 m. Flow of Atlantic Deep Water is stopped between Madagascar and the mainland, forced back and flows eastwards south of the Madagascar Ridge. He felt that the most important question not solved at this time was the existence of seasonal and annual changes in the deep water circulation.

Zaklinskii (1963) investigated the deep circulation of water making use of Mamayev's (1955) theory and determination of the level of no motion in the Indian Ocean (1960). In this way he found, at 1500 m, a general west-east flow away from Madagascar, a cyclonic eddy in the northern mouth of the Mozambique Channel and a large anticyclonic eddy northeast of Madagascar. At 2000 m the west-east flow remains, but the two eddies are reversed in direction. He felt that the bottom relief has a considerable effect on this circulation.

In 1968 Shcherbinin again revived the controversy about the relative horizontal extent of the North Indian and Antarctic Intermediate Waters making use of all the available data up to that time. Dealing with the Antarctic Intermediate Water he decided that its influence is terminated at about 5°N by a transitional zone of Banda Water (Rochford 1966) flowing westwards. He drew topographic maps showing the vertical extent of, what he calls, the Antarctic Deep Circumpolar Water Mass, and interpreting these, showed how the Agulhas gyre is visible in the upper boundary of this water. As the source of the North Indian Deep Waters he specified the Arabian Sea and the Gulfs of Aden and Oman, including the inflow of Red Sea and Persian Gulf water into these. Depending on the relative concentrations of these, he divided the North Indian Ocean into 4 characteristic areas.

An analysis of the Southern Ocean using the isentropic method was made by Taft (1963) on the 26.81, 27.07, 27.28 and 27.49 σ_t -surfaces. This included the Indian Ocean. He came to the conclusion that Banda Sea Water penetrates the South Indian Ocean as a salinity minimum at 10°S that extends westward to 60°E . He also found that, on all these surfaces, low-oxygen highly saline water penetrates through the Mozambique Channel southward from the equatorial regions.

Ivanenkov (1960) used lines of stations from the 1956 cruise of the Ob to discuss the water masses of parts of the Indian Ocean. He dealt extensively with all the water types present in the western and eastern Indian Ocean (following closely Muromtsev (1951)) showing the boundaries, hydrological characteristics and directions of movement of all these water

masses. He found that the maximum phosphate concentration at the region where the North Indian Deep Water forms follows a simple annual cycle.

Much work on different water types, especially in the North and East Indian Ocean has been done by Rochford. In 1958 he analysed the characteristics and flow paths of the Intermediate Waters on the 27.20 and 26.80 σ_t -surfaces, but restricted his research to the area east of 60°E . On both these surfaces he finds a movement of Banda Sea Water at 500 m to 800 m travelling west at about 30°S across the 60° meridian. Influence of Arabian Sea Water and Antarctic Intermediate Water is also marked. In 1964 he dealt in detail with the different origins of the North Indian Deep Water and the various flow paths of these different water masses that, altogether, form this water mass. For this he drew a large number of T/S diagrams and made T/S assemblages for the different densities using the oxygen minima as points of least flow where salinity maxima cannot exist. In this way he distinguished between five different water types making up the North Indian Deep Water. These include Red Sea Water (at 800 m), Persian Gulf Water (at 500-200m) and Arabian Sea Water at 100 m. All of these have two main flows, one south towards the northern mouth of the Mozambique Channel and the second east-south-east reaching no further than approximately 10°S , where they are partially entrained by the South Equatorial Current.

In a similar attempt to define the source regions of the oxygen minima in intermediate depths in the Arabian Sea, he found (1966) Subtropical oxygen maximum water spreading north-

ward on 26.85 σ_t to about 10°S , streams penetrating to the equator and beyond. Antarctic Intermediate Water (26.90-27.30 σ_t) moves north, below the South Equatorial Current and then between Persian Gulf and Red Sea Water (below) to about 15°N .

In two other papers in 1966 Rochford described the inflow into and continuation of Banda Intermediate Water in the Indian Ocean. This low salinity water flows due west along latitude 10°S , flowing with the South Equatorial Current to be swept along by the East African Coastal Current when it reaches the African coast.

Darbyshire (1964) used the Natal cruises of 1962-3, in which lines across the Agulhas Current were carried out, in an attempt to disclose any seasonal variation in the flow of this current. In his sections he shows the distribution of the parameters.

Off Somalia Swallow & Bruce (1966) showed a southward flow at 1000 m while Warren, Stommel & Swallow (1966) could show little at this depth. At depths greater than 2000 m a narrow northward flow close to the coast was found.

In June 1961 the Africana II undertook a cruise in the South West Indian Ocean and Orren (1963) presented the data in vertical sections along the four lines of stations. Along a line east from Lourenzo Marques the Mozambique Current stands out on the σ_t distributions as well as a northerly flow just west of Madagascar although the latter one was mainly in deeper water. A salinity minimum at 1000 m and an oxygen minimum at 1500 m across the width of the line are other main features. The two minima are found at this same depth on a

line southeast from Madagascar. This line shows no current moving westward except at 35°S , the rest being a slow steady flow east. The same current distribution holds for a meridional line south of Mauritius except that just south of the island the flow below about 500 m is westwards but above this eastwards. Oxygen and phosphate information was incomplete. Along a line eastwards from Port St. Johns to 60°E the slow Agulhas Current Return Flow seems clear, except from 50°E eastwards where the current is reversed. This phenomenon was to be shown clearly by Visser & van Niekerk (1965) who used some of the same data. The oxygen minimum along this line lay at about 1800 m. Orren found the Tropical Convergence at 24°S similar to that mentioned by Deacon (1933, 1937) for the Atlantic Ocean.

Visser & van Niekerk (1965) did an analysis of water movement at 1000, 1500 and 3000 m in the South West Indian Ocean. To supplement this they calculated the distribution of salinity and temperature on these levels as well as temperature, salinity and depth distributions on the closely corresponding σ_t surfaces 27.20, 27.40 and 27.60. The current directions on the level and σ_t surfaces correspond very well and although the isohalines and isotherms do not contradict these results, they do not significantly support them either. At 1000 m the whole of the Agulhas Gyre is reproduced very well. Water flows west across the Madagascar Ridge up to 37°S . Very prominent features of the circulation are the big perturbations in the direction of flow as the currents, flowing east or westwards, cross the Madagascar Ridge and the Mid-Ocean Ridge. The circulation at 1500 m (relative to 2000-) shows very little difference except that the perturbations are magnified.

In 1962 and 1963 the Africana completed its work for the IIOE to the south of its 1961 cruise and Orren (1966) described the results. He divided the non-surface water into the categories Subsurface Water, Central Water, Deep Water and Bottom Water. Subsurface currents, shown by subsurface salinity maxima in the Agulhas Water, are due to the sinking of Subtropical Water below the Tropical Water of the Agulhas Current. The Central Water, sinking north of the Subtropical Convergence, moves northwards at 200 to 800 m mixing with the water masses above and below. The Antarctic Intermediate Water was found at 900 to 1300 m rising slightly as it went northwards, part turning round and flowing southwards in the lower levels of the Agulhas Current.

Gallagher (1966) also discussed the various water types and their movement in the Indian Ocean. He dealt i.a. with the Antarctic Intermediate, North Indian Deep and Indian Ocean Central Water. The Indian Ocean Central Water sinks at the Subtropical Convergence and spreads northwards reaching its furthest northern extension on the western side of the ocean at 10°S . Using the collected data of the National Oceanographic Data Centre he found that the subsurface water masses are the most limited in spatial extent and remain within defined areas. For the western part of the ocean Central Water is found between the Subtropical Convergence and 5°S ; Equatorial Water between 5°S to just north of the equator with Arabian Sea Water north of this.

In 1970 Whithers showed a few interesting aspects of the movement of Antarctic Intermediate Water using two lines of Anton Bruun stations along meridians 55°E and 65°E . At the

first the core of this water rises from 1200 m at 40°S to about 600 m at 15°S where some of the deeper water seems to descend steeply. At 65°E water that has risen to 700 m at about 15°S starts sinking very sharply. A similar sinking of the deeper part of this tongue takes place at 23°S . This same type of sinking and rising was shown very clearly by Tchernia (1958) using lines of stations by the Norsel at 55°E and 75°E .

2.4 RESEARCH ON SURFACE CURRENTS AND SURFACE WATER MASSES

Problems that have been readily available for research because of their accessibility are the surface currents and the formation of surface water masses. When the large scale circulation of the Indian Ocean had been described and research started concentrating on details of water flow the immense complexity of these became clear.

One of the first workers to concentrate on problems of a regional character was Dietrich (1935). Using all the available oceanographic stations around the southern tip of Africa, he discussed the Agulhas Current and its area of dispersion. He stated that a remarkable steep slope of denser subsurface water is to be found along the coast of south-east Africa, covered by lighter water of Subtropical origin. At a depth of 1000 m this lighter water has the denser water on both sides. This characteristic of the mass distribution controls the surface current structure. These findings he supported with many sections, velocity profiles and lateral maps of water characteristics.

By 1950 the number of oceanographic stations available in this area had increased and Clowes used these in his study of the hydrology of South African waters. He described the water masses at the hand of characteristic diagrams as well as the currents in surface and subsurface layers. He believed that the Central Water is not a watermass on its own but a mixture between surface and Antarctic Intermediate Water. The isentropic method is used to analyse the movement of Sub-tropical and Antarctic Intermediate Water and he shows that the large anticyclonic gyre on the surface is partially impressed on the circulation of the Antarctic Intermediate Water.

Lacombe in 1951 did an analysis of the dynamic topography of the whole of the Indian Ocean, using as reference levels 1000, 2000 and 3000 decibars. Although, especially for the 3000 db level, the distribution of stations was very meagre, he got some interesting results. He showed that the axis of the South Equatorial Current does lie north of Cape St. Ambre and that only a small part of it breaks off on the African coast to flow south as the Mozambique Current. The Agulhas Return Flow passes Cape St. Marie at about 30°S and "drags along" water that is trying to pass westwards past the southern point of Madagascar. In both the Agulhas Return Flow and the West Wind Drift a very prominent feature is the marked deflection of the direction of the currents as they pass over the ridge south of Madagascar. These main features hold in various degrees for all three reference levels and relate rather well with maps of surface currents compiled from ships' drift. In a similar vein Le Pichon (1960) stated

that the Mozambique Ridge at 35°E and the Agulhas Plateau have a quite noticeable influence on the direction of the current causing large divergent eddies on the axes of the ridges. He also pointed out the strong north-east component of the Agulhas Return Flow.

Menaché's (1961,1963) very important contributions on the currents in the Mozambique Channel followed on the cruises by the Robert Giraud in 1957 and the ORSOM I campaign in 1958. In contrast to all that had gone before he showed, using the dynamic topography, that the Mozambique and Agulhas Currents are not continuous in October-November but that the Mozambique Current doubles back on itself flowing north along the western side of Madagascar. The Agulhas Current is fed solely by water passing south of Cape St. Marie. This is not confirmed everywhere by surface drift of the ship, although surface isohalines and isotherms seem to affirm this.

The three cruises of the Africana II for the IIOE were analysed by Orren (1963,1966). On the surface Tropical and Subtropical Surface Water is limited by the Tropical Convergence at about 24°S . The Agulhas Current system is composed mainly of Tropical Water mixed with Subtropical Water; the Agulhas Current varying in width from 50 to 100 miles with a velocity of 2 to 4 knots. A northward moving counter current at half this speed lies on the outer boundary of the current. This shows up more clearly in Shannon (1967) when he summarised some of this work. Subtropical Surface Water on the whole showed little movement.

Darbyshire (1964) calculated the dynamic topography of the surface relative to 1000 db for the four different seasons.

In January he found the Agulhas Return Flow to be strong and it then has a branch parallel and quite close to the Agulhas Current. He was not able to correlate the current directions with the bottom topography, but the distribution of temperature and salinity tend to confirm his dynamic calculation. He showed that the Agulhas Current is strongest in April and weakest in October. That the Agulhas Current is persistent to depths of 1300 m was also shown by Taft (1963) using the depth contours of four isosteric surfaces.

In April 1964 the Almirante Lacerda carried out a cruise in the Mozambique Channel (— 1964) the sections of which show little of the circulation proposed by Menaché (1963). This data was used by Lutjeharms (1968) to construct maps of dynamic topography and isentropic surfaces for various depths on most of which the Mozambique Current is clearly shown as continuing southwards past Lourenço Marques.

Some indication of this sort is also given by Crepon (1965) who published the only extensive results of GEK measurements in the Indian Ocean. In a meridional line from Cape Guardafui to Cape St. Ambre all current sets are westwards up to 4°S from where they are all eastwards. In the Mozambique Channel itself the Mozambique Current and current setting north west of Madagascar are clear, but at the northern mouth of the Channel no sign of the Mozambique Current is seen although measurements continued to 30 miles offshore. The South Equatorial Current, a broad flow, is clear. Of the branch of the East Madagascar Current past Cape St. Marie there is some, but spatially very limited sign. Flow on a line due east of Durban is intermittent and variable in direction.

Darbyshire (1966) used all the newly accumulated data to deal with the surface waters near the coasts of Southern Africa. She classified two distinct water masses: the Subtropical Water and the Agulhas Water with an area of boundary water between them and showed the location of these for her own and other authors' data.

Anderson has also made an extensive study of the Agulhas Current off Durban. In 1965 he showed that an inshore counter-current exists at times and that there is a marked variation in current speeds, distance offshore and current profiles of the Agulhas Current with time. Similarly Stavropoulos (1966) reports finding an inshore counter current, the core of the Agulhas at 50 km offshore and a countercurrent from 120 km offshore. He showed that the Agulhas Current is still moving rapidly at 500 m. In 1968 (Anderson 1968) an attempt was made to tie up the variations found in 1968 with the surface temperatures as measured by airborne radiation thermometer. This was partially successful. This followed on the work by Harris & Stavropoulos (1967) which showed a big variation in surface isotherm distribution from day to day. Snyman (1969) showed the same variations on more regular and extended flights.

Tripp (1967) investigated the seasonal variations in the Agulhas Current when he analysed the accurate ships drift between Cape Town and Durban. He showed that the Agulhas Current sets strongest in the vicinity of the 100 fathom-line and roughly parallel to it and that it is strongest in Spring and Autumn and weakest in Summer and Winter.

Due to the considerable interest shown in the reversing flow off Somalia and the influence of wind in changing current

patterns, this area of the Indian Ocean has attracted much attention. Warren, Stommel & Swallow (1966) and again Swallow & Bruce (1966) dealt intensively with the flow patterns and water masses during the Southwest Monsoon. Bruce (1968) contrasted the surface dynamic topography for the two monsoons. The resulting current system for the Northeast Monsoon is very complicated, various eddies being formed. The South Equatorial Current and the Equatorial Counter Current appear, but no connection between them is to be found. The flow from Cape St. Ambre to Cape Delgado is clear, but no clear branching, north or south, is evident. Duing (1970) dealing with the same problem on both theoretical and imperical grounds, drew the dynamic topography of the sea surface for the different seasons. In the Northeast Monsoon season, both the Somali and the East African Coastal Current stand out clearly, the latter recirculating with the South Equatorial Current from about 58°E . The Mozambique Current starts between the Comores and Madagascar from where it flows towards the African coast. There is no sign of an East Madagascar Current branch from the South Equatorial Current.

The surface circulation in the northern mouth of the Mozambique Channel was further described by Donguy & Piton (1969) who showed a variation in circulation from season to season. During summer an anticlockwise circulation around the Comores Islands and a southern set on the western side of the Channel is noticeable. During winter a general drift north occurs. This confirms partially the results of Gerard (1964), Angot (1965) and Angot & Gerard (1965) who observed the montly variations at a fixed station in these regions.

Truesdale (1971) found a similar circulation of which he attempted to measure the volume transport.

Further south Rochford (1967), describing the variation in the directional flow of surface currents, did not consider the branch of the East Madagascar Current to be flowing past Cape St. Marie throughout the year. In summer the Agulhas Return Flow crowds in very close to this current but flows far to the south in winter.

Bang & Pearse (1970) described the surface circulation of the retroflexion area of the Agulhas Current with the aid of surface temperature and ships drift data acquired by the Thomas B. Davie in 1969. The correlation between the velocity vectors and the temperature is quite remarkable, showing as it does the core of the current, the return current as well as the cyclonic eddy developed off Port Elizabeth. Later in 1970 Bang enlarged upon this work in his publication Dynamic Interpretations of a Detailed Surface Temperature Chart of the Agulhas Current Retroflexion and Fragmentation Area in which he showed the point of retroflexion lying at about 22°E with various anti-cyclonic eddies detaching themselves and moving west.

Latterly, a few researchworkers have paid attention to the coordination and interrelation of the various currents using all or some of the newly accumulated data. Harris (1970) was the first to confirm the winter vortex circulation in the Madagascar Channel as proposed by Menaché (1961) using the dynamic topography of the surface although he shows that some small percentage of Mozambique Water may pass south. He describes various eddies within the Agulhas Gyre and a branch-

ing from the Agulhas Return Flow which he considered may cause some measure of recycling. The North Indian Deep Water was traced to the southern mouth of the Mozambique Channel. On theoretical grounds he showed that the diverse bottom topography may be the cause of the sharp deflexions in the Agulhas Return Flow. This he further develops in his paper (1970) on Planetary-type waves in the South West Indian Ocean.

Duncan (1970) used all the available data in an attempt to define the Agulhas Current System as a whole, its source waters and the mass transports of its individual parts. From using station-pairs in the main core of the current he showed that the use of 1000 m as reference level for dynamic topography calculations is justified. He described the dynamic topography of the sea surface for four seasons, as well as its attendant salinities and mass transports. He found, as an inherent part of the system, three big gyres: in the Madagascar Channel, east of Madagascar and one as part of the Agulhas Current itself. The flow east of Madagascar is very strong. Seasonal fluctuations in the South Equatorial Current and the East Madagascar flow and the influence of these on the Agulhas Current were described.

This then, in some detail, is a survey of the research work that underlies our knowledge of the circulation in the South West Indian Ocean today. Much of it is of a contradictory nature due, in some degree, to measuring techniques that have changed considerably, but probable also to the inherent complexity of the system and variations of varying degree that afflict the whole flow.

CHAPTER III

OUTLINE OF THE PROBLEM

3.1 INTRODUCTION

From the preceding chapter, describing the work done in the South West Indian Ocean, it emerges that there are many outstanding problems that have not been solved, or only been partially solved. Many of these represent very definite gaps in our knowledge. Since it is the object of this thesis to fill some of these gaps and since the nature of a problem will determine what research methods are applied to it, these remaining problems will be discussed in this chapter in the light of the previous research.

3.2 LACK OF LARGE SCALE ANALYSES

The first publications on the Indian Ocean were of the nature of collections of surface drifts and later for surface drifts for various seasons as for instance Michaelis (1923) and Paech (1926). Some inferences were drawn about the relation of various current branches to one another, but these were of a very gross statistical nature and served as preliminary pioneer work. Some work of a large scale nature was that done before World War II, but it was all handicapped by the severe lack of data (Möller 1929), especially in certain areas. Sverdrup (1942), for instance, stated that at this time any

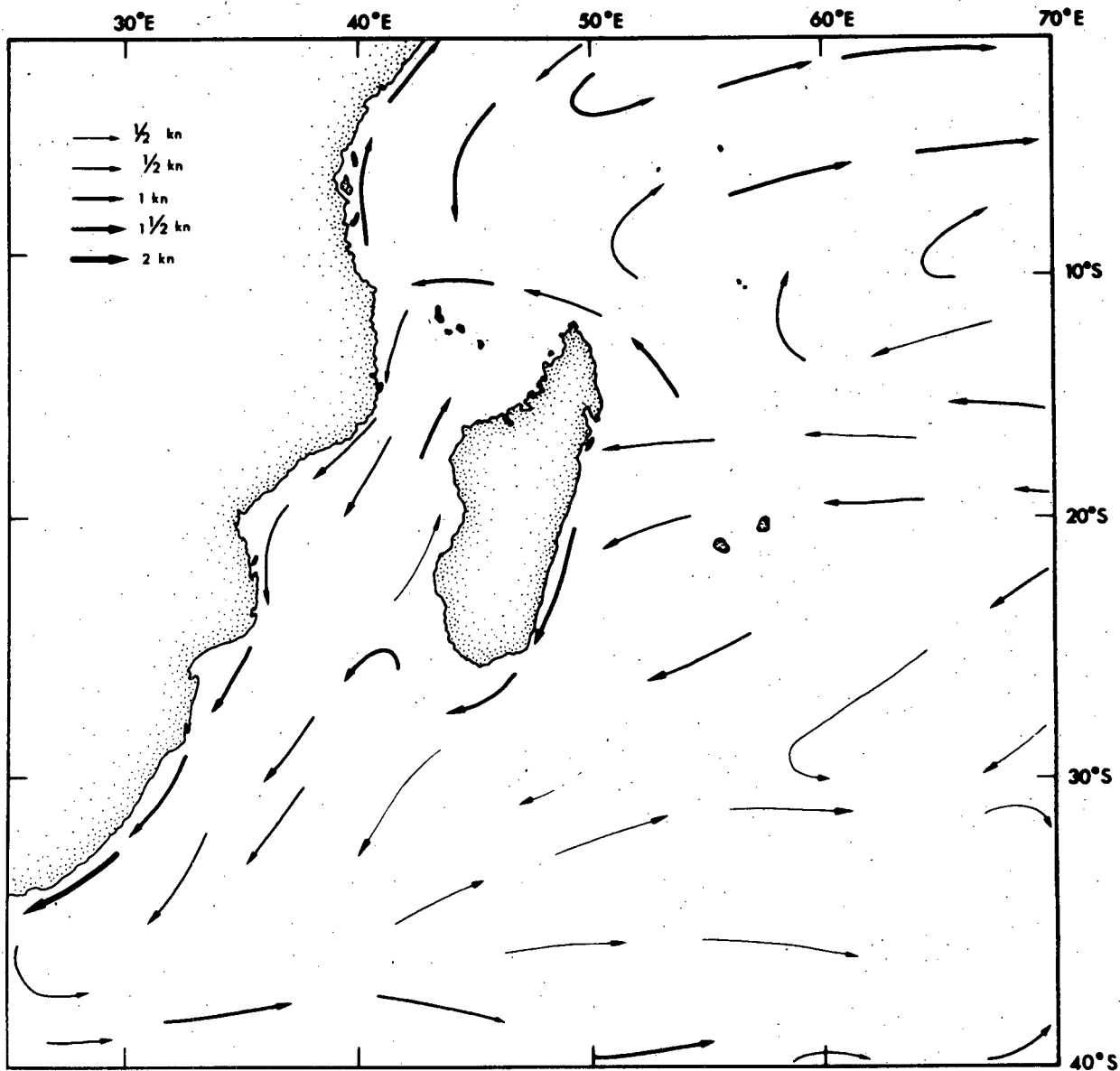


figure 3.1

Surface currents in the South West Indian Ocean in April from ships' drift according to the British Admiralty Routeing Chart - Indian Ocean - April - 5126(4).

discussion of the types of water in the Indian Ocean had to be of a preliminary character due to the lack of data. After the war little large scale research was done and researchers such as Orren (1963,1966), Visser & van Niekerk (1965), Bruce (1969), Clowes & Deacon (1935) and many others, on the whole concentrated on specific regional areas. Although the International Indian Ocean Expedition rectified the lack of data, most of the cruises were one-ship cruises researching specific areas or problems of interest.

Lately a few scientists have made a definite start on the large scale type of analysis. Hamilton (1967) has done an isentropic analysis for the whole area and the forthcoming Oceanographic Atlas of the International Indian Ocean Expedition by Wyrtki will deal extensively with various σ_t and core layers for the whole of the Indian Ocean. Lacombe (1951) and Duncan (1970) have constructed the dynamic topography of large parts of the Indian Ocean, but the problem of explaining the Agulhas Current System as a whole and in depth has not been solved completely. No isentropic analysis of σ_t layers for the whole area and for different seasons, supported by some quantitative data such as synoptic current measurements or volume transport with depth, has as yet been published. Harris (1970), dealing with the greater part of the South West Indian Ocean, states that: "... the full value of the increased quantity of observational data has yet to be realised".

It seems clear that a large scale, coherent analysis of the whole of the South West Indian Ocean System, describing the interrelationship and interaction of the different current branches, source waters and characteristic water masses, is

sorely needed. This would have to include the connection between the flow in various branches of the system (fig.3.1) and how they influence each other, the coherence or lack thereof between surface currents and deeper flow as well as the volume transport for various characteristic water masses.

3.3 NEED FOR ISENTROPIC ANALYSIS IN DEPTH

Having established the need for more analyses on a large scale, the need for the application of certain specific research methods arises.

The method that usually lends itself best and is most commonly used for any description of water movement with depth is the dynamic topographic method. This method has been used in the Indian Ocean with varying degrees of success by various authors. Bruce (1968) used it to analyse the changing current systems off Somalia, Menaché (1963) used it in the Mozambique Channel and Lacombe (1951), Harris (1970) and Duncan (1970) have used it for larger scale analyses. Although this method aspires to quantitative results, in many cases the analyses carried out in the South West Indian Ocean have shown large discrepancies between the calculated currents and the currents as observed from the ship's drift at the same time. This has been shown by Darbyshire (1964), Shannon (1967) and others. Shannon, discussing the Agulhas Current, states that: "Current strength computed from the variations in dynamic height tended to be on the low side, seldom exceeding 60 cm/s, while observations extracted from the actual ship's drift indicated velocities a factor two or three times higher". The most probable

reason for this kind of discrepancy is the fact that the dynamic method depends on a choice of reference level for minimum velocity.

Another method which is used extensively for ocean wide circulation problems and which does not suffer from the attendant difficulties of choosing a reference level is the isentropic method. In this method one can combine the topography of a σ_t -surface, to determine theoretical direction of flow, with distribution of parameters such as salinity, temperature and oxygen to trace the actual water movement. This method has seen only a limited application in the South West Indian Ocean. Visser & van Niekerk (1965) used it in conjunction with the dynamic method for deeper layers, Duncan (1970) used it on only two levels covering the whole South West Indian Ocean and an atlas (— 1967) has been published of this type (Hamilton 1967), but up to the present no thorough analysis in depth of carefully chosen σ_t -levels has been done. For the actual tracing of lateral water movements, especially in deeper water, this method would seem indispensable and of a valuable complementary nature to the many vertical sections already done in many parts of the ocean.

3.4 PROBLEMS OF REGIONAL CHARACTER

One of the reasons why the need for a large scale analysis makes itself felt so clearly, are the many unsolved problems of a regional nature that might be better understood when seen in the context of the surrounding flow and the basic circulation.

The basic circulation and the directions of the main surface currents over the seasons in the South West Indian Ocean has been known for some time from ships' drift measurements (fig.3.1). The statistical refinement attendant upon the accumulation of information of this sort over the years is noticeable when one compares for instance the maps constructed by Barlow in Indian Ocean Currents (— 1939) on the one hand and the newest editions of the Routeing Charts - Indian Ocean as published by the British Admiralty (— 1970) and the Monatskarten für den Indischen Ozean as published by the Deutsches Hydrographisches Institut (— 1960) on the other hand. Insofar as these atlases give the statistical mean of the general flow they are satisfactory, but in certain, and usually variable, areas the atlases, by their very statistical nature, are not of great assistance in explaining the connection between various current branches. Three such areas in question are the area between Cape d'Ambre and Cape Delgado, the eastern part of the Mozambique Channel and the area south and southwest of Cape St. Marie.

The northern mouth of the Mozambique Channel between Cape d'Ambre and Cape Delgado is the origin of the Mozambique Current and the East African Coastal Current in the Northeast Monsoon Season and also the area where the South Equatorial Current, the East Madagascar Current and the West Madagascar Current have their confluence. The conclusions as to the actual configuration of the current systems vary widely from author to author. Bruce (1968) shows, for the Northeast Monsoon, no sign of either Mozambique Current or East Madagascar Current, but shows the South Equatorial Current flowing

directly towards the African coast. The Monatskarten für den Indischen Ozean (— 1960) show, for February, the end of the South Equatorial Current immediately north of Cape d'Ambre and the beginning of the Mozambique Current directly east of Cape Delgado with seemingly no connection. Duing (1970), on the other hand, does show a clear connection in the Northeast Monsoon season between the South Equatorial Current and the Mozambique and East African Coastal Current, but finds no sign of the East Madagascar Current. His dynamic topography describes the Mozambique Current as flowing between the Comore Islands and Cape d'Ambre, to flow southwest from there towards the African coast. Donguy & Piton (1969) show, for the same season, the current between the Ile Mayotte and Nossi-Bé setting the opposite way.

Whether the current known to set north on the eastern side of the Mozambique Channel (i.e. the West Madagascar Current) is part of an eddy or a continuous current of its own has remained a problem. Michaelis (1923) and Peach (1926) differed on this, Michaelis thinking of it as a continuous stream. Schott (1935) described the flow as continuous, but only up to 20°S . Menaché (1963) and Harris (1970) both found strong continuous flows being the return flow of the Mozambique Current. Lutjeharms (1968) using Lacerda (— 1965) data for dynamic topography calculations found no current of this type. Duncan (1970) shows a flow of this nature, sometimes as part of an anti-cyclonic eddy, sometimes as a flow on its own, depending on the season.

The area south and southeast of Cape St. Marie is an area in which the lack of data precludes a clear understanding of what might be a complicated system of interacting currents.

Duncan (1970) writes: "... the region south and southeast of Madagascar should be investigated ... to fill the data gap which exists". His dynamic topographies show no relation between the current south of Cape St. Marie and the East Madagascar Current. Lacombe (1951) shows such a relationship, but the current south of the Cape is very limited in meridional extent. The Admiralty Routeing Charts (— 1970) do show this current, but varying greatly from month to month.

From these three examples it is clear that there are a number of smaller features of the current system that have not been understood although they may have an important effect on the total flow.

3.5 LACK OF VOLUME TRANSPORT FOR VARIOUS LAYERS

In 1942 Sverdrup stated that: "The data from the Indian Ocean are too scanty to permit many quantitative calculations as to the amount of water carried by the different branches of the (Agulhas) current". Although the data has increased perhaps threefold since that time, very little of this nature has been done (Bruce 1969, Truesdale 1971). The major work of this kind is by Duncan (1970) who calculated the mass transport for all the surface currents of the South West Indian Ocean for the four seasons. These are integrated geostrophic transports from the surface to 1000 m. Transport calculations for the various depths or for various water masses is lacking for this part of the Indian Ocean.

This lack also impinges on another incompletely solved problem. This concerns the relationship between the intense

deeply flowing surface currents that are mostly winddriven and the thermohaline movement of the sluggish intermediate water masses. A few authors (Möller 1929, Clowes 1950), dealing with the spreading of intermediate waters, have concluded that the deepflowing surface currents make their effect felt on the intermediate waters. Le Pichon (1960), for instance, finds that water above 2000 m is always influenced by the deep currents like the Agulhas.

A detailed analysis of transport with depth at various positions in the ocean, would conceivably also give an indication of this type of relation or lack thereof.

3.6 VARIABILITY OF THE SYSTEM

In the Indian Ocean one of the most distinctive features is the current reversals with seasons, consequently the question of variability in current velocities, water transports and inter current influence is of considerable importance. This would have a direct effect on all the other remaining problems previously mentioned, including the connection between the flow in various branches, the changes in transport and the variation in influence of surface currents on deeper water. The seasonal variability has consequently raised the early interest of research workers. Barlow (1931) was the first to show the relationship between the velocities of the Somali, East African Coastal, Mozambique and Agulhas Current. The latest work of this nature was by Duncan (1970) who showed how the transports of the various branches of the South West Indian Ocean varied with season.

A variation which could be of even greater importance in our understanding of the results of cruises from different years but the same season that are combined, would be a variation of currents from year to year. This is quite conceivable and many authors have commented on this in passing (Crawford 1970, Truesdale 1971, Clowes & Deacon 1935, Sverdrup et al. 1942, Le Pichon 1960) and all fixed stations that have been occupied for the same season over some years show, in a lesser or greater degree, a variation of this sort. Sverdrup (1942), discussing the outflow of Red Sea Water, says that: "A seasonal variation in the outflow appears to be well established, but great year-to-year differences may also occur and such fluctuations complicate the conditions at greater distances". Orren (1963) when contrasting the surface (0 to 100 m) salinity of the Indian and Atlantic Oceans states: "... it may be concluded that the annual difference (1959-60; in the South Western Indian Ocean) is greater than the apparent Atlantic/Indian oceanic difference ...". The long term analyses of oxygen, salinity and temperature in the vicinity of Nossi-Bé (Angot 1965, Angot & Gerard 1965, Gerard 1964) also point to a year-to-year variation.

This problem has not been probed in any definite manner in the Indian Ocean and emerges from the survey of the literature as perhaps one of the most important gaps in our knowledge to date, bringing into question the use of any combination of non-synoptic data.

CHAPTER IV

DATA AND METHODS

4.1 INTRODUCTION

It is clear from the previous chapter that the problems confronting research workers on the South West Indian Ocean are not of such a nature that one or two extensive research cruises would supply enough data to resolve them. Although the author did take part in the Agulhas Current Project (Bang & Pearse 1970) of which some data is used in this work, the remainder of the data was a selection of the published data in this ocean.

If the application of a research method is to produce the best results, this research method, as was stated before, should be tailored to fit the specific problem that is the object of the investigation. Because of the various types of problems presenting themselves in the South West Indian Ocean, as discussed in chapter III, the method applied here was a rather unorthodox combination of those aspects of accepted research methods that were thought would result in the most lucid description of the actual water movements.

4.2 THE DATA

As a start to the research an all inclusive compilation was made of the oceanographic cruises that had done research in the South West Indian Ocean and for which the results had

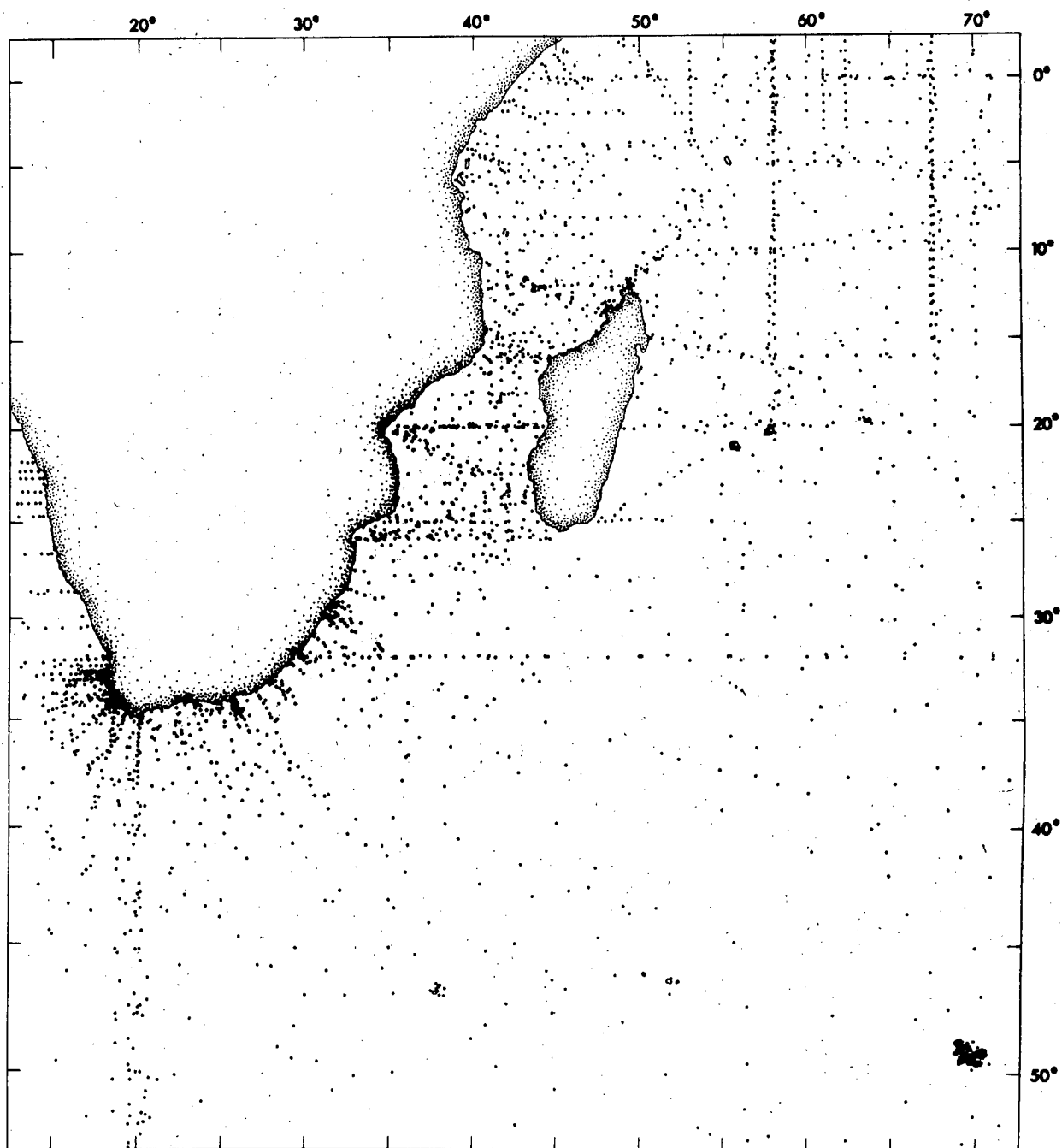


figure 4.1

Position of all available oceanographic stations in the South West Indian Ocean and adjacent areas.

been published. In this regard extensive use was made of the following publications:

Reference sources for oceanographic station data,

(— 1961), NODC

Reference sources for oceanographic station data I,II,

(— 1965), NODC

Special catalogue of data from the IIOE (— 1967), NODC,
WDC(A)

Selected IIOE track charts (— 1966), NODC

Catalogue of accessioned publications 1957-1967 (— 1967),
WDC(A)

A partial bibliography of the Indian Ocean (— 1962),
Woods Hole.

The publications by Wüst (1964) and Samuel (1965) were also consulted. A selection from these cruises was then made excluding all those cruises carried out before 1940 that had not been incorporated in the NODC data. This included cruises such as the Valdivia, Möwe, Challenger, Gazelle, Waterwich, Novarra and the Pickle.

Complete sets of computer printouts and computer cards of the oceanographic data available from the NODC for the area bordered by the latitudes 10°N to 50°S and the longitudes 10° to 70°E were then obtained and these, together with published data not in NODC files, were used as the basic research data for this study. Data on the computer cards was as described in the NODC publication M-2: "Processing physical and chemical data from oceanographic stations" (— 1962).

The geographical distribution of these oceanographic stations is depicted in figure 4.1. From this map it is clear

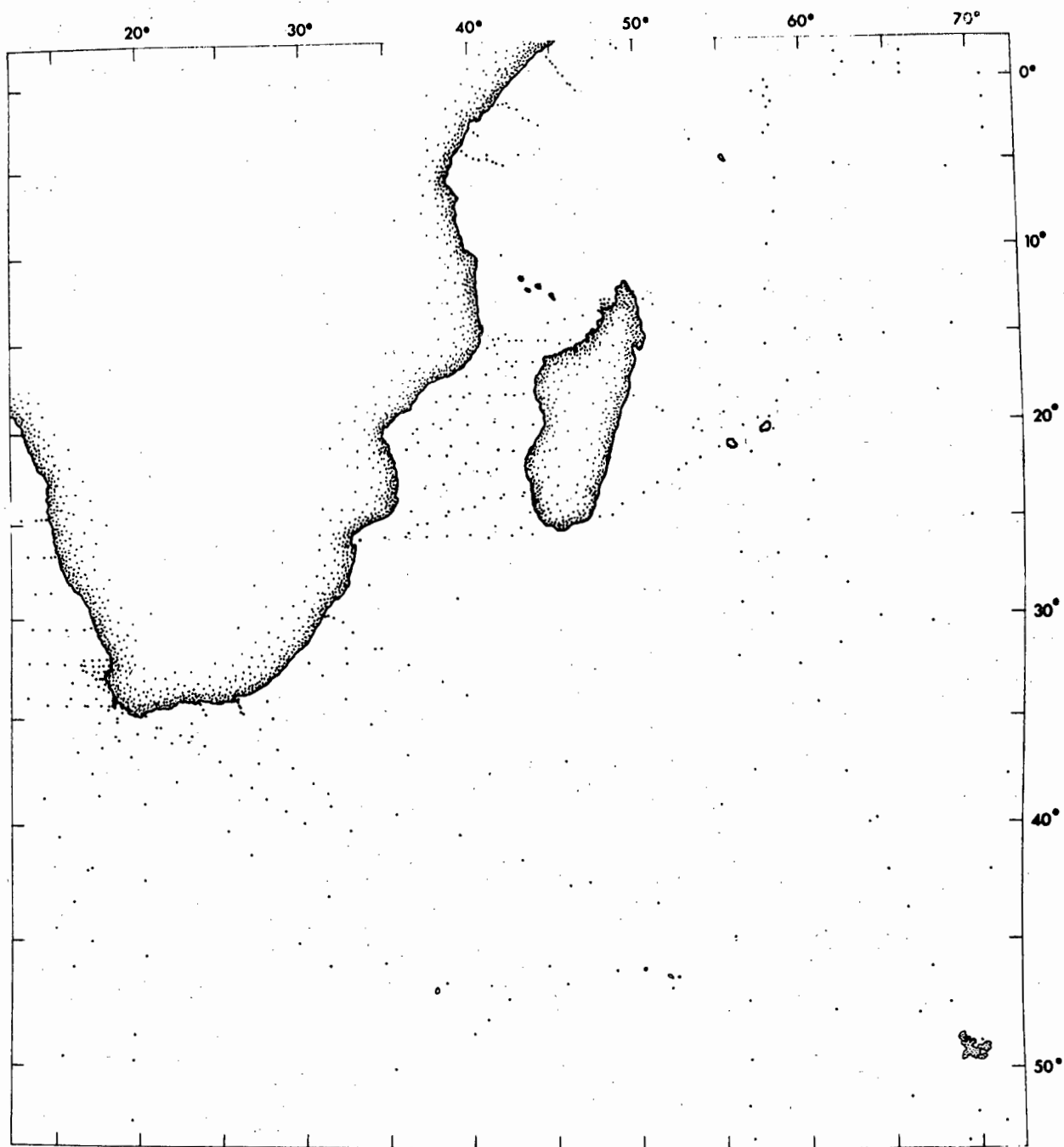


figure 4.2

Position of available oceanographic stations in the South West Indian Ocean and adjacent areas for November through January.

that the distribution is very inhomogeneous. Whereas areas such as the Mozambique Channel and the coast of South Africa are well covered, the crucial areas south and east of Madagascar have fewer stations. When the distribution of stations is broken up into three monthly periods the lack of stations, especially in certain areas, becomes even more conspicuous. Two periods of three months each are depicted in figures 4.2 and 4.3. It may be noted that during the period February to March the only area covered well is off the South African coast. The Mozambique Channel and the area northeast of Madagascar are covered sparsely, but the whole area lying south of 20°S and east of 40°E , has only one line of stations. For the period November to January the distribution shows up clearly the fragmentary character of coverage in this area. Whereas the Mozambique Channel, the close inshore Somali coast and the South African coast are covered fairly well, the rest of the ocean is dotted sparsely with stations.

A further complication in an analysis that attempts to consider water flow at depth, is the fact that the number of stations that are available at a certain depth diminishes rapidly as one goes deeper (see figure 4.13). For any deeper work the station distribution is thus depleted even further.

From the foregoing it is clear that the distribution of stations seriously hampers any large scale analysis of this ocean. Since the circulation is subject to seasonal variation one would try to avoid the distortion brought on by this variation by choosing the shortest time period possible in which to do one's analysis. On the other hand, the diagrams discussed above show that, were we to use three month periods the complete change in distribution of the available stations from

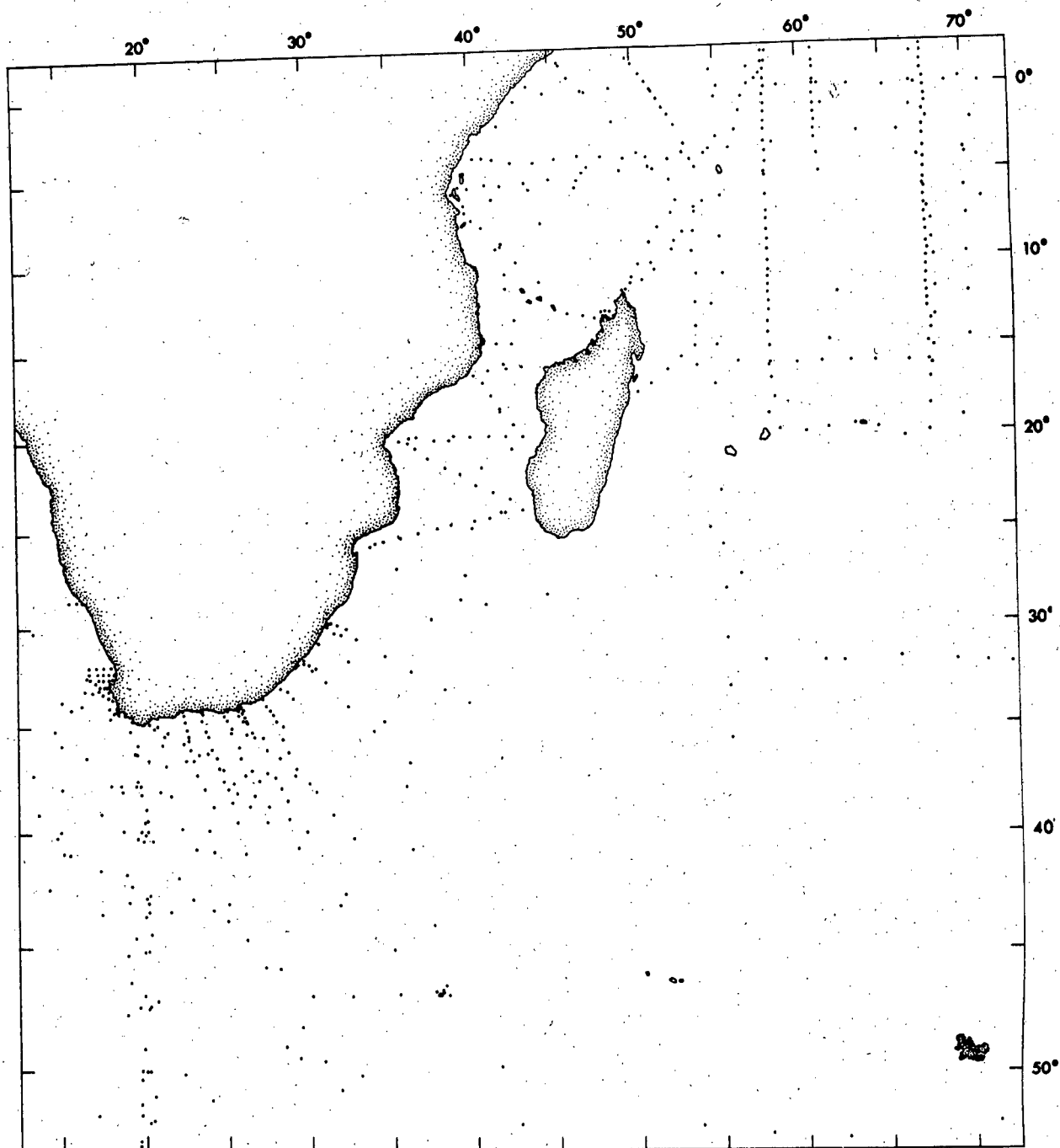


figure 4.3

Positions of available oceanographic stations in the South West Indian Ocean and adjacent areas for February through April.

three month period to three month period might introduce even larger distortions. For this reason one would thus like a longer time period for the analysis. In many areas the coverage is so sparse that any contouring of parameters would be subjective to an extent that would make proper interpretation impossible.

The natural seasons of the Indian Ocean are the Southwest Monsoon Season (Northern Summer) and the Northeast Monsoon Season (Northern Winter). Between these there is a time of change which varies in time from place to place and, less noticeably, from year to year. It was therefore decided to choose a monsoon season as the period of investigation. Not only would it fit in with the natural period of change as it exists, but a five month period would also have an adequate coverage of stations.

Of the two monsoon seasons the one which would be preferable for this type of analysis would be the one during which the main currents were strongest and the system as a whole best developed. This would then present sharper contrasts and hopefully an easier interpretation. A scrutiny of the literature pointed to the Northeast Monsoon Season as the period in which this happens. Barlow (1935) showed that the East African Coastal Current (between 20°S to 6°N) reached its maximum southward flow in January, between 2°S and Cape Delgado in February, as did the Mozambique Current and that the maximum velocity south was reached by the Agulhas Current in April. Also according to Darbyshire (1964) does the Agulhas Current reach its maximum velocity in April. This is corroborated by an analysis of Tripp's (1967) data which shows that the maximum velocity as averaged over eight positions in the Agulhas

Current is 66 nautical miles per day and occurs in April.

Shannon (1966) supports this since he found that the penetration of Agulhas Water to the West Coast of South Africa was most marked during late summer/early autumn.

In choosing the Northeast Monsoon Season as the season in which the current systems were probably best developed, it was necessary to make a careful analysis of the exact months in which this effect was most likely to occur. Monthly presentations of surface drift such as depicted on the Admiralty Routeing Charts (— 1970) are not detailed enough to be used for this purpose. In Currents in the Arabian Sea (— 1956) the changeover month from one monsoon to the next was portrayed as November.

Consideration of the 80°F isotherm on the mean temperature charts as presented by La Violetta (1967) or the World Atlas of Sea Surface Temperatures (— 1944) would seem to indicate May and November as changeover months. These indications are vague and of a rather subjective nature.

An analysis of the cycles of water behaviour from the data by Darbyshire, Barlow, Tripp and Angot give some more interesting results. Darbyshire's (1964) description of the surface velocities of the Agulhas Current shows an annual cycle reaching a peak of 50 cm/s in April declining to less than 20 cm/s in October. This he relates directly to a variation in the South Equatorial Current as subject to the Monsoon Winds. Barlow (1935) used ships' drift measurements and portrayed the Agulhas Current velocity as reaching a peak of 27 miles/day in April with a secondary peak of 25 miles/day in August.

A careful analysis was done of the data presented by Tripp (1967) to determine the variation in current strength of the

Agulhas Current over four seasons at eight positions along its main line of flow. The mean of the variations at the eight positions was also calculated. This data had been collected over a period of two years and all eight positions, as well as the mean, show a twice yearly cycle in current strength that has maxima in April and October and minima in July and January. In five out of the eight positions the peak in April is the highest value for the year. Since the shape of this curve relates so well with Barlow's (1935) analysis we are forced to the conclusion that Darbyshire's (1964) analysis is incorrect and his deductions concerning the influence of the South Equatorial Current on the Agulhas velocity based on faulty premises. Other data that lent itself to this type of analysis were the monthly measurements of surface temperature and oxygen in the vicinity of Nossi-Bé (Angot 1965). This also showed, although less clearly, a cycle with peaks of oxygen concentration in April and August - October and of temperature in April and December.

The best work on variations in directions of the currents in the Indian Ocean was done by Verploegh (1960). He portrays i.a. the direction of the surface currents for each month for a meridional strip between 62° and 68° E running from 20° N to 10° S. To facilitate the analysis he has drawn lines connecting areas with minimum constancy i.e. when the currents are in the process of changing direction. According to these the change, in the domain of the monsoons, takes place in May for most latitudes and in October to December as the latitude north decreases towards the equator. South of the equator the picture is more complicated and the lack of data predominates so that no definite conclusion can be reached here.

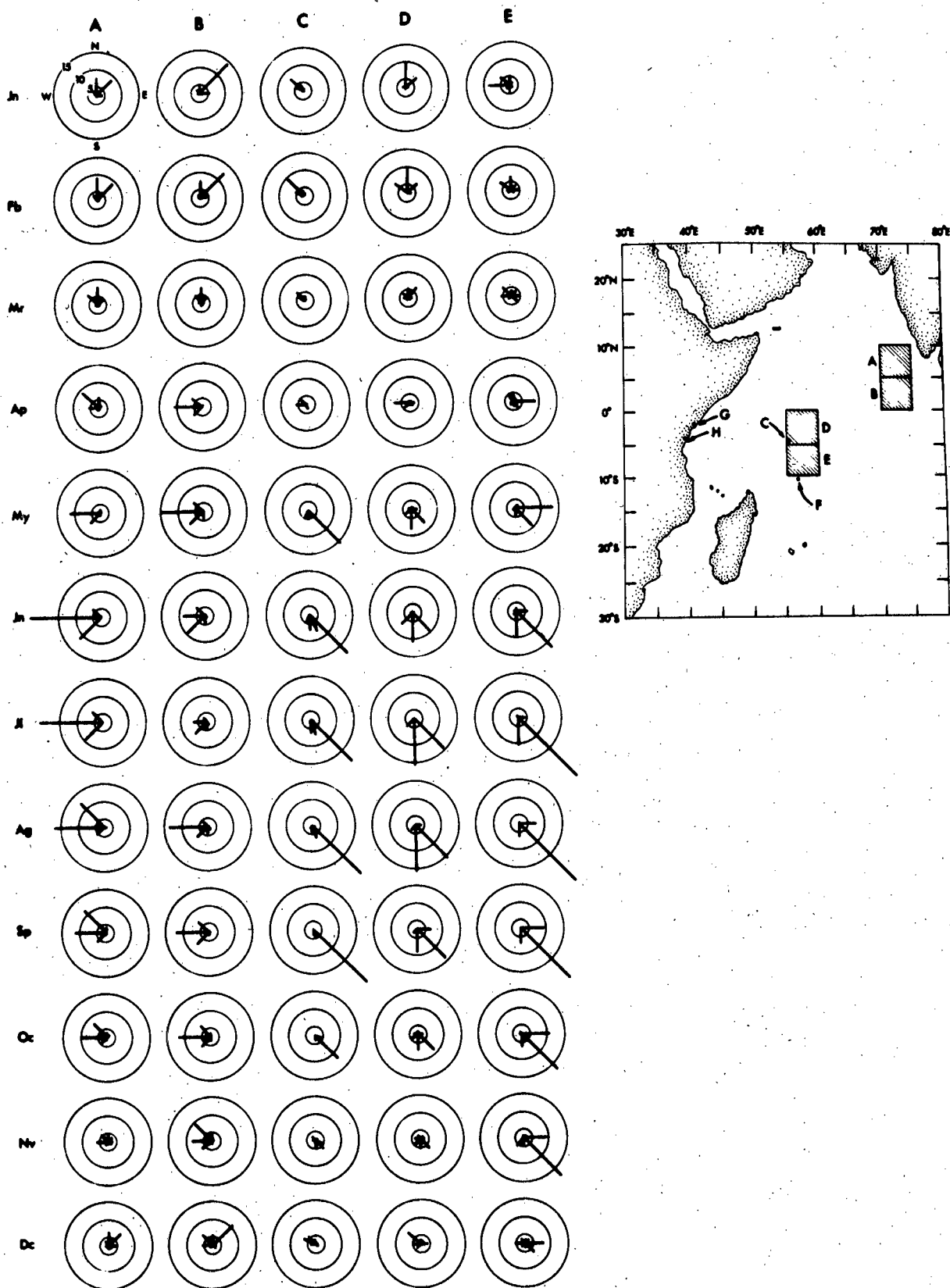


figure 4.4

Monthly wind roses at selected observation points in the North Indian Ocean. C denotes the Seychelle Islands; F, Agalega; G, Mombasa and H, Malindi.

The analysis of the cycle of water behaviour is not entirely satisfactory in defining which months may be chosen as a "Northeast Monsoon Regime" in the water flow. The general meteorological conditions are better known and more results are available for this kind of choice. The Meteorological Office of the U.K. Air Ministry (— 1962) states that, at the Seychelles, the Southeast Trade wind blows from May to October, the Northwest Monsoon from November to March or sometimes April (p. 24). For the same meridional section described above Verploegh (1960) portrays the change as taking place in April and in end-October to middle-December going from 20°N to the equator. Comparing the winds and currents for this same meridional section it is important to note that, when the Northeast Monsoon starts, its effect is noticeable in the surface currents within two to three weeks whereas when it stops the water only starts changing direction after about four weeks.

To investigate this time of changeover further an analysis was carried out of wind regimes at Mombasa (— 1965), Malindi (— 1965), Agalega (— 1962), Mahe (— 1962) and the areas as depicted in figure 4.4 (— 1962). The windroses shown in this diagram depict the product of the percentage frequency of wind direction in a certain octant and its speed, covering the whole day. Since the velocity of surface drift currents is directly proportional to the wind producing it (Durst 1924) this type of windrose will give a better indication of when the influence of the windregime changes than other types of analyses. From the windroses it seems clear that in the area D (0° - 5°S , 55° - 60°E) the changeover takes place in April and November. So also for Mahe in the Seychelles Islands (C)

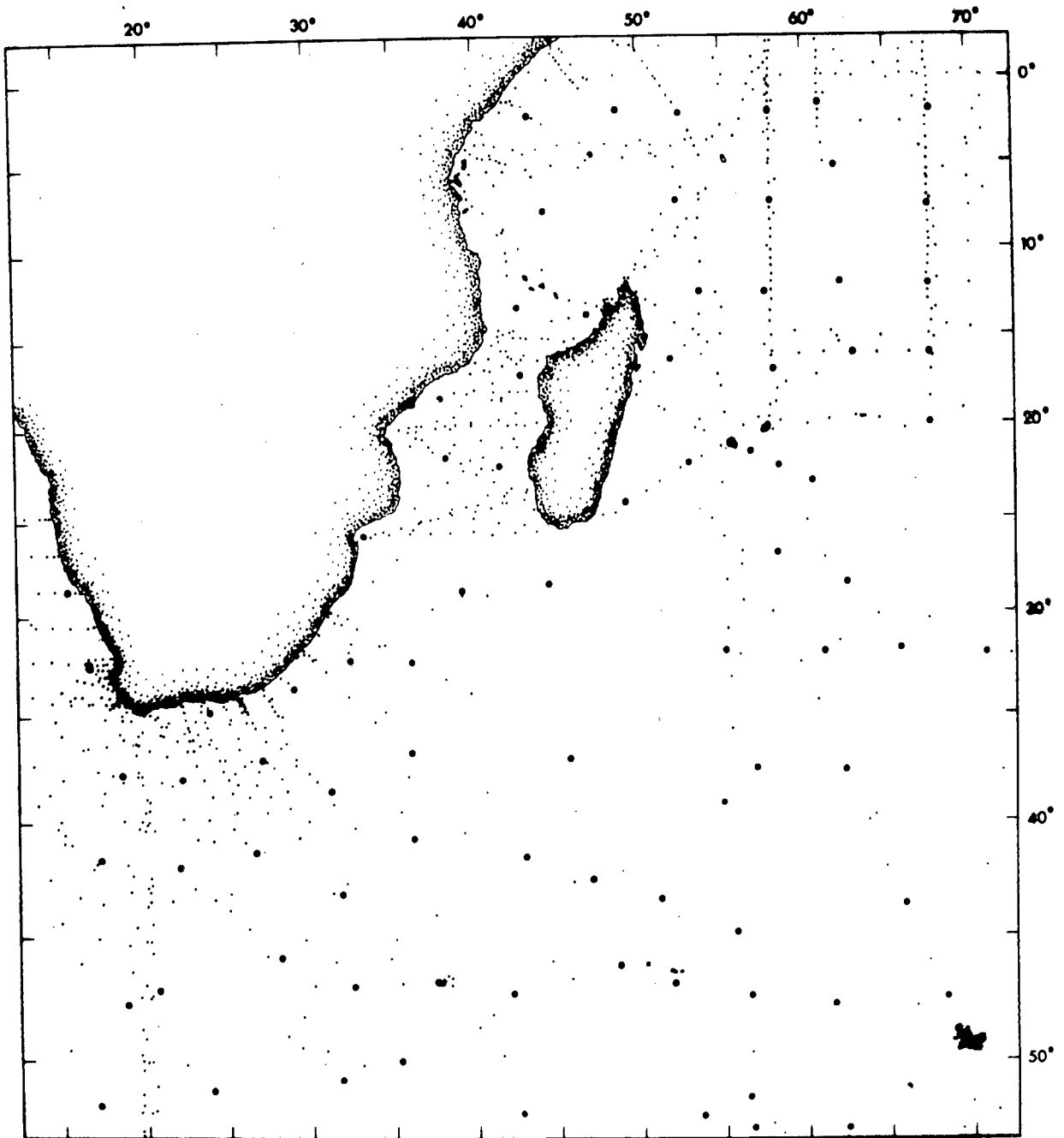


figure 4.5

Position of all oceanographic stations available in the South West Indian Ocean during the Northeast Monsoon season as well as positions of stations used for T/S scatter diagrams.

and A (5° - 10° N, 70° - 75° E). In B (0° - 5° N, 70° - 75° E) the change-over month is March and the beginning of the Northeast Monsoon must be between November and December. The beginning of the Northeast Monsoon season in E (5° - 10° S, 55° - 60° E) is the same, but the changeover month at the end of the season is May.

On considering the above investigations and bearing in mind the need to include as many stations as possible, it was decided to consider as the Northeast Monsoon Season, for the purpose of this study, the months November to April inclusive. However, in the actual selection of stations for use it was attempted to concentrate on February, March and April where possible. This will be discussed later. Having delimited the Northeast Monsoon Season in this way, the distribution of oceanographic stations available for this period is depicted in figure 4.5. Most of the stations are presented in table IV.1 in Appendix IV.

4.3 CHOICE OF RESEARCH METHOD

Having decided on the timespan of the investigation and therefore, indirectly, on the stations to be used, it is now necessary to come to a decision on the research methods to apply to this data. As pointed out in paragraph 3.3, there exists a real need for a large scale isentropic analysis of the South West Indian Ocean.

The isentropic method of analysis has its origin in meteorology. In meteorology one of the basic requirements is to be able to identify a mass of air by certain unchanging characteristics and to be able to follow it from day to day. Rossby (1932) presented a method for the identification of air

masses by potential temperature and specific humidity. Under ideal adiabatic conditions these elements will retain their identities and the air will flow along surfaces of equal entropy, or isentropic surfaces. To differentiate between the individual parcels of air on a given surface an indicator is needed. Rossby (1937) proposed that this need is met by the specific humidity. When radiation or condensation occurs however, a body of air may change its potential temperature and move across isentropic surfaces.

An adaption of this method has been applied to the ocean. Water below a certain depth is no longer subject to direct surface influences such as long-wave radiation, evaporation or precipitation and thus preserves its potential density and salinity except through mixing. Parr (1938) argued that since water masses must thus flow along surfaces of equal potential density a study should be made of the distribution of identifying properties such as salinity and temperature on these surfaces. Montgomery (1938) pointed out that since potential density is so nearly equivalent to σ_t , except at great depth, it is sufficient to use surfaces of constant σ_t . This method is loosely called the isentropic method after the similar method in meteorology, although theoretically this is not quite correct.

Some of the shortcomings of this method spring from this fact. Defant (1961) stresses that the direct application of what is essentially a meteorological method to ocean problems is not entirely legitimate. In the atmosphere surfaces of constant potential temperature and constant potential density coincide with surfaces of constant entropy. This is not the case in the ocean. In assuming these surfaces to be identi-

cal in the ocean we are completely neglecting the very important part played by the salinity. Since both temperature and salinity are used for the determination of the density of seawater, when we again use one of these as an identifying property to be plotted on levels of equal density we are actually using a dependent variable. Unfortunately independent properties such as oxygen and phosphate content are not conservative. Another objection by Defant (1961) is the fact that the theory of the isentropic method depends very largely on the assumption that mixing on an isentropic surface occurs predominantly in horizontal and not vertical directions. He feels that this is not entirely justifiable since outside the density transition layer, where the stratification is severe, there is no reason to assume that the effect of vertical mixing is less important than that of lateral mixing.

Two more objections against the method are raised by Montgomery (1937). In the first place he shows that two samples of water of the same density at one pressure do not in general have the same density at another pressure. Secondly, when two samples of equal density, but different temperature mix, the resulting mixture has a greater density than the original samples. In this way water on an isopycnic (or "isentropic") surface will gain density as it mixes with other water masses and thus pass across these surfaces. Nonetheless he was convinced that these effects might be negligible in most practical applications. Numerous successful applications of this method in later years have borne out this conviction.

This then, in short, is the theoretical background and limitations of the isentropic method. Under the circumstances described this method was felt to be the most useful. The

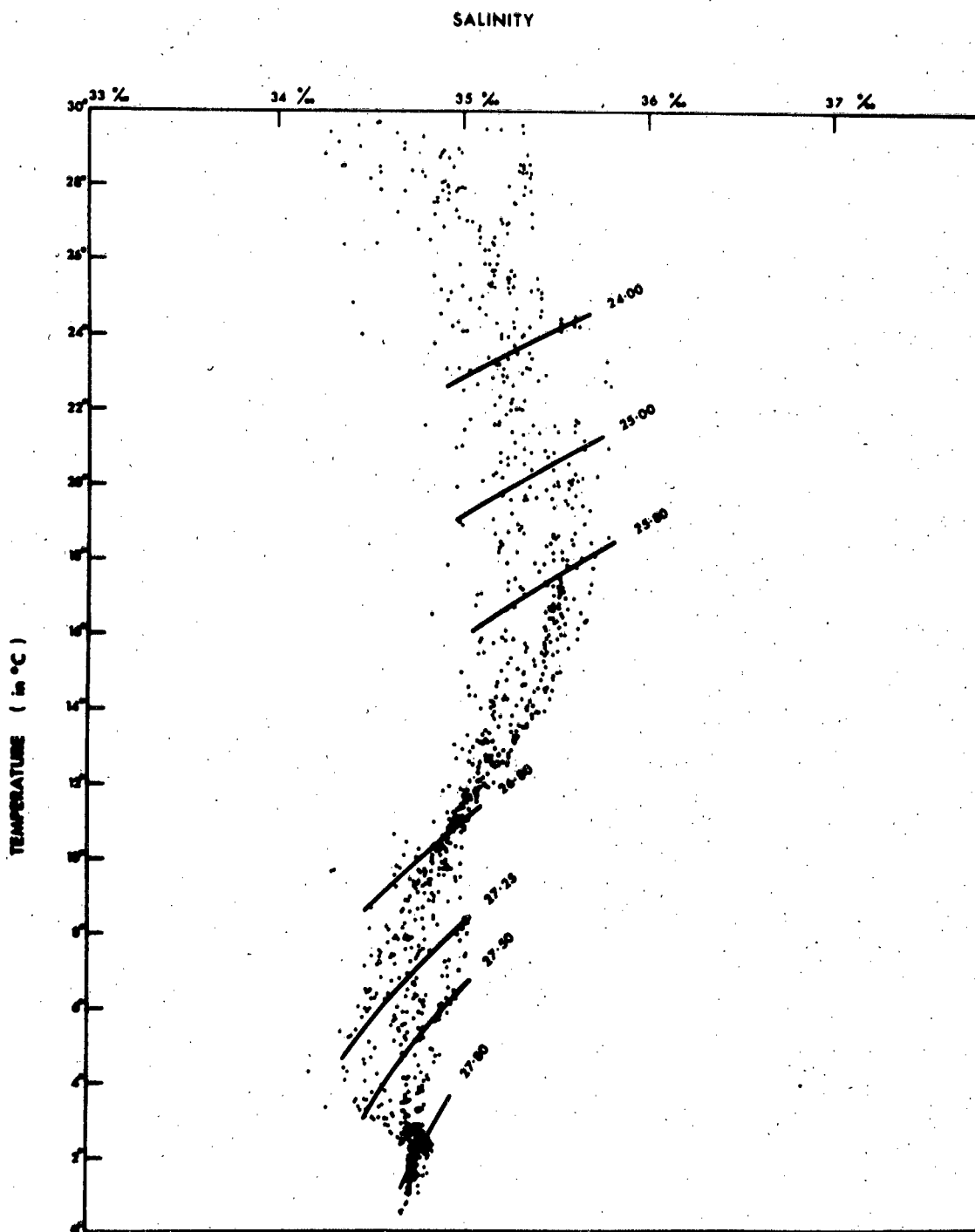


figure 4.6

T/S scatter diagram for the South West Indian Ocean showing selected σ_t levels.

other practicable method would be the method of dynamic topographies. This has already been used by Duncan (1970). It has the danger that it depends on the choice of a reference level which may have a varying topography of its own (Mamayev 1960). Orren's (1966) discussion of Darbyshire's (1964) inability to find an Agulhas Counter Current is a clear example of the danger of choosing a wrong reference level. Orren (p. 5) shows that Darbyshire chose a reference level at 1000 m while others found significant velocities in this region at 1500 m. The depth contours of a σ_t -surface can indicate the sense of motion along them in very much the same way, but this method then has, apart from being independent of a reference surface, the added advantage of the confirmation of this movement by the distribution of identifying properties. This was discussed in paragraph 3.3. In the rather unusual case where there is an increase in water velocity with depth, the usual interpretation of the depth contours of a σ_t -surface do not hold.

Defant (1961) favours the "core" method, introduced by Wüst (1935) to trace water masses. This method is a direct three-dimensional extension of correlating T/S relationships and does not go beyond its premises. Many of the theoretical objections against the isentropic thus fall away here. It makes use of the fact that any extreme value of an identifying property, such as a salinity maximum on a T/S curve, to be maintained must usually represent a point of water flux. If the values of some property at these maxima or minima are now plotted on a chart they will act as tracers of this particular water mass. Its use is restricted to the study of the flow of such characteristic water masses and for this reason was dis-

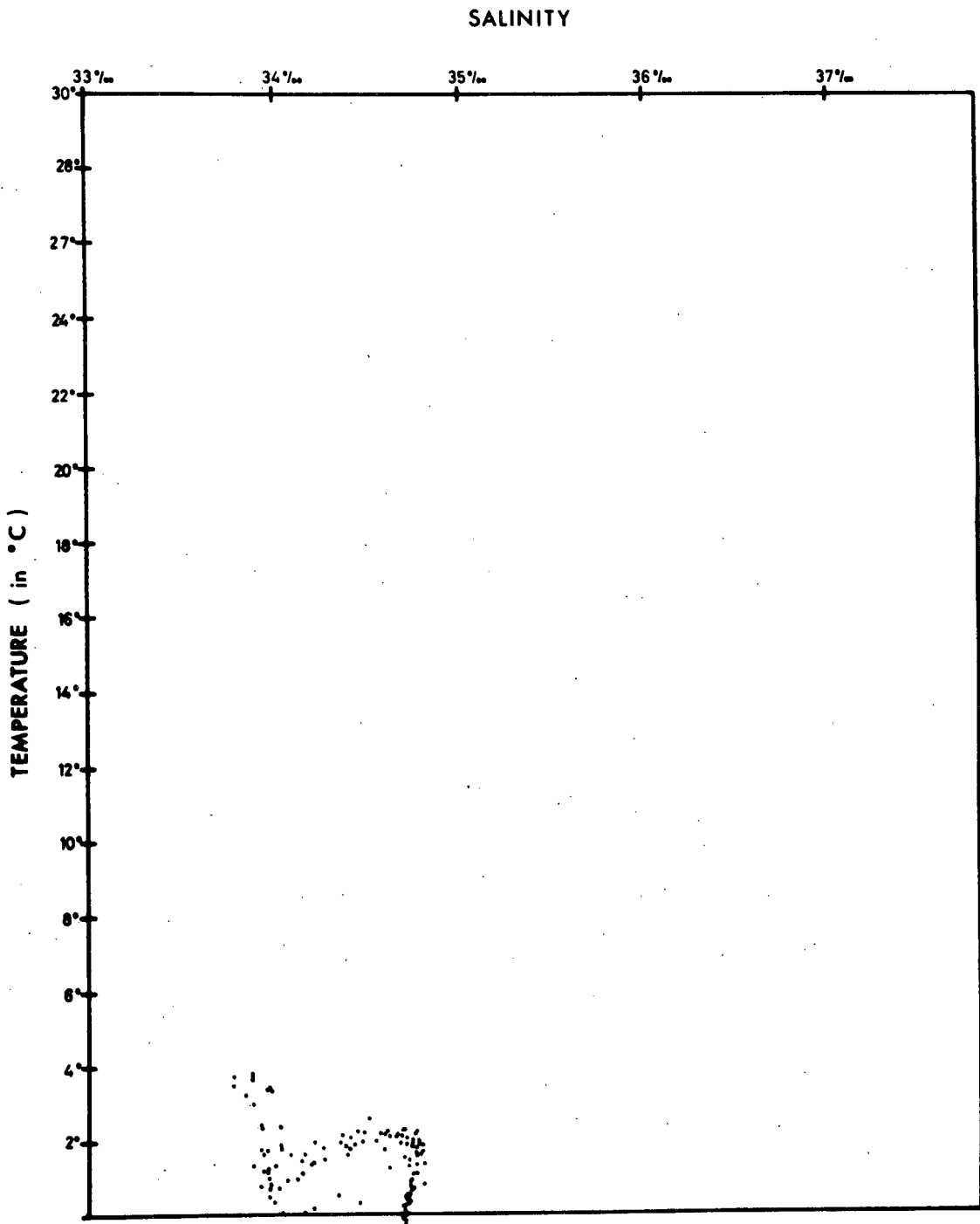


figure 4.7
T/S scatter diagram for stations south of Antarctic Polar Front.

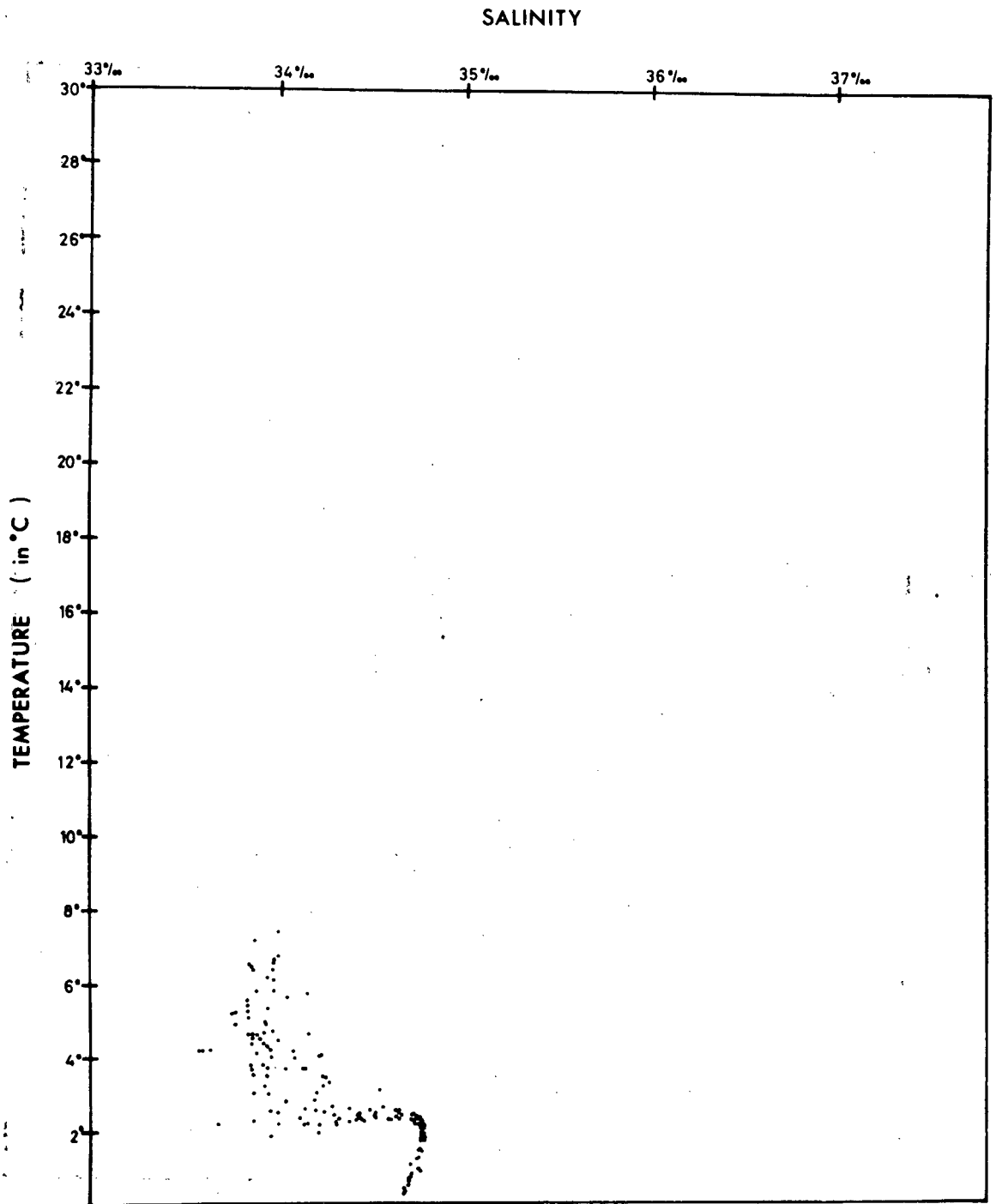


figure 4.8

T/S scatter diagram for stations between the Antarctic Polar Front and Subtropical Convergence.

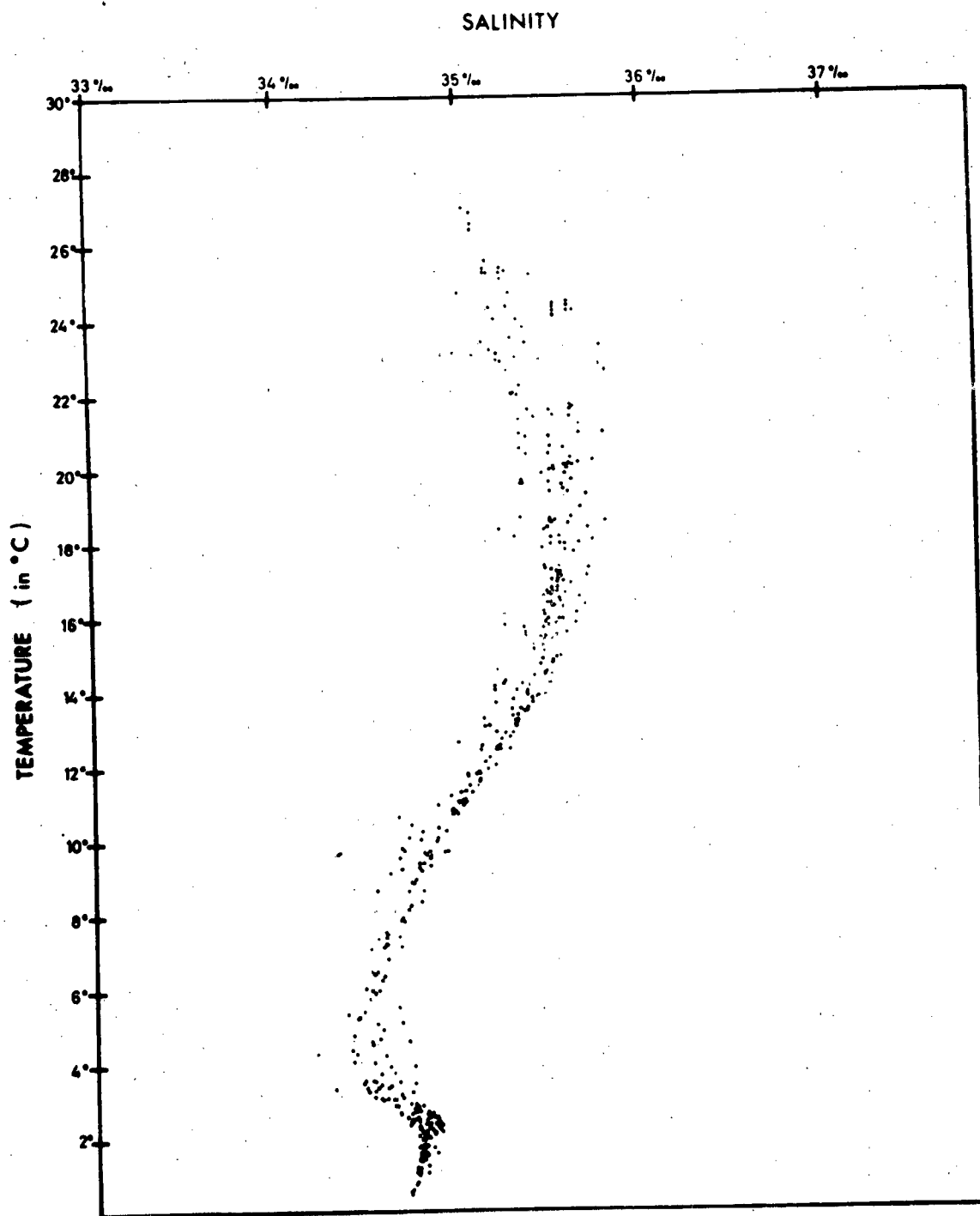


figure 4.9

T/S scatter diagram for stations between the Subtropical Convergence and the "Tropical Front".

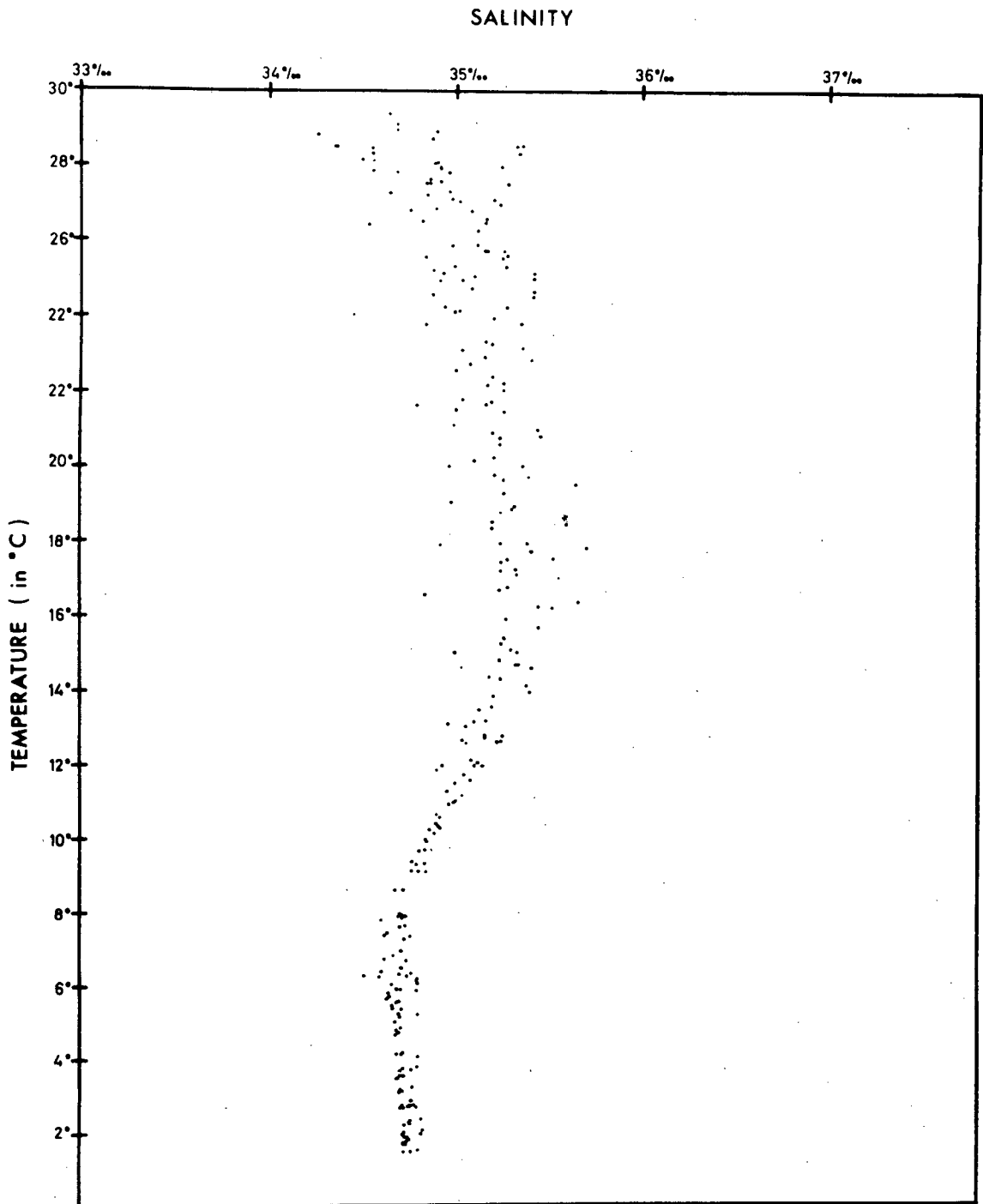


figure 4.10

T/S scatter diagram for stations between "Tropical Front" and 10° South.

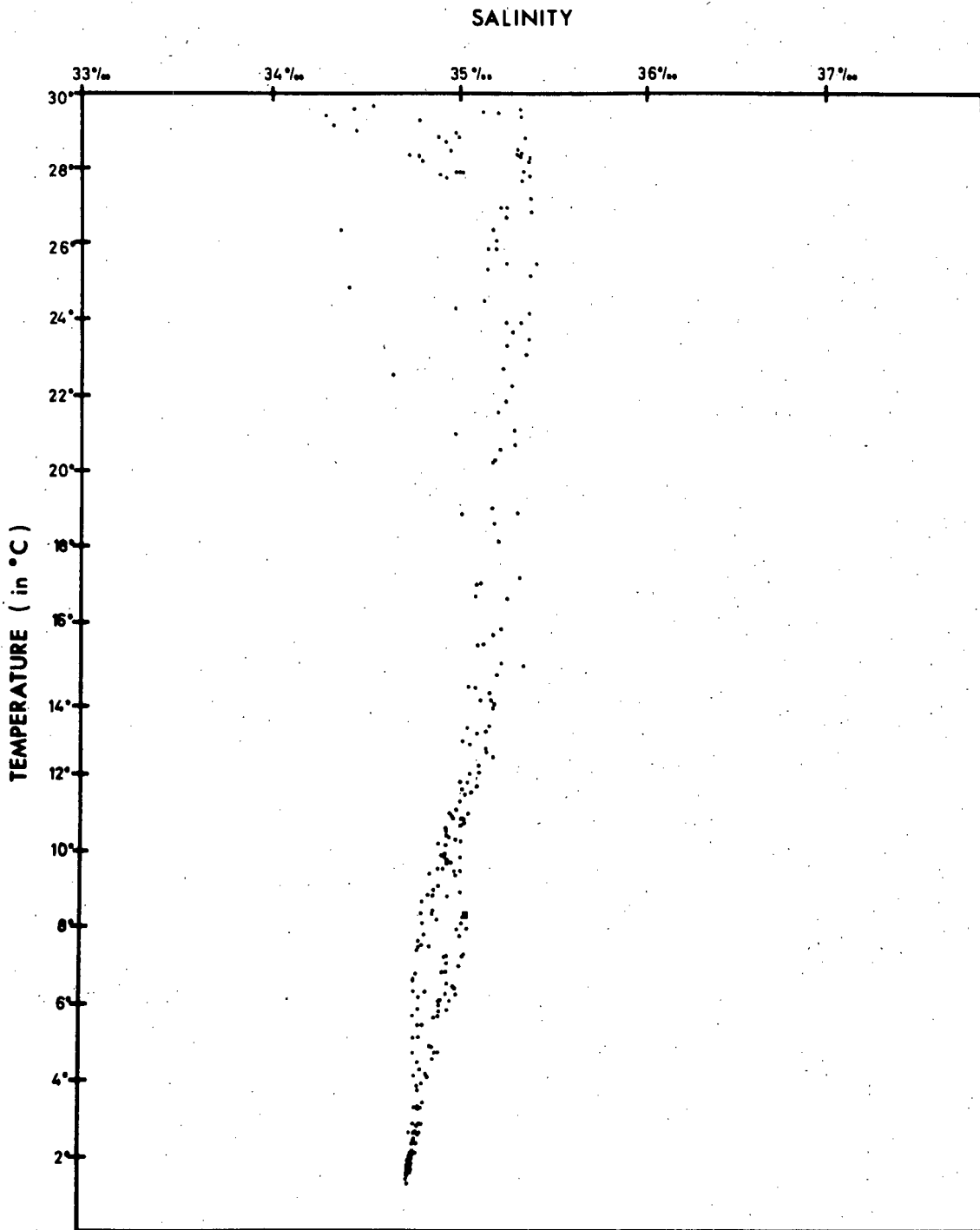


figure 4.11

T/S scatter diagram for stations between 10° South and the equator.

carded in favour of the isentropic method.

In an attempt to incorporate some of the good elements of the core method, the σ_t -surfaces used in the isentropic method were chosen with great care. It was felt that a σ_t -layer chosen in such a way that, on the average, it lay near the core of a water mass would in practice differ very little from the core itself as far as the distribution of identifying properties is concerned.

To this end an oceanographic station was selected in every 5° square where possible and the measured characteristics of this station transposed onto a T/S scatter diagram (figure 4.6). The stations selected for this scatter diagram are ringed on figure 4.5 and are, wherever possible, close to the centre of the square and have deep measurements. Table IV.4 is a list of these stations. The characteristic diagrams fell into four natural categories: those stations south of the Antarctic Polar Front, those between the Antarctic Polar Front and the Subtropical Convergence, those between the Subtropical Convergence and 10°S (the South Equatorial Current) and those between 10°S and the equator. The group falling between the Subtropical Convergence and 10°S formed a dispersed scatter diagram until a separation was made into two natural groups. This natural division seemed to indicate a "Tropical Convergence" at about 25°S as mentioned by Orren (1966) and Deacon (1933,1937), which might be the boundary between the Indian Ocean Central Water and Indian Ocean Equatorial Water (Sverdrup et al. 1942). These five scatter diagrams are presented as figures 4.7 to 4.11. The way in which these stations were distributed for the various categories is given in table IV.6 in appendix IV. On closer examination of these scatter

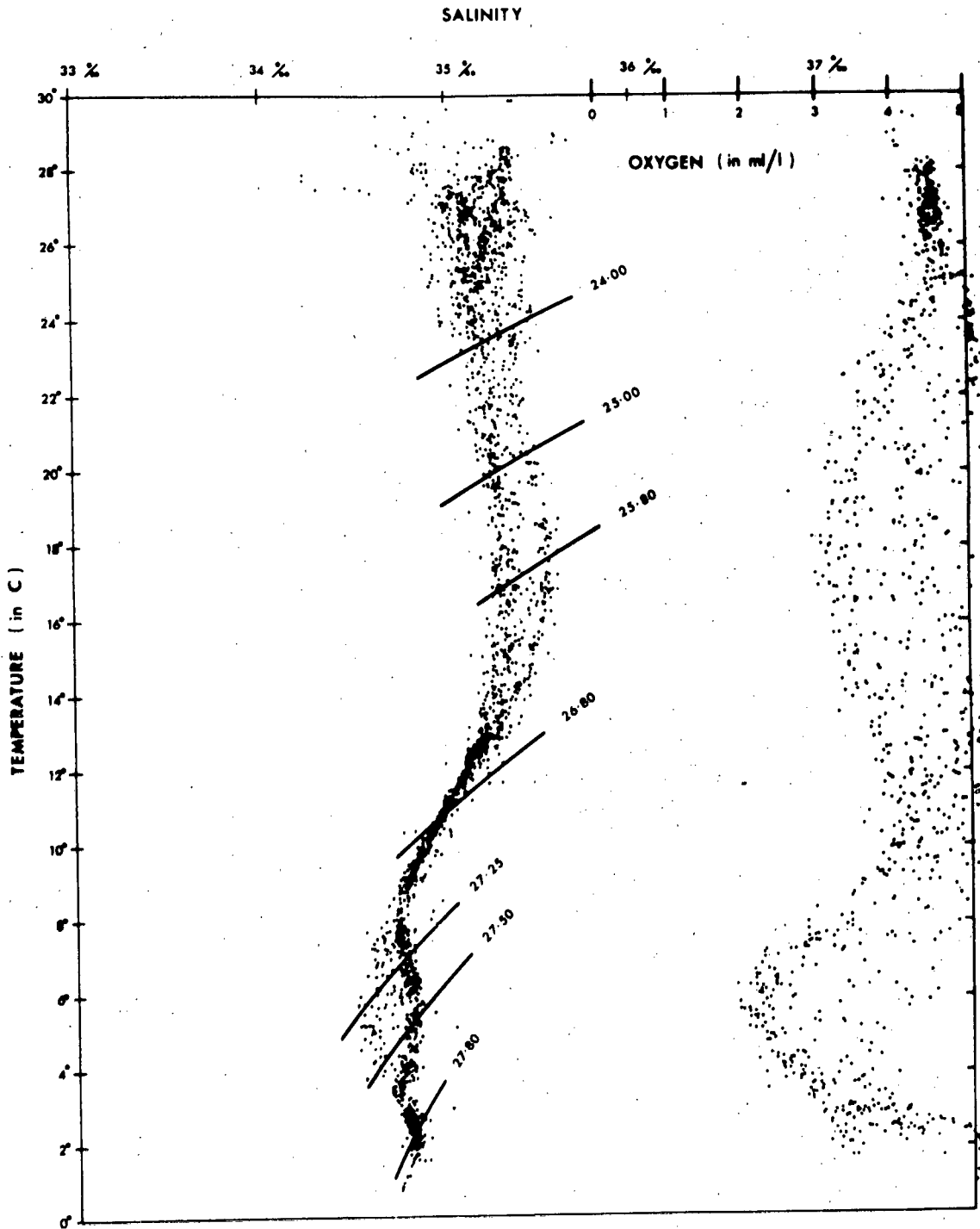


figure 4.12

T/S and T/O₂ scatter diagrams for the Mozambique Channel showing selected σ_t levels.

diagrams it was decided not to include into this study the area south of the Subtropical Convergence. It was felt that the natural boundary for the South West Indian Ocean would be the latitude 40°S . This would exclude the complications of dealing with the water masses at the Antarctic Polar Front and Subtropical Convergence. The equator was chosen as the northern boundary so as to include the whole of the South Equatorial Current and at least part of the Equatorial Counter Current. The western limit was decided on as the 25°E meridian. This includes the bulk of the Agulhas Current without covering the complicated area of the recurvature of the Agulhas. The eastern boundary was chosen to be 70°E .

To support the general T/S scatter diagram, a detailed scatter diagram was drawn for a restricted area including all the available stations in this area for the Northeast Monsoon period. The Mozambique Channel was chosen for its natural boundaries as an ocean area and because both the Antarctic Intermediate and the North Indian Deep Waters are present there. A temperature/oxygen-scatter diagram was also constructed on the same diagram. These are depicted in figure 4.12. The σ_t -surfaces chosen for the isentropic method are given on both figure 4.12 and figure 4.6. The average σ_t -values for the various maxima and minima of the identifying properties salinity, oxygen content and phosphate content were calculated for about a hundred stations with equal numbers coming from each Marsden square. From these the following σ_t -surfaces were chosen. Apart from the sea surface which was selected for general interest, the σ_t 24.00 surface was chosen as being within 50 m of the surface and giving an indication of surface flow without being completely dominated by surface

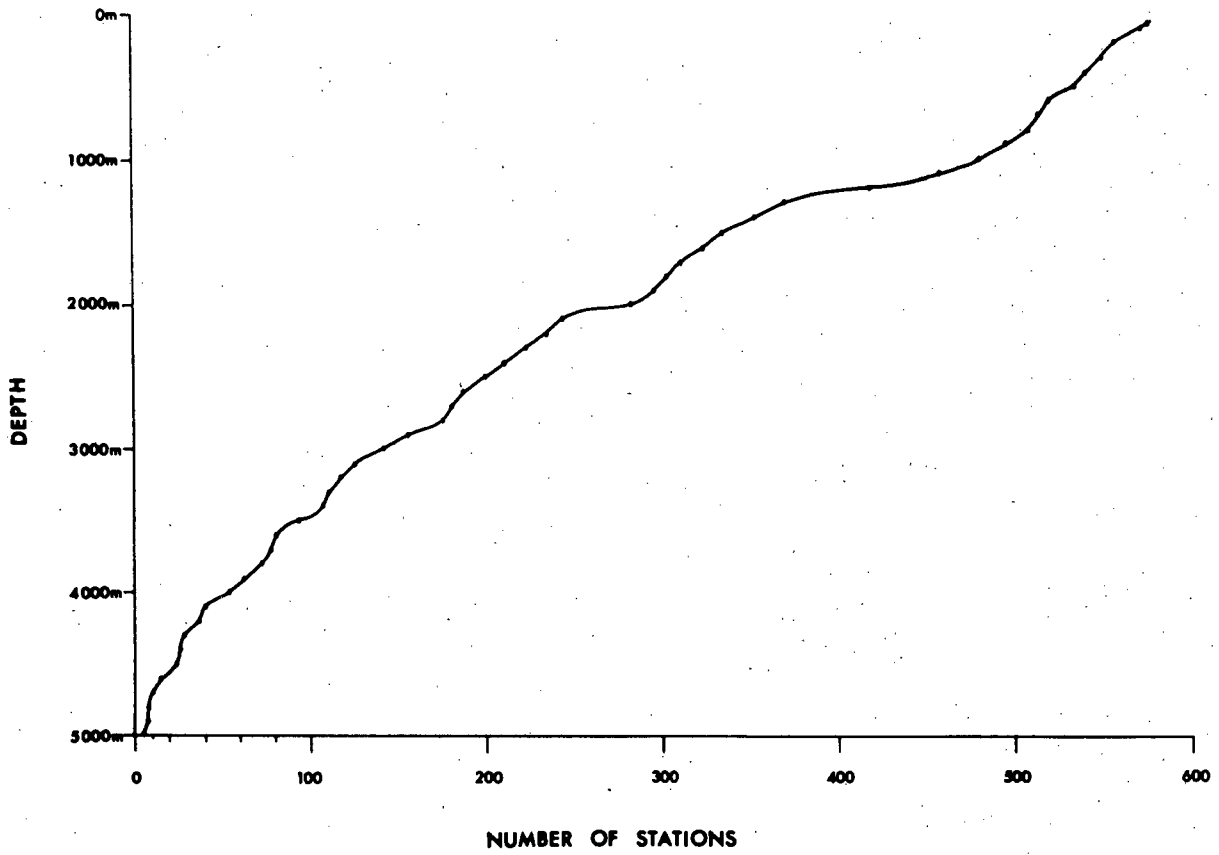


figure 4.13

Curve relating number of oceanographic stations in the South West Indian Ocean to sampling depth.

variability. The σ_t 25.00 surface was chosen for the same reason, with more reason to believe that it would not be overly influenced by surface changes. The first salinity maximum coincided with the 25.80 σ_t -surface which lies at about 200 m. The σ_t 26.80 surface was chosen for its oxygen maximum and for lying in the middle of the Central Water. It lies at about 500 m. At about 1000 m the salinity minimum of the Antarctic Intermediate Water is found which has a σ_t value of 27.25. The other two σ_t -surfaces are the 27.50 surface (salinity maximum, oxygen minimum, North Indian Deep Water) at 1200 m and the 27.80 surface (salinity maximum) showing signs of the North Atlantic Bottom Water at 2400 m. At depths greater than this the isentropic method is unreliable.

4.4 PROCESSING OF THE DATA

Having decided on the oceanic area to investigate, the time of year to cover and the method to apply and having collected all the available data, it was now necessary to extract from the data the values of the identifying properties on the chosen σ_t -surfaces. A computer program was developed to draw the characteristic diagrams for each station, plotting all the measured values and drawing a smoothed curve through them. This program is presented and discussed in appendix I. An example of such a set of curves as drawn by the program is portrayed in figure 4.15. It shows the ease with which the needed information can be extracted. To judge the accuracy of the extracted information is difficult. The actual measuring values are plotted as exact as the plotter will allow which

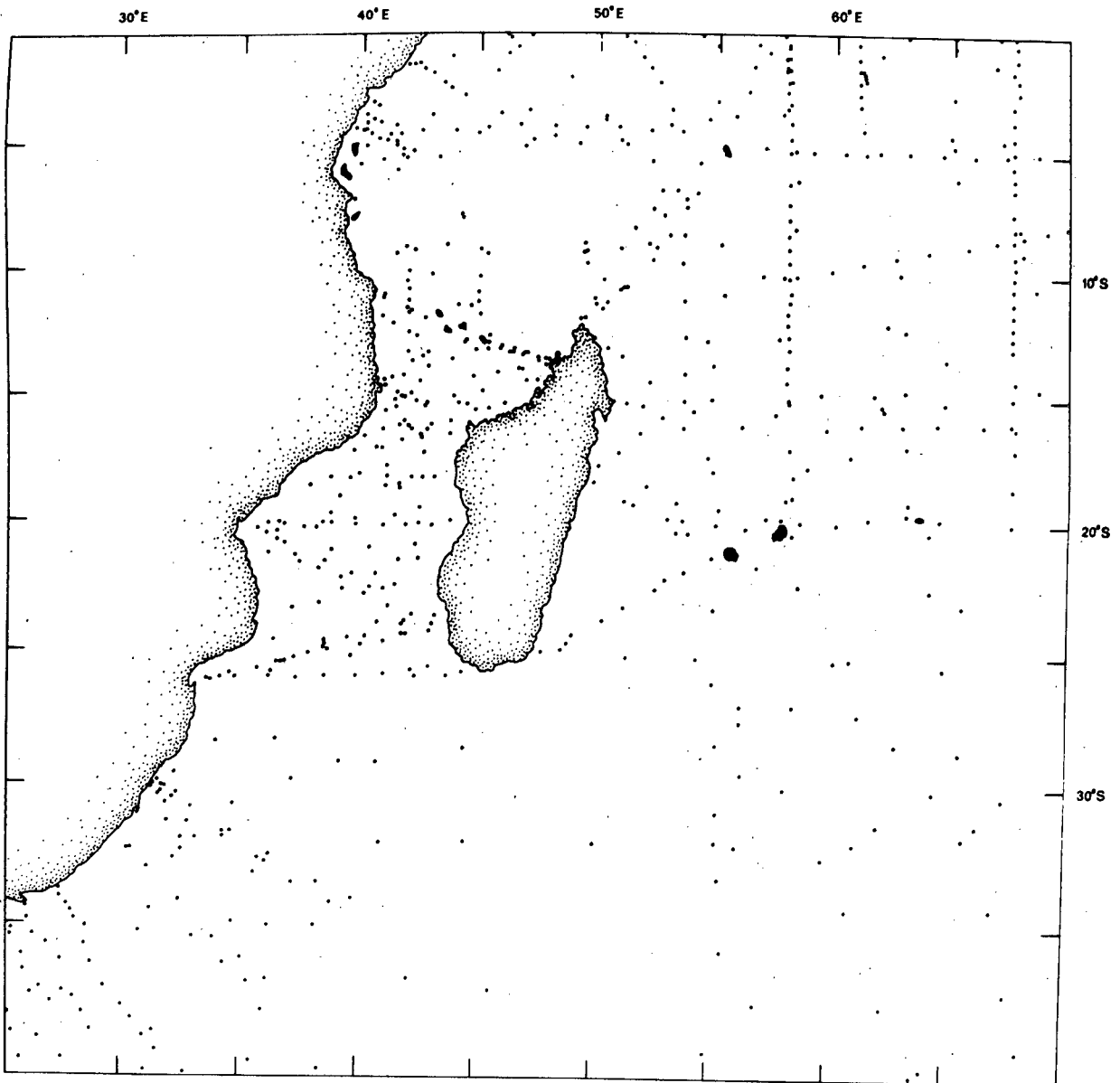


figure 4.14

Positions of all oceanographic stations used for the Northeast Monsoon season.

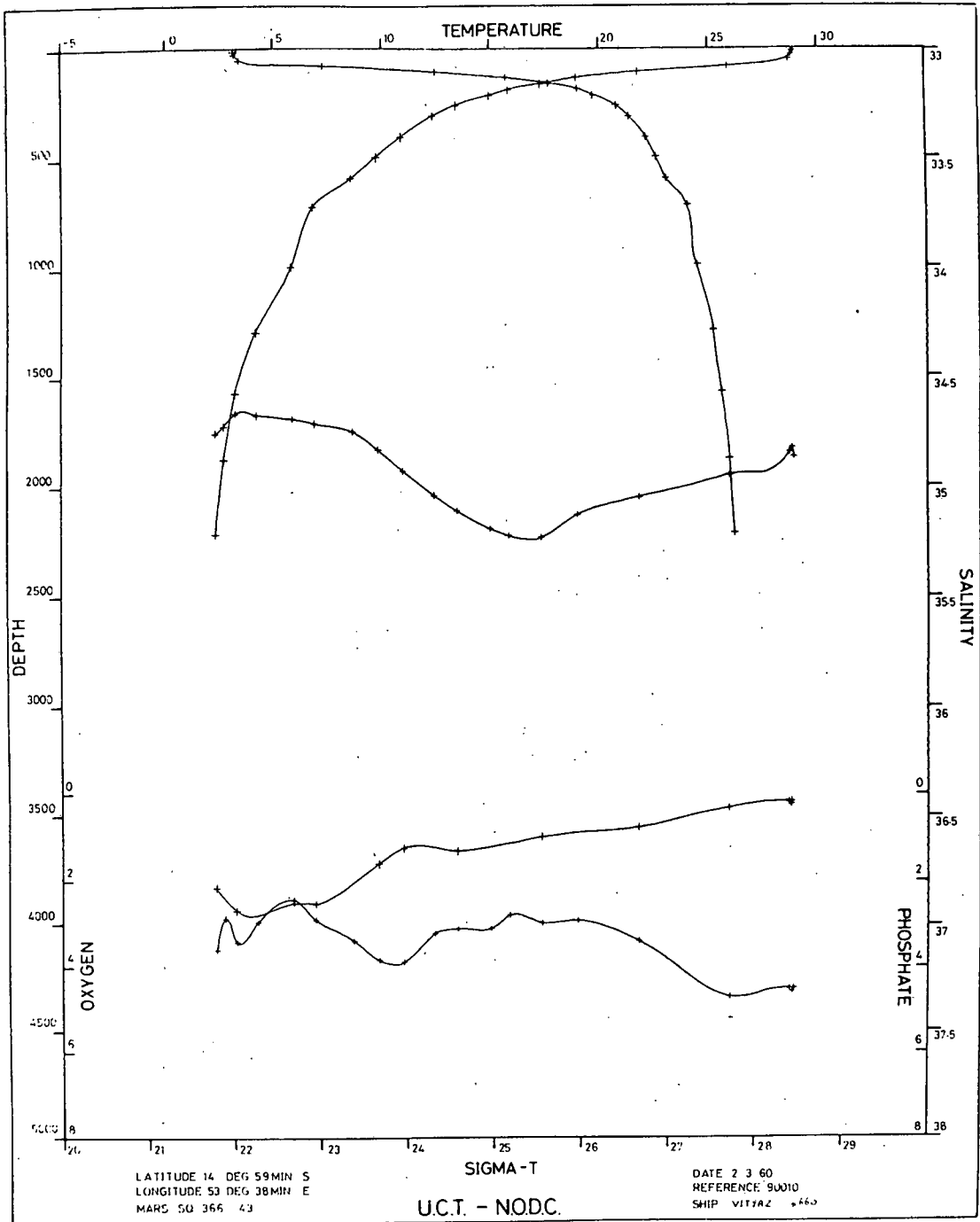


figure 4.15

An example of the set of characteristic curves as drawn by the computer program.

is an order of ten smaller than the measuring accuracy. The interpolation is objective in so far as it is done by a machine but there is no reason to believe that the second degree polynomial fit used approaches to actual ocean conditions. Suffice to say that it is better than a linear interpolation.

All the stations for which characteristic curves were drawn and which were subsequently used to construct σ_t -surface diagrams are depicted in figure 4.14. Stations actually used on a particular σ_t -surface were selected as follows: all stations falling in a one-degree square were considered for depth, month and age. Preference was given to the most recent stations that were occupied closest in time to the April end of the Northeast Monsoon Season. Near the surface the choice was wider (see figure 4.13) so that 60.0% of the stations used here fell in the months March and April. In the deeper layers the choice was restricted and at σ_t 27.50, for instance, only 41.1% of the stations used fell in the months March and April. In the deeper layers the seasonal changes would be less likely to have much effect. The use made of stations that were occupied earlier in the season to make up for a deficiency of deep stations occupied towards the end of the season would thus probably not be felt. Taking into consideration the correlation between the wind regimes and current regimes as shown by Verploegh (1960) and discussed before, this choice of stations should succeed very well in capturing the impression of this season. For the very deep water a few stations were used in areas of no data-coverage that fell right outside the Northeast Monsoon Season. The list of all the stations used is in table IV.1.

When the positions of the stations selected in this way

were plotted on the diagrams for the σ_t -levels (figures 5.1 - 39) only the actual positions of some stations were plotted. These included close inshore stations and stations in areas where accuracy was thought to be important such as the Davie cruise in the Agulhas dispersion area. Positions of other stations were plotted in the middle of the one-degree square to which they belong. This would give an 80% probability that the plotted position was within 30 nautical miles from the actual position, an accuracy which, in view of the scale used, was thought to be quite sufficient for the type of work.

Contouring of the isolines for the different identifying properties was done by hand as objectively as possible (see also Crawford 1970). Wherever, due to the lack of stations or the nature of the data, contouring had a stronger element of subjectivity, dashed lines were drawn.

The average depth of all σ_t -surfaces were calculated from all the stations used for a particular σ_t -surface. Bearing in mind the particular depths of the σ_t -surface for close inshore stations, the line where this σ_t -surface cuts the sea-bottom was drawn on the diagrams. The bathymetry used for this was that of Chart 123A by Simpson & Forder (1969) and in the northern part the Carte Générale Bathymétrique des Océans (— 1938) as published by the International Hydrographic Bureau (see figure 6.1).

4.5 CHOICE OF SUPPLEMENTARY METHODS

The interpretation of the isolines of any identifying property on a σ_t -surface is the basis on which the whole isentropic method rests. This is closely aligned with the whole theory of the tonguelike distribution of properties. The dynamic method, which neglects viscosity and therefore by implication mixing, gives an interpretation of tongues of properties that is, in the case of factors effecting density (i.e. temperature), the exact opposite to that of a core analysis of water masses (Lacombe, 1965, p.133). The core method follows the extreme values of an identifying property. In a vertical section this would imply an interpretation that the spread of water is jetlike and that the axes of the jet-currents would coincide with the tongues of the identifying property being considered, in other words, that the water moves perpendicular to the isolines. The form of these tongues has been discussed by Defant (1961, p.106). Sverdrup et al. (1942) points out however, that in a horizontal (or level) section the dynamics of the system have to be borne in mind, and that in this case, according to the dynamic method, water would flow parallel to the isolines. This he proved to be the case by direct measurement. In other words, on a horizontal section the two methods give completely different interpretations. Whereas in a section that is level the interpretation of water flow perpendicular to the isolines does not take into account the pressure gradients from the distribution of mass, in the isentropic method the σ_t -surface is not level, but has a topography of its own that does take this into consideration. Another

problem in interpreting tongues arises however.

This hinges on the facts that we are only dealing with a limited part of the ocean and that the speeds of the various currents on the same level may differ greatly. We are assuming in the isentropic analysis that the water as a rule moves perpendicular to isolines. If the intervals of the isolines have been chosen in such a way that water enters and leaves the area without having changed its identifying property enough to merit a new isoline, the isolines run parallel to the main flow.

Yet another problem arises in the case where there exists say, an area of high salinity opposite an area of low salinity with water of medium salinity flowing between these. Although the isolines may be shifted bodily, the medium salinity water will show little sign of its movement as it flows parallel to the isolines. If the high and low salinity values of the two adjacent water masses are not mirrored in similar high and low values for other identifying properties, the flow of medium salinity water will show up in the distribution of these other properties. These two extreme cases illustrate the danger inherent in the interpretation.

To overcome this danger, to make the analysis less dependent on combinations of non-synoptic data and to add some measure of three-dimensionality to the analysis, it was decided to select lines of synoptic stations in suitable localities, to calculate the volume transport across the vertical sections these form and to make a detailed analysis of velocity and transport for all the density layers across these sections. This would enlarge the scope of the original analysis by adding some quantitative measurements and furthermore, with the help

of velocities at certain density levels, help with the interpretations of the isolines, i.e. to determine whether the main flow is parallel or perpendicular to these.

At this point it is important to stress that due to the non-synoptic nature between the data forming a vertical section and those lying next to it, the velocities at certain σ -surfaces are not a rigidly full-proof way of determining the nature of the flow relative to isolines but only give an important indication of the possible flow and may therefore act as a guide only. Since the isolines are drawn according to stations which include those used for the sections the isolines will, close to the sections, show a remarkable agreement with the calculated velocities. One should be careful not to attach too much importance to this, since this is only to be expected in applying different methods to the same data.

As part of the results of this study the depth topography of all σ -surfaces was drawn, indicating the water movement on these by arrowheads on the isobaths (see figure 5.5 for example). This was always done keeping the deeper part of the σ -surface to the left of the flow. The directions of the currents depicted on a certain σ -surface in this way may be misleading since theoretically, keeping the deeper part of the σ -surface to the left is only correct if the water velocity with depth decreases. In cases where velocity with depth increases the σ -surfaces slope the other way and the arrowheads on the isobaths may thus be deceptive. The second important reason for calculating the velocities at the σ -surfaces was then to be able to correctly interpret whether the isobaths in a certain locality depict the direction of

flow correctly.

The standard Witte-Margules equation (Neumann 1968) was used for velocity calculations. This states that

$$\tan \gamma = - \frac{f}{g} \frac{\rho_1 V_1 - \rho_2 V_2}{\rho_1 - \rho_2}$$

where γ is the slope of the density interface of water masses with densities ρ_1 and ρ_2 , f the Coriolis parameter, ρ_2 representing the density of the lighter water and V_2 its velocity. Calling $\rho_1 - \rho_2 = \Delta\rho$, the density interval, and replacing ρ_1 and ρ_2 by ρ_m , the mean density, this equation becomes

$$V_1 - V_2 = \frac{g \Delta\rho}{\rho_m f} \tan \gamma$$

Since the velocity V_2 of the layer with density ρ_2 depends on the velocity V_1 of the layer below this with density ρ_1 , the absolute velocity can only be determined if we select a reference level at which the velocity is zero.

As mentioned previously, the choice of a reference level is also part of the dynamic method and some research has been done on this (Mamayev 1960). Le Pichon (1960), after a very careful investigation decided that a reference level between 2000 m and 2500 m for this region agreed best with both the core method and the Defant method. Darbyshire (1964) used 1000 m as reference level but Orren (1966) showed that this was erroneous. Visser & van Niekerk (1965) found the 2000 db level a far more satisfactory reference surface. Duncan (1970) decided that the 2500 m level was most satisfactory, but that shortage of stations forced him to use 1000 m. He then also

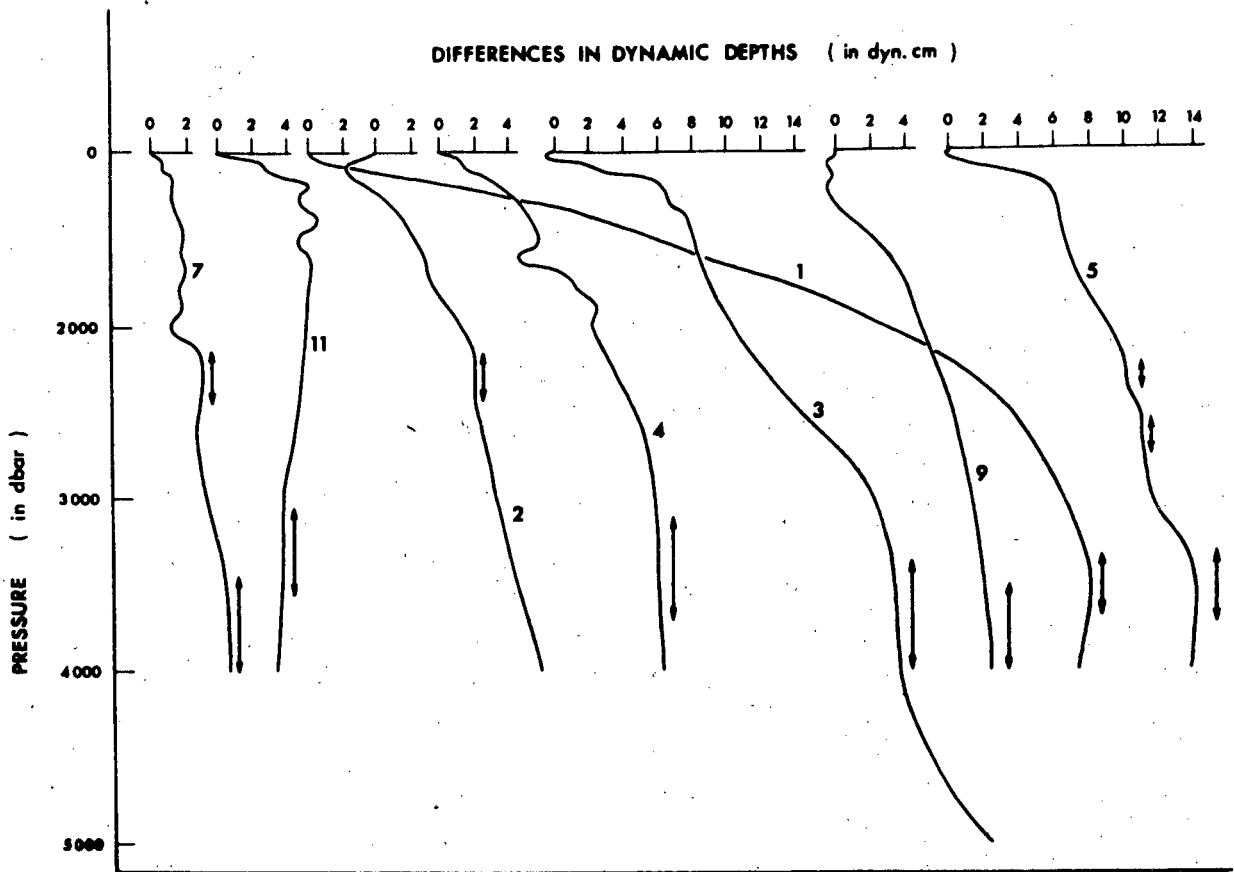


figure 4.16

Vertical distribution of differences on the dynamic depths of the standard pressures of a few selected pairs of neighbouring stations. (Defant's method) The numbers relate to station pairs as shown in figure 4.17.

used this level for his mass transport calculations. He justifies this by showing that the mass transport above 1000 m bears a constant relation to that between 1000 and 2500 m. For this he uses a mean curve for the velocity/depth relation of pairs of stations in the core of the current. Since he then extrapolates to the whole ocean area where velocity/depth relations are different (see figure 4.17), this seems a rather doubtful method.

To decide on a reference level for this work Defant's method was used. This method (Defant 1961) calls for the plotting of the differences in dynamic depths of standard pressure levels of two neighbouring stations against depth. In a graph of this sort there usually exists a layer of considerable vertical thickness in which the differences in dynamic depth are constant or almost constant. It is then assumed that this layer contains the reference level.

This method was applied to the data available. About a hundred stations, the measurements of which exceeded depths of 3000 m, were extracted from the data. From these only 15 synoptic station pairs were suitable for this type of calculation. Eight of those analysed are shown in figure 4.16. Arrows have been incorporated to show areas which may include a reference level. From these it is clear that a reference level probably exists at about 2500 m and a possible secondary one at about 1200 m. The same stations were also used to determine the curves relating velocity to depth according to the Witte-Margules equation. In this case the level of no motion was taken as the depth of the deepest measurement for each particular station pair. Some of these curves, as well as the geographical positions of the station pairs used, are

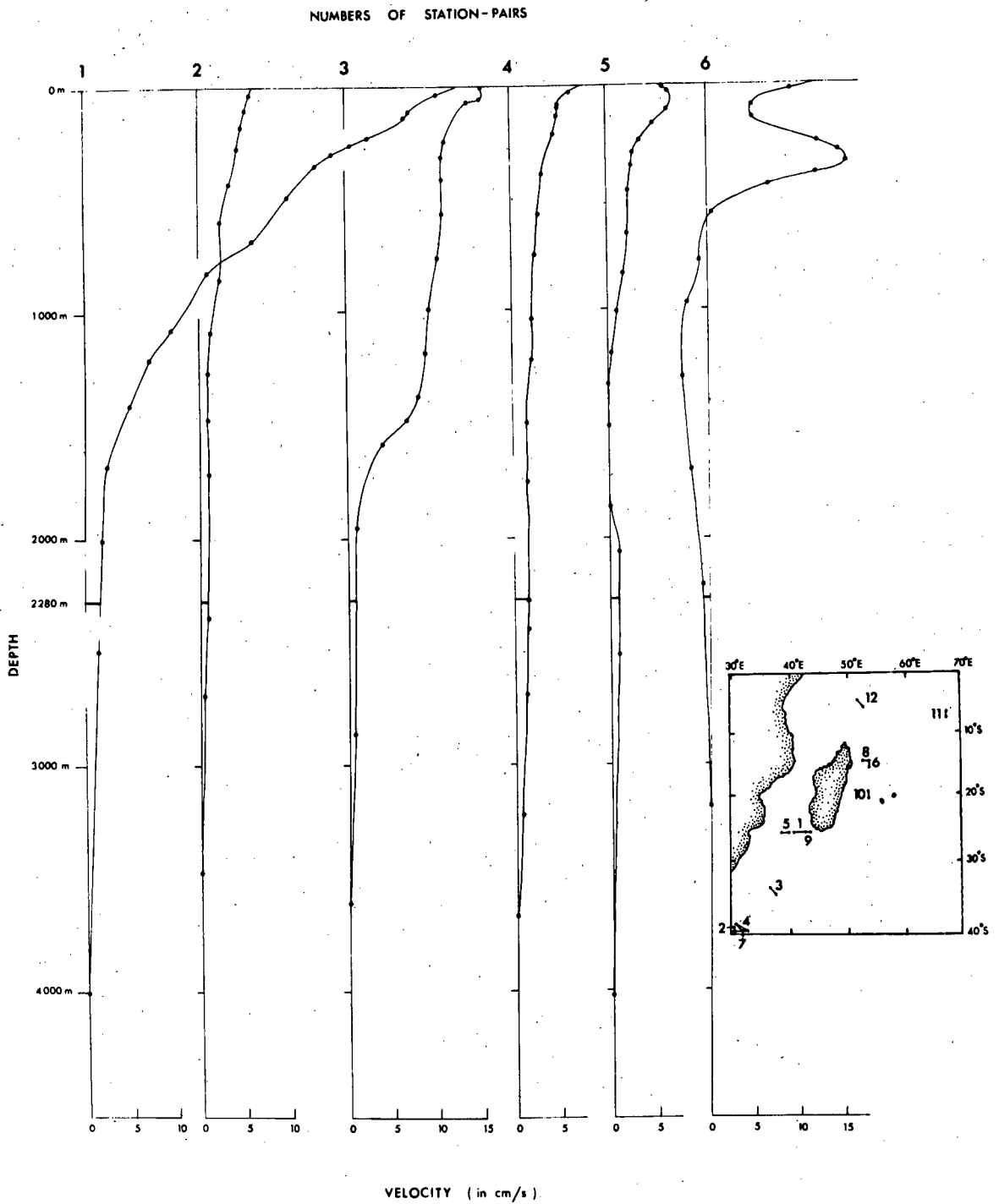


figure 4.17

Curve relating water velocity to depth for selected pairs of deep oceanographic stations.

depicted in figure 4.17. The stations used for these two analyses are given in table IV.3. From these curves it emerges that the velocity at 2250 m does not vary greatly from station to station. The average over ten selected deep stations is 0.75 cm/s with a standard deviation $\sigma = 0.51$ cm/s, hence, with a 67% probability, the velocity lies between 1.26 and 0.24 cm/s. The velocity above 2500 m and above 1000 m varies greatly from station pair to station pair however, so that the volume transport above 1000 m bears no constant relation to the volume transport between 1000 and 2500 m as shown by Duncan for station pairs in the main line of the current.

With the results of previous work and the two above calculations in mind, as well as for practical reasons, the 2280 m level was chosen as the reference level. If the level-of-no-motion had been chosen as the ocean bed, the additional transport would be very small, so that the error in the calculations is negligible.

Having decided on the method to be applied and the reference level, the actual lines of stations were chosen. These are shown in figure 4.18. Each one (excepting G) belongs to one synoptic cruise during which the stations for each line were done consecutively. Of about twenty possible lines that were available, these were chosen for their depth of measurement, closeness of measuring points both horizontally and vertically, position in the ocean and month in which they were done. Since one of the objects of the incorporation of these vertical sections into the work was to avoid using only combinations of non-synoptic data, only in one case was non-synoptic

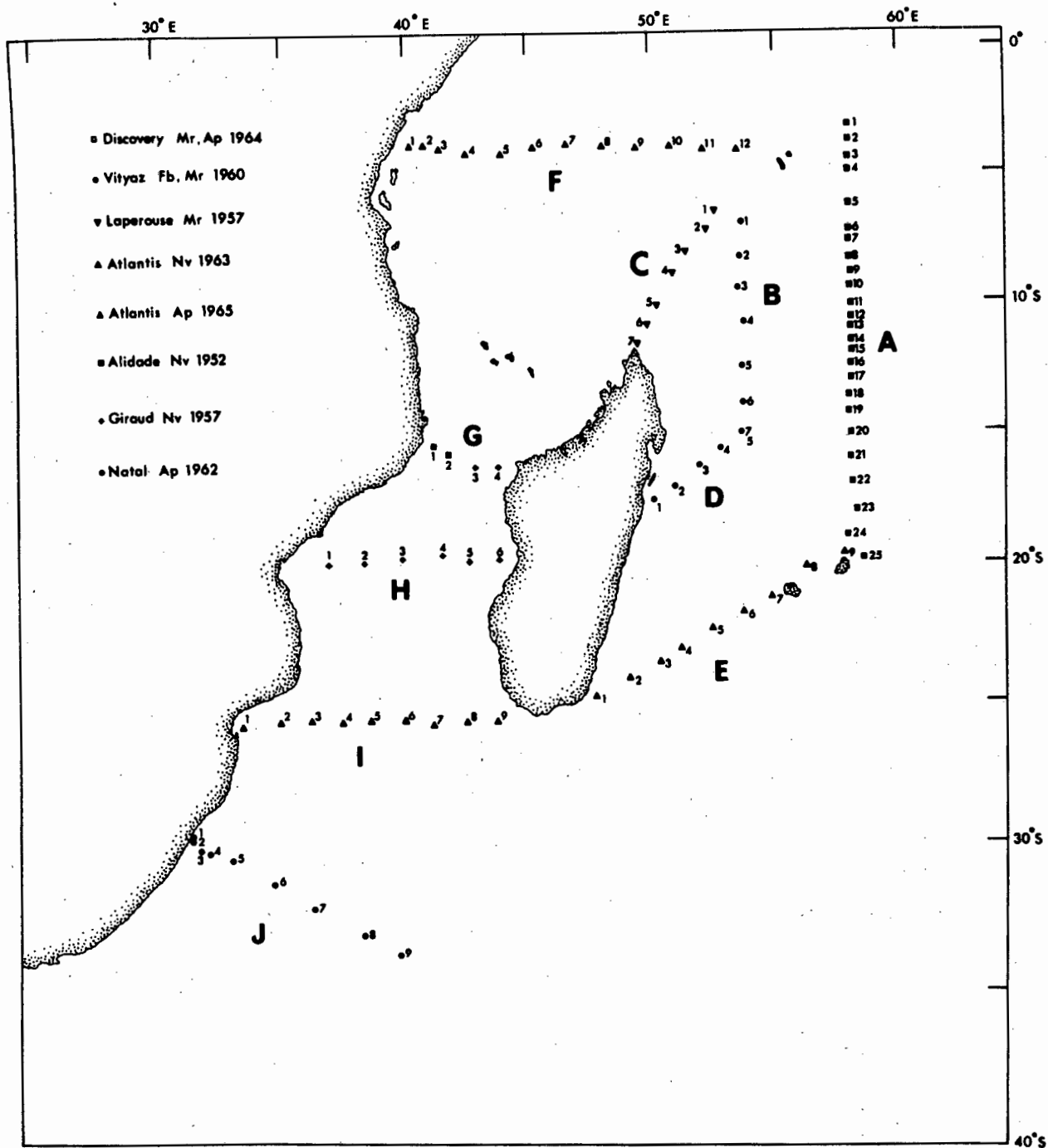


figure 4.18

Geographical location of lines of oceanographic stations selected for vertical sections.

data combined. Otherwise the sections will give the true volume transport within the assumptions of the Witte-Margules equation, velocity profiles and oxygen distribution for each line of oceanographic stations. Some lines or part of lines (F; A, B, C) are quite near the equator which may seem unsuitable for velocity or transport calculations since theoretically the Coriolis force disappears at the equator. Lacombe (1965, p.118) states that for depths of the order of 200 m the Coriolis force still exceeds the force of friction for latitudes of 30' south or north. Tchernia et al. (1958) have shown this experimentally when they proved that very close to the equator in the Indian Ocean the surface velocity as measured by G.E.K. and the calculated geostrophic velocity were still comparable. Kendall (1970), working on the Pacific Equatorial Countercurrent found that at 30' south calculated velocities were still of the order to be expected. It would thus seem that the geographical position of our vertical sections falls well within acceptable limits for the type of calculation carried out.

4.6 PROCESSING OF THE DATA FOR THE SUPPLEMENTARY METHODS

Having decided which stations to use, the necessary information on density and oxygen content was extracted from the characteristic curves as plotted by the computer program in the way described before. The bottom topography for each vertical section was carefully determined from the two bathymetric charts mentioned in the previous paragraph. The isolines of the density and oxygen content on these sections were

then drawn. A second computer program was developed that would calculate the cross-sectional area of each 0.20 σ t-layer between two adjacent stations, the velocity of this water according to the Witte-Margules equation and its transport. It also adds up the total transport between stations, the total transport for a 0.20 σ t-layer for the whole section as well as the total transport across the section as a whole. This program is presented and described in detail in appendix II together with two flow diagrams to facilitate its understanding (figures II.1 and II.2).

CHAPTER V

RESULTS

5.1 INTRODUCTION

Having decided on what methods would probably be most useful in solving the existing problems and having applied them, the results presented in this chapter were obtained. They are all in the form of diagrams, most of which are self-explanatory, consequently the accompanying text only draws attention to the main contents of the diagrams. The diagrams fall into eighteen groups of four or five diagrams each, depicting the various identifying properties on a specific σ -surface or the various isolines and transports for a vertical section. Each group is treated as a unit in the text.

The interpretation of these results, the discussion of their implications and what conclusions can be drawn from them will not be done here but extensively in the next chapter.

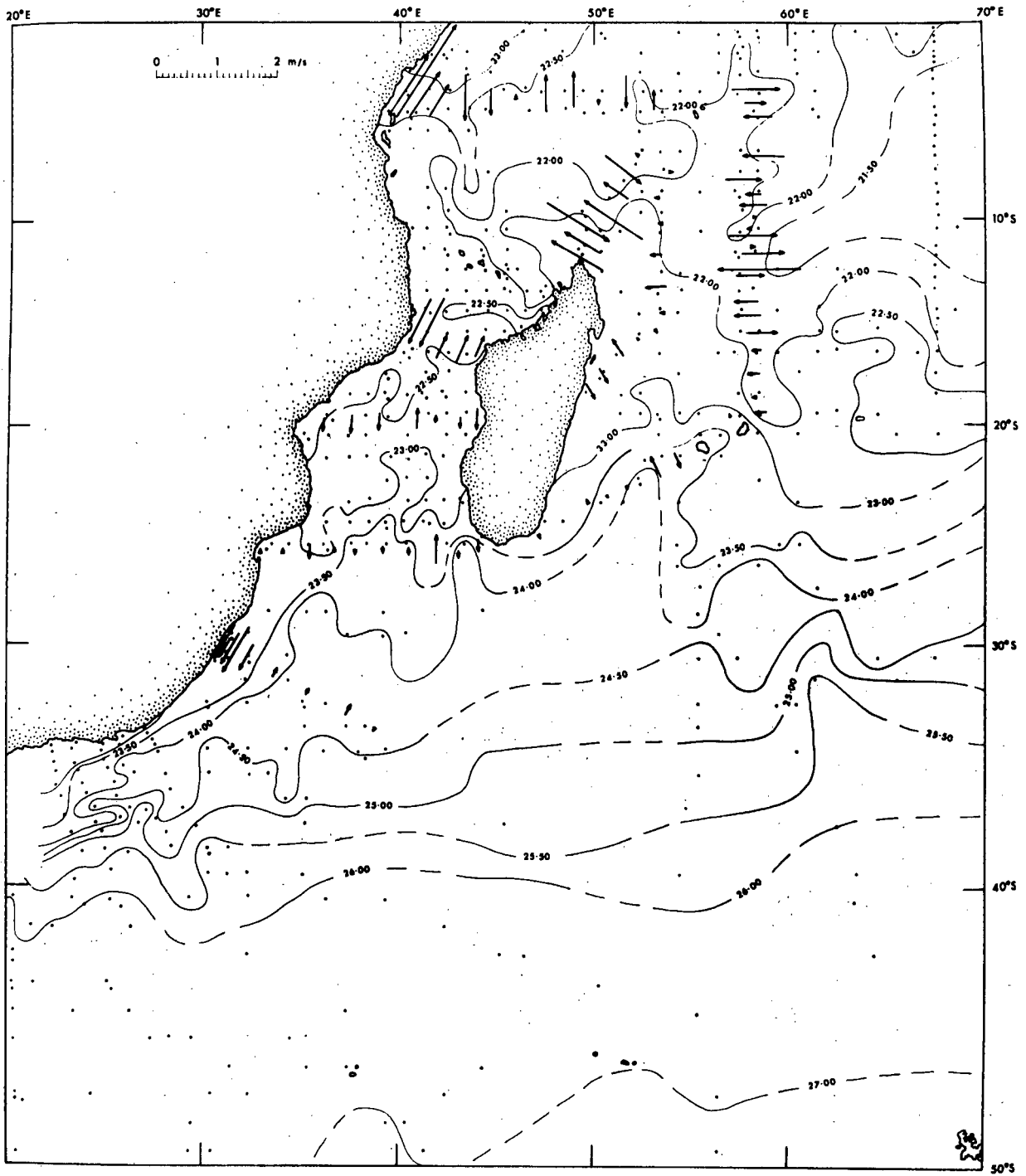


figure 5.1
Distribution of density on the sea surface in the South West
Indian Ocean.

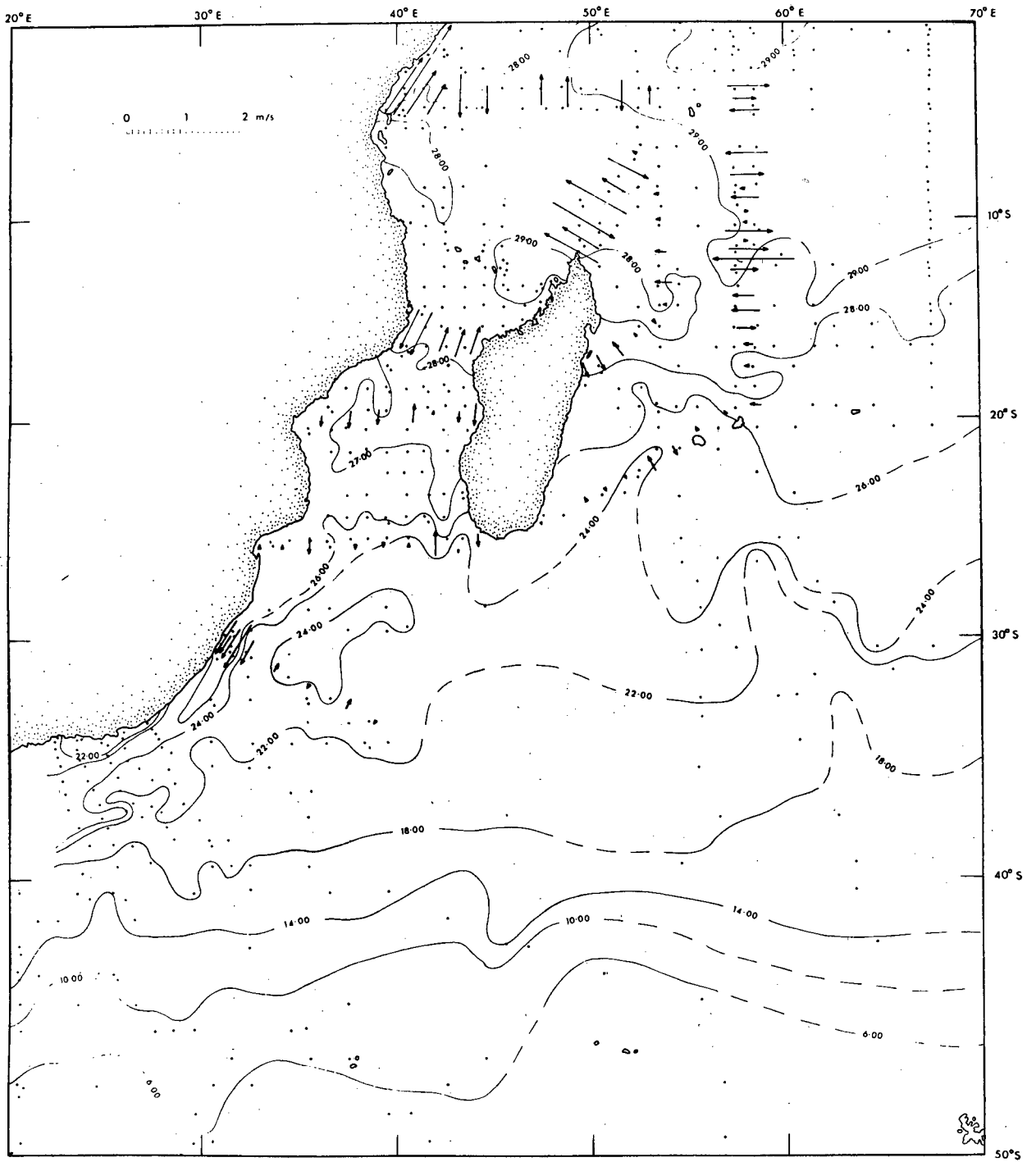


figure 5.2

Distribution of temperature on the sea surface in the South West Indian Ocean.

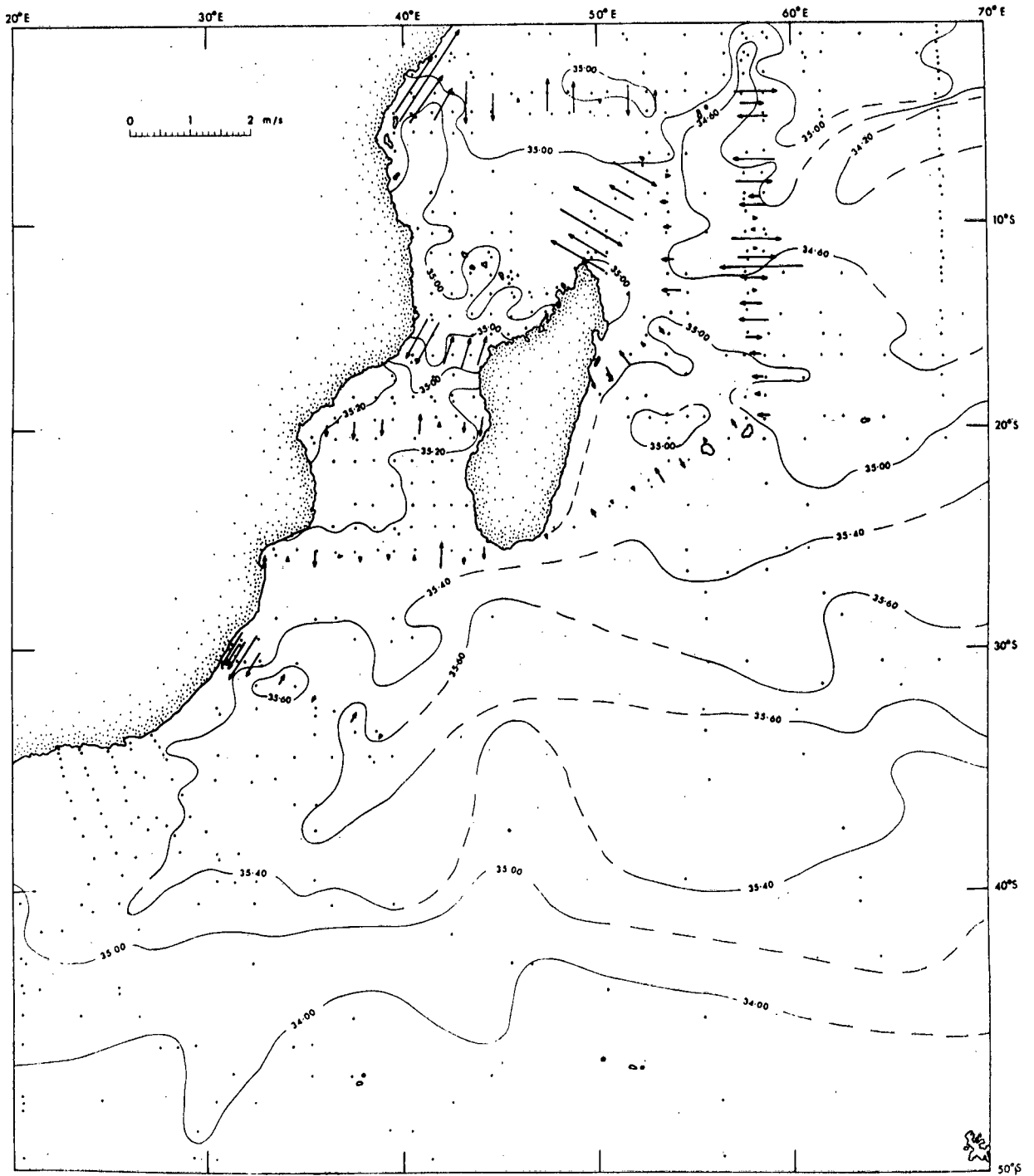


figure 5.3

Distribution of salinity on the sea surface in the South West Indian Ocean.

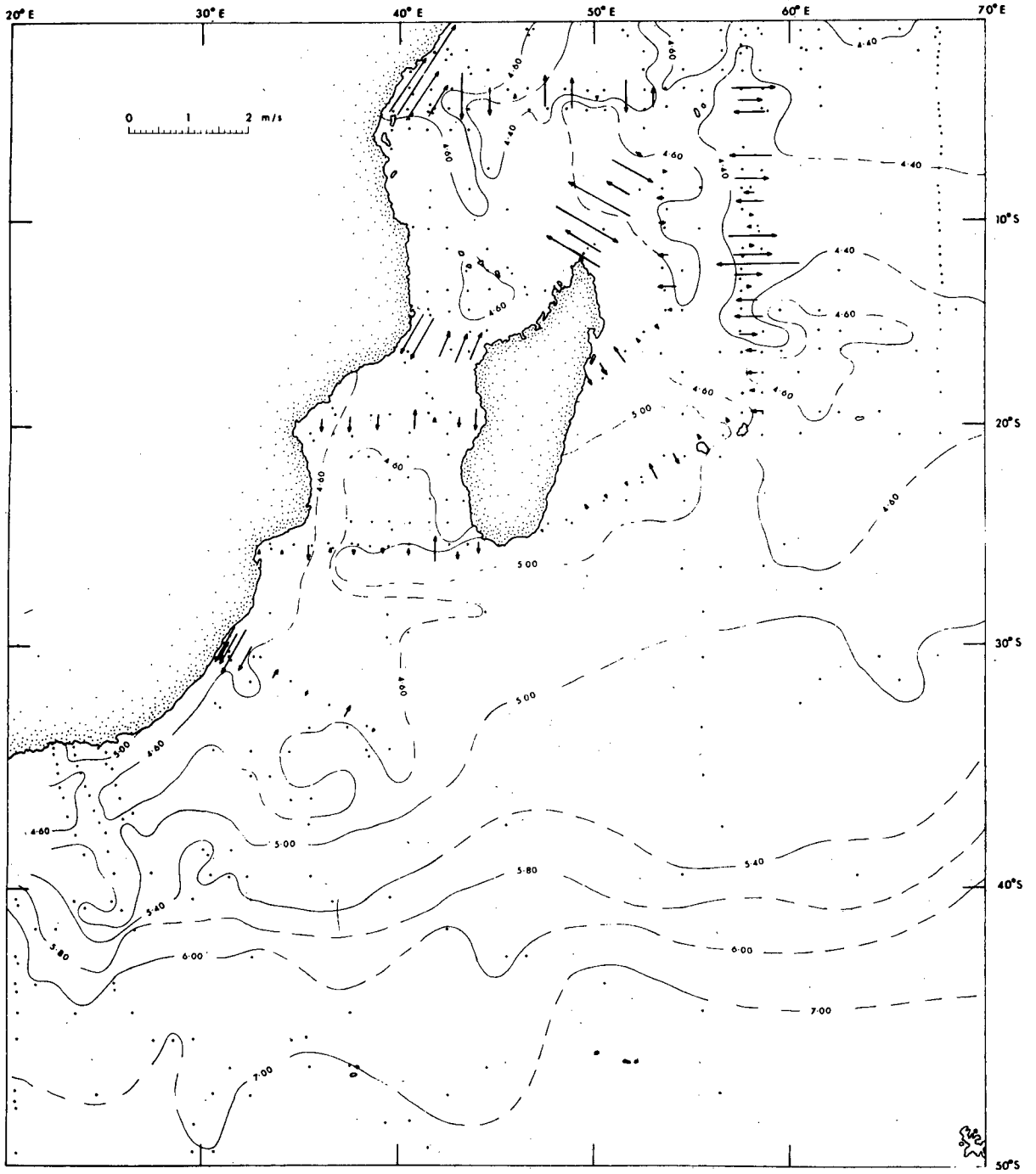


figure 5.4

Distribution of oxygen content on the sea surface in the South West Indian Ocean.

5.2 THE SEA SURFACE (figures 5.1 - 5.4)

The first set of diagrams, depicting the sea surface, covers a greater geographical area than do the succeeding diagrams. By showing the distribution of temperature, salinity and oxygen on the sea surface the reason for using the latitude 40°S as the southern boundary for the investigation stands out clearly. Although the scarcity of stations at this latitude, especially south of Madagascar, makes interpretation difficult, the marked boundary occurring at the Sub-tropical Convergence manifests itself clearly in the temperature and the oxygen distributions.

In a few cases the isolines on the diagrams are not at regular intervals. Extra lines have been added wherever it was thought this might aid interpretation and lines have been omitted where it was felt that their presence added no new information but only confused the interpretation. Wherever the contouring involved contained a large element of subjectivity, a broken isoline was drawn. The dots on the diagram, as mentioned before, represent the approximate positions (± 30 miles) of the stations and have been inserted to give an indication of the trustworthiness of the contouring. In complicated areas such as the retroflexion area of the Agulhas Current and close to the coast, dots represent actual station positions. The positions of the ten vertical sections A to J as depicted in figure 4.18 show up on the σ_t -surface diagrams as rows of arrows. These arrows represent the calculated velocities on the σ_t -surface under consideration and have been calculated between the stations forming the section. They

can be assessed by the scale given in the top right-hand corner of each diagram. These general remarks hold good for all the ot-surface diagrams.

From the combined interpretation of the current arrows and the isolines the basic features of the surface circulation emerge. At about 10°S a tongue of light, warm water of low oxygen and low salinity goes westward from 70°E . From the current arrows it would seem that this tongue depicts the South Equatorial Current with its main axis just south of 10°S . At about the meridian of the Seychelles this water is diverted in its zonal flow, some flowing north (figure 5.1, 5.3 and 5.4) and some flowing south (figure 5.1 and 5.4). Figure 5.1 shows that some of this water carries on past Cape St. Ambre and then flows north and south. The other figures do not show this as clearly, although the current directions support it. The East African Coastal Current and a counter flow seaward of it are shown up well by the arrows and supported by the isopycnals, isohalines and partially so by the oxygen distribution. The Mozambique Channel presents a complex picture with the main current on the western side, a northerly flow towards the middle and a narrow southerly flow in the east. This is borne out best by a combination of the isopycnals and the current arrows. The flow directly east of Madagascar seems not to be very well developed and although it may pass south of Madagascar and flow towards St. Lucia, the mouth of the Mozambique Channel seems to present somewhat of a hydrological barrier (figure 5.1, 5.2). The Agulhas Current itself stands out clearly in all diagrams with an eddy offshore (figure 5.2 and 5.3) noted by the arrows. Some kind of break-

ing off of water from this current takes place at about 35°S (figure 5.1 and 5.4) with an anticyclonic circulation being introduced in this separated water. The northward deflection of the isolines north of the Subtropical Convergence that is most noticeable in figures 5.1 and 5.4 may show that the Agulhas Return Flow has a northerly component. Unfortunately a severe shortage of stations makes any interpretation difficult here.

Since the surface waters are under the constantly varying external influences the results cannot be expected to show up more than just the very gross current structure. The distribution of phosphate content on the surface was so unintelligible that it was not reproduced.

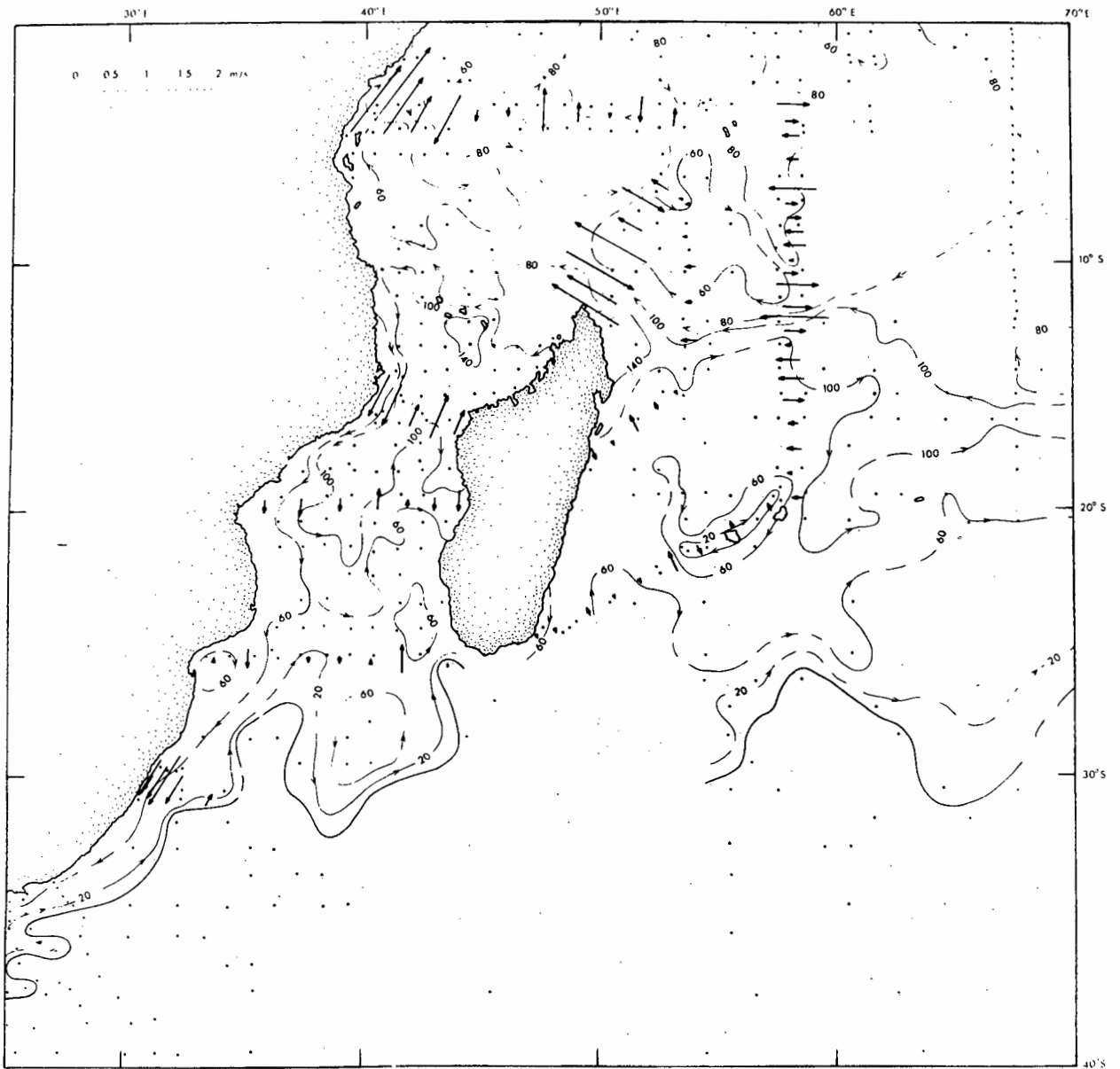


figure 5.5
Depth of σ_t 24.00 level.

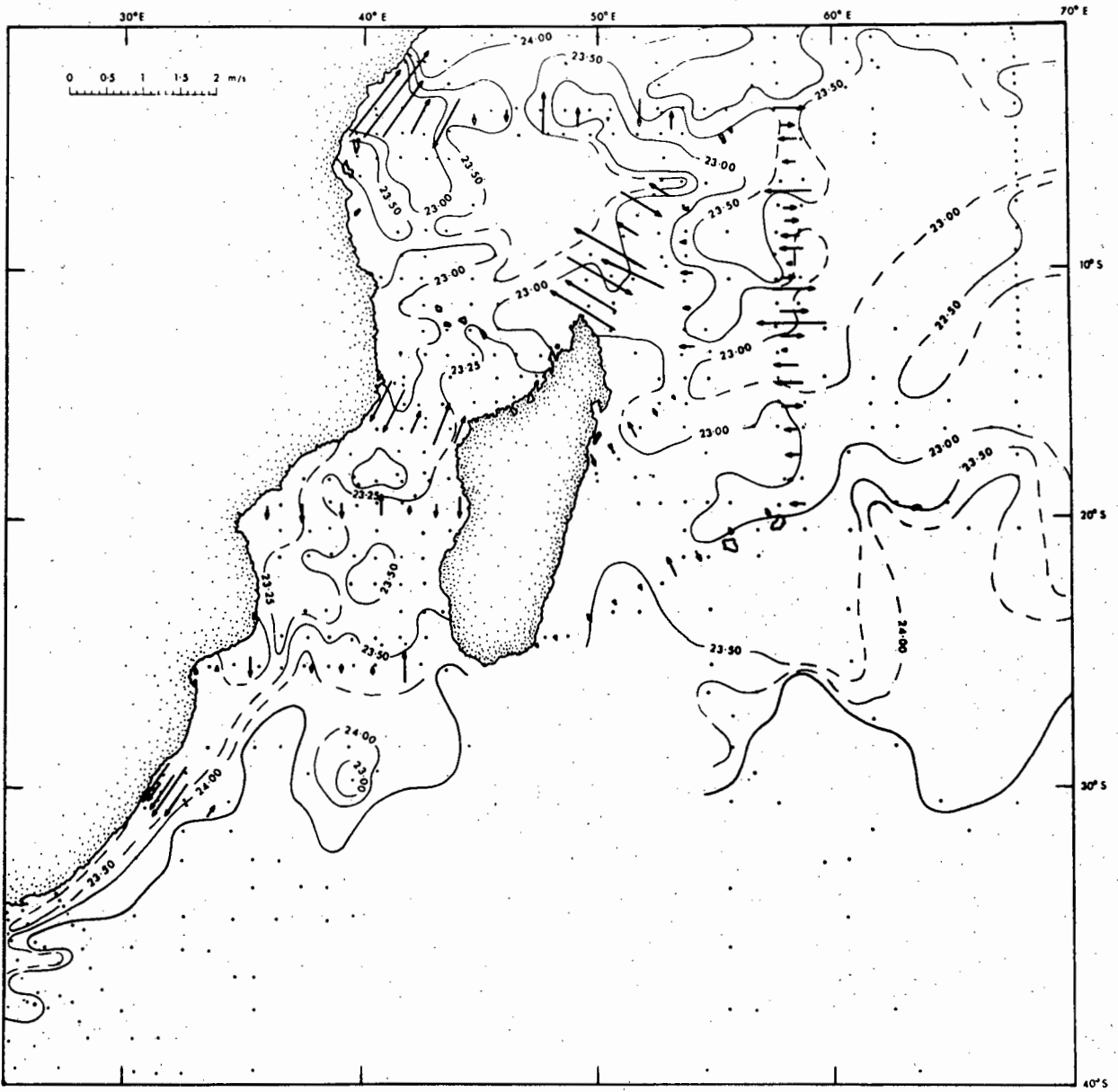


figure 5.6

Distribution of temperature on the σ_t 24.00 level.

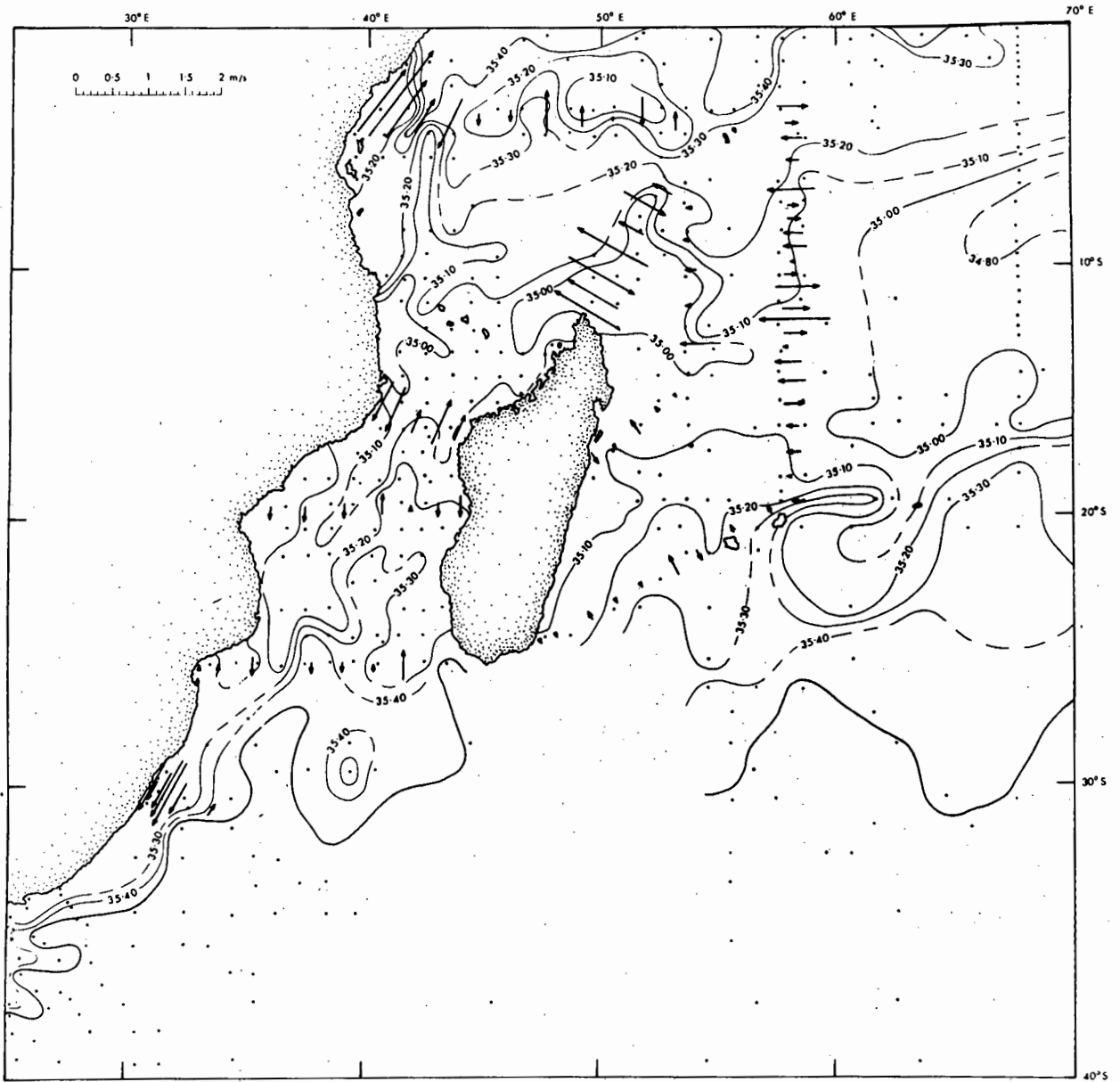


figure 5.7

Distribution of salinity on the $\sigma_t 24.00$ level.

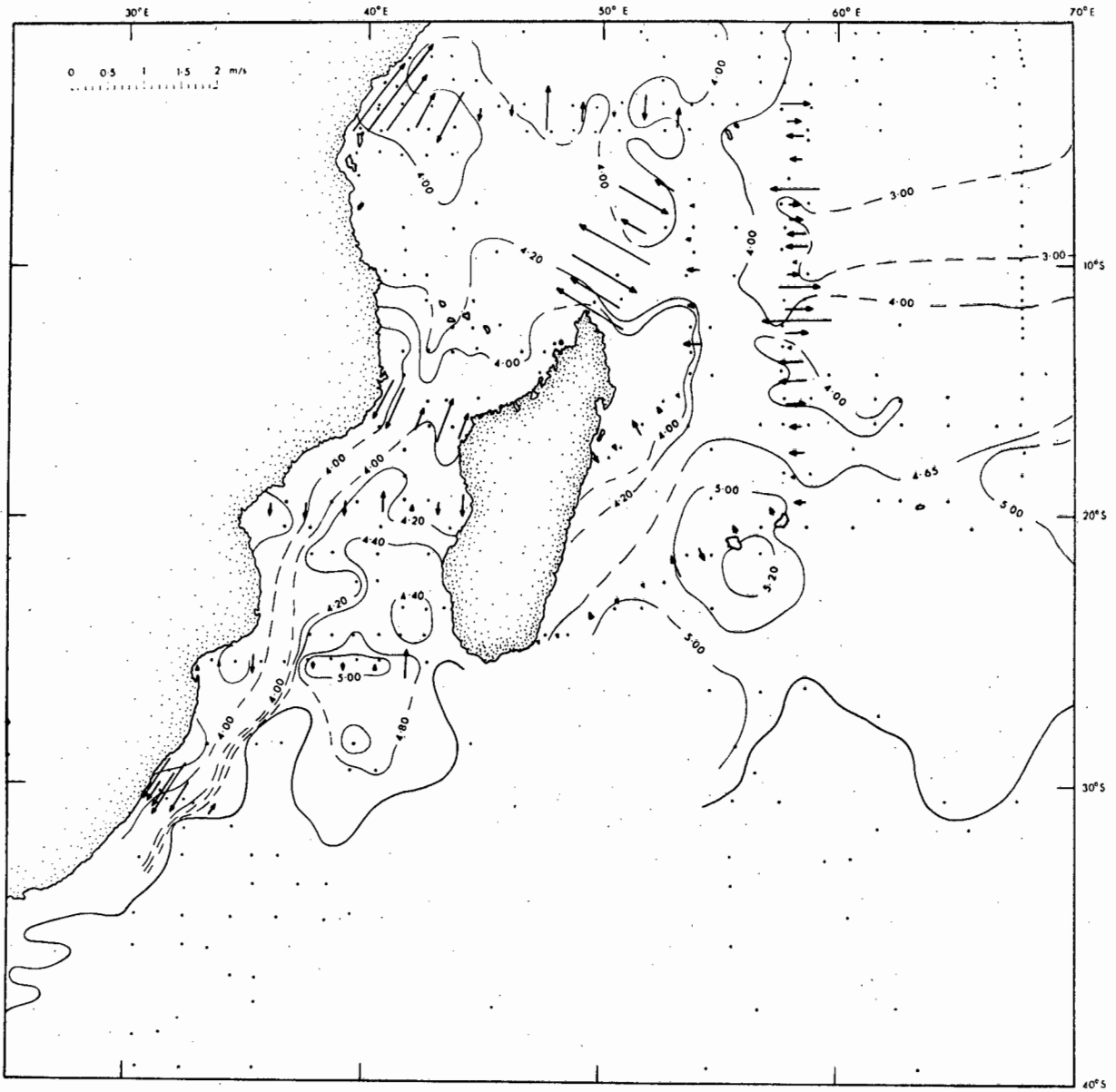


figure 5.8

Distribution of oxygen content on the σ_t 24.00 level.

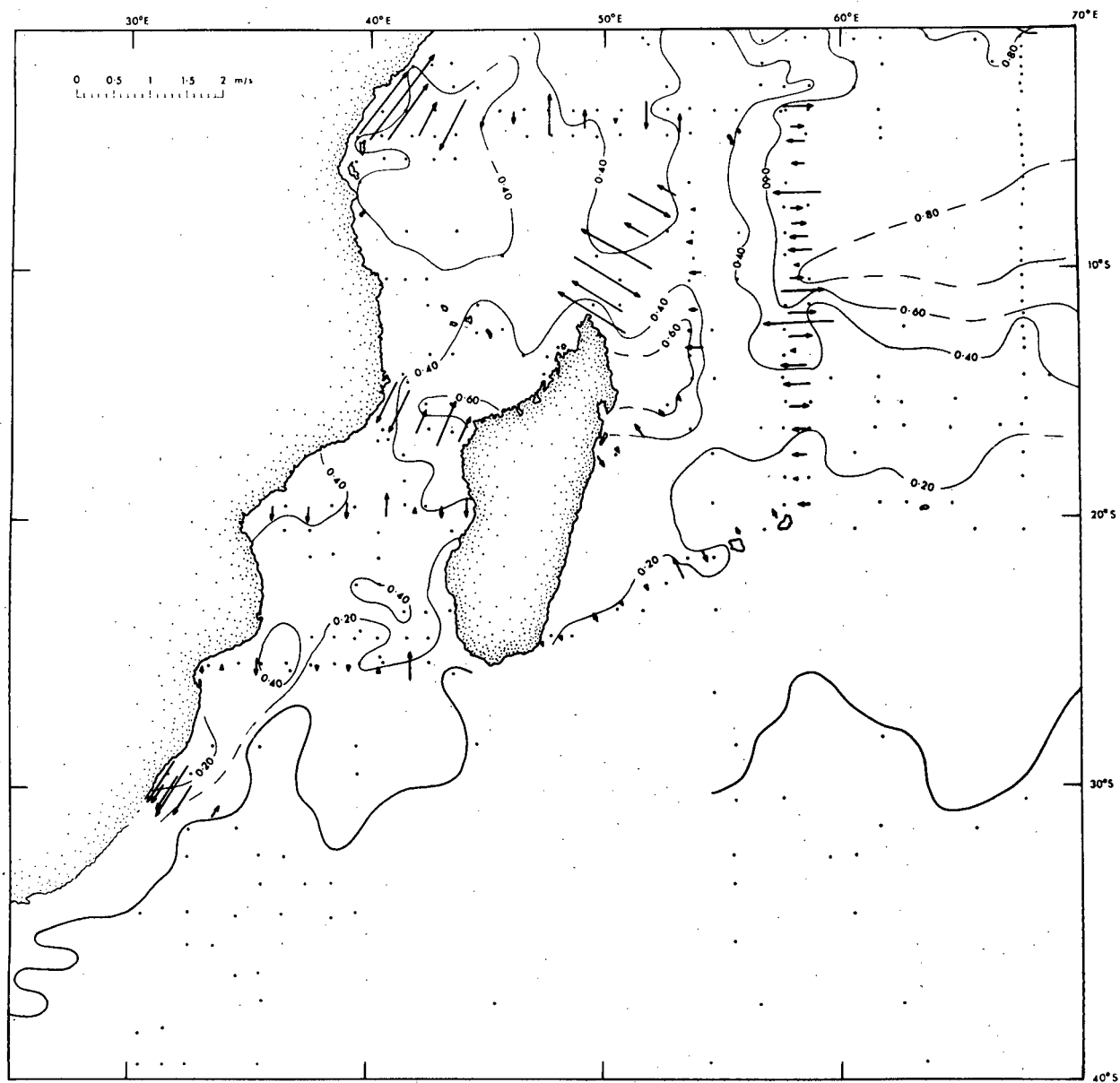


figure 5.9

Distribution of inorganic phosphates on the σ_t 24.00 level.

5.3 THE σ_t 24.00 SURFACE (figures 5.5 - 5.9)

This surface, which lies about 50 m deep, was chosen to represent the surface water movement without being under the immediate influence of varying conditions on the surface. The position where it intersects the sea surface is shown by a thicker line at about 30°S . It is conspicuous that this σ_t -level depicts the currents much more clearly. Additional information from the variation in depth of the σ_t -surface is now available, but since the possibility of vertical movement of water across a σ_t -surface so close to the sea surface is high, care should be taken in the interpretation of this information.

The South Equatorial Current is, as before, quite clear, except that on this level two branches from the Equatorial Counter Current seem to impinge on it from the north. The lesser one at about 67°E is depicted by the 80 m isobath (figure 5.5) and a tongue of high temperature, salinity and phosphate on figures 5.6, 5.7 and 5.9. A more developed tongue is present at about 57°E shown again by the 80 m isobath (figure 5.5), high temperature and high salinity. It is also depicted on the other figures. According to the isobaths, the South Equatorial Current clearly flows past Cape d'Ambre, but such continuity does not show up in the isotherms or isohalines. A vague inference of continuity could be drawn from the oxygen and phosphate contours. This type of lack of continuity is most marked for the East Africa Coastal Current. The Mozambique Channel presents the clearest picture of water flow. Figures 5.6 and 5.7 combine to give a coherent and

detailed description of the Mozambique Current, a general flow northwards to the east of this and a possible flow south on the west coast of Madagascar. The latter might also be interpreted as a cyclonic eddy west of Cape St. Marie, which would be supported by the oxygen distribution (figure 5.8). The area south of the mouth of the Mozambique Channel is subject to a large anticyclonic eddy, the isobaths being supported by all the other distributions of properties. The East Madagascar Current is inconspicuous except in the salinity distribution (figure 5.7) and little of it seems to pass south of Madagascar. What would seem to be a cyclonic circulation round Mauritius is clearly shown in figure 5.5 and 5.7 supported by the oxygen distribution (figure 5.8). The Agulhas Current once more stands out clearly with the possibility (figure 5.5) of a counter current just outside it, shown also by the current arrows. Off Lourenço Marques a clockwise eddy is formed on the shore side of the Mozambique Current.

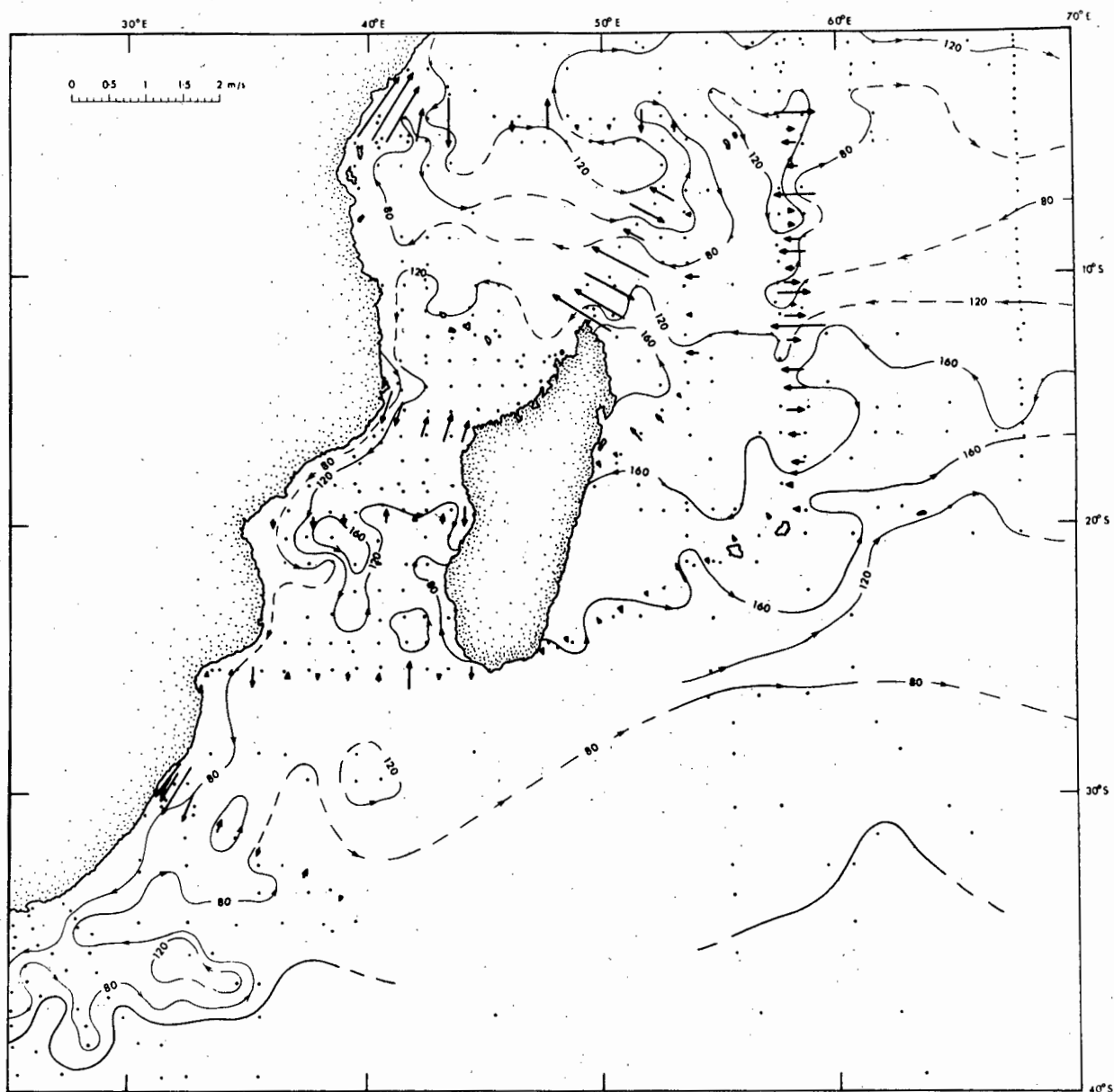


figure 5.10
Depth of σ_t 25.00 level.

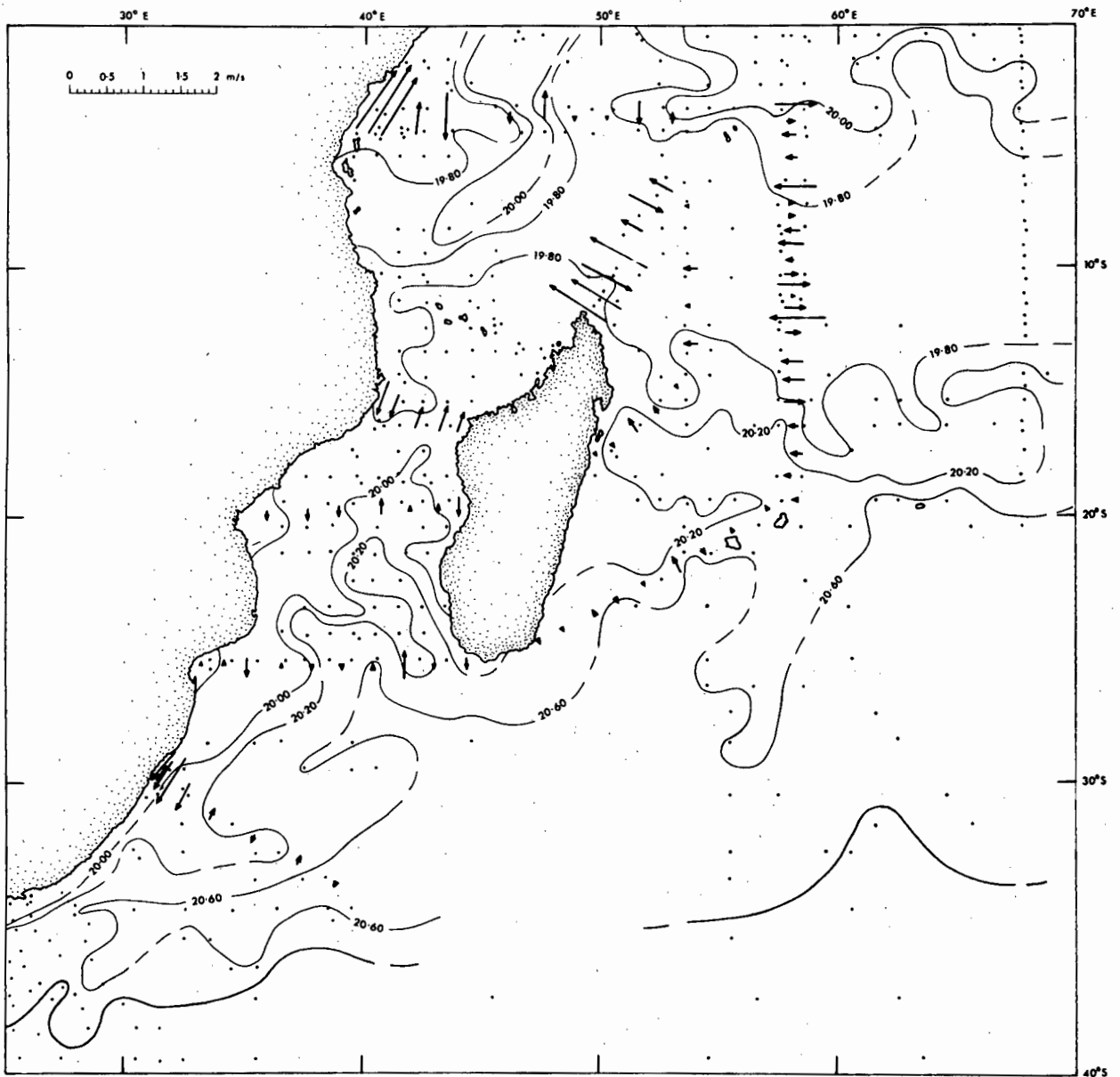


figure 5.11

Distribution of temperature on the $\sigma_t 25.00$ level.

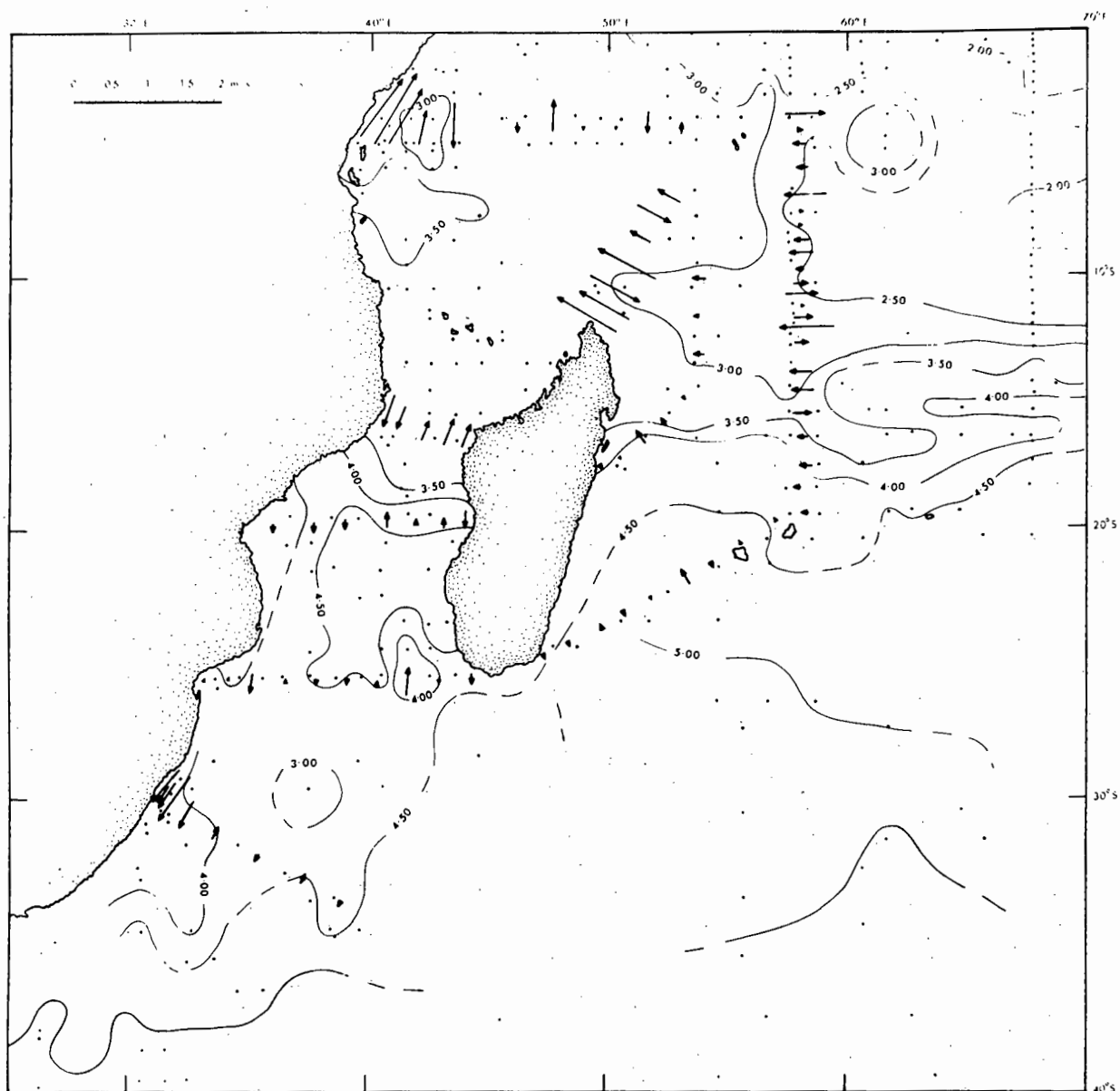


figure 5.13
Distribution of oxygen content on the σ_t 25.00 level.

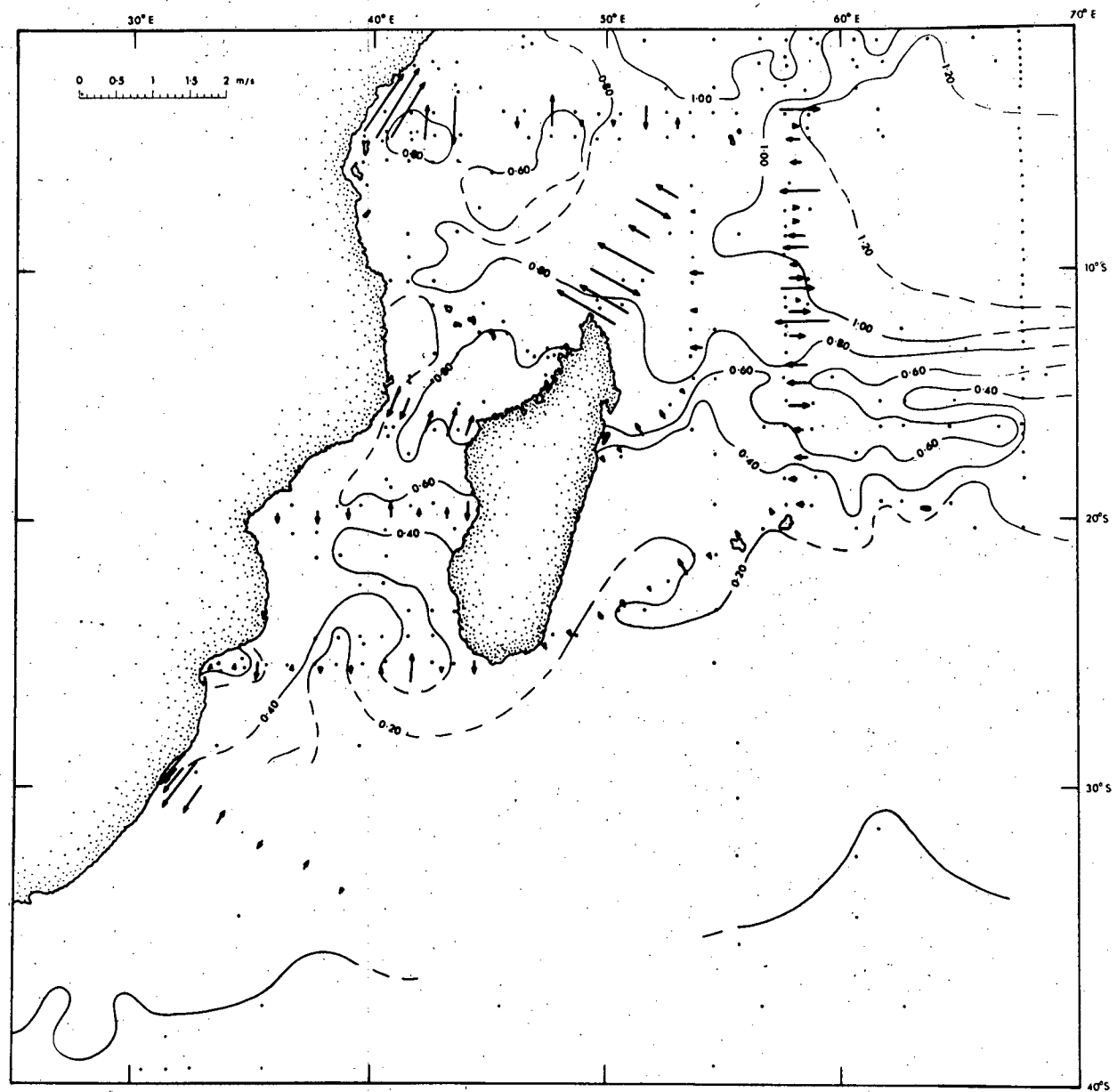


figure 5.14
Distribution of inorganic phosphate on the $\sigma_t 25.00$ level.

5.4 THE σ_t 25.00 SURFACE (figures 5.10 - 5.14)

The surface, which was chosen to show the surface circulation without interference from short term variations, does not present as lucid a picture as was hoped. It lies at an average depth of about 100 m.

The broad flow of the South Equatorial Current seems to be again influenced by watermasses branching from the Equatorial Counter Current. This is especially noticeable on the salinity distribution (figure 5.12). Near Africa the South Equatorial divides forming the Mozambique in the south and the East African Coastal Currents in the north. As on the σ_t 24.00 surface (figure 5.5), the Mozambique Current appears to branch off only very near the African coast. An important feature is the flow southwards on the seaward side of the East Africa Coastal Current. This is brought out very clearly by figure 5.10, the temperature (figure 5.11) and in a lesser degree the salinity (figure 5.12). The East Madagascar Current could possibly be inferred from figures 5.12 - 14, from their salinity, oxygen and phosphate distributions, but does not in any way emerge from the bathymetry of the 25.00 σ_t -surface. For the first mentioned cases the interpolation, due to a lack of data, is very subjective. Excepting the distributions of oxygen and phosphate content, the diagrams again present a coherent and detailed delineation of the movement of water in the Mozambique Channel. The Mozambique Current stands out clearly as does the northern flow in the middle of the channel. As on the previous level the flow on the eastern side of the channel is southwards, but complicated

by an anticyclonic eddy in the southern mouth. Although the isobaths on figure 5.10 might be interpreted as a curving back on itself of the Mozambique Current with only a small proportion flowing south, the isotherms and isohalines give no indication of this. The area just south of the southern mouth of the channel is difficult to interpret due to the lack of stations. Figure 5.10, 5.12 and 5.13 show the possibility of an anticyclonic eddy, while figure 5.11, and to a lesser degree figure 5.14, might be interpreted as some measure of recirculation. In all cases contouring was very subjective. The Agulhas Current is depicted in all diagrams, but not clearly in figure 5.13, and shows some eddy formation or branching off to seaward in most of the diagrams. This is particularly noticeable in figure 5.10. In figure 5.11 this branching off might be part of some type of recirculation. The northward extent of the Agulhas Return Flow to nearly south of Cape St. Marie is presented quite well by most of the diagrams although, due to the few stations, contouring is again very subjective.

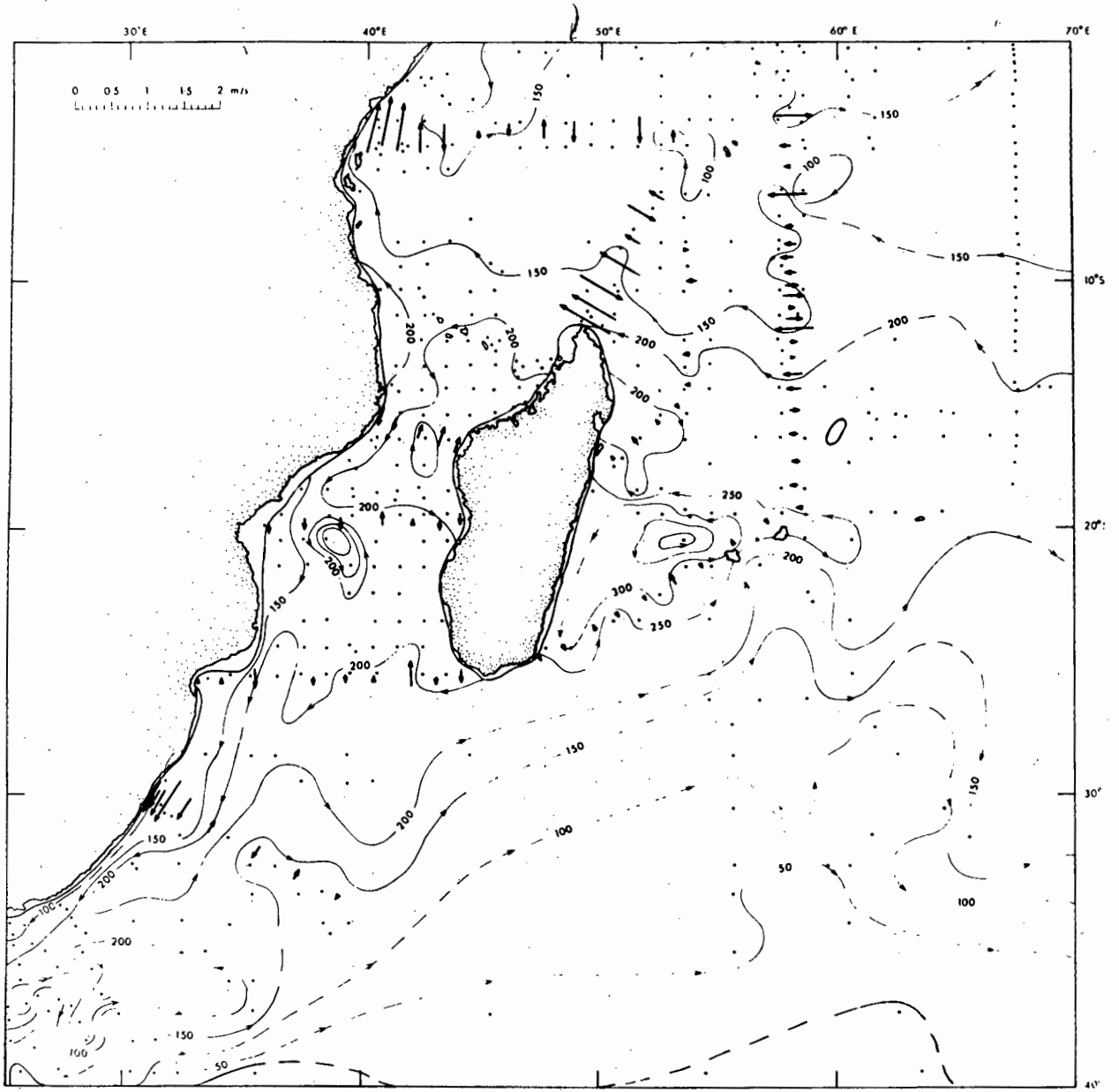


figure 5.15

Depth of the σ_t 25.80 level.

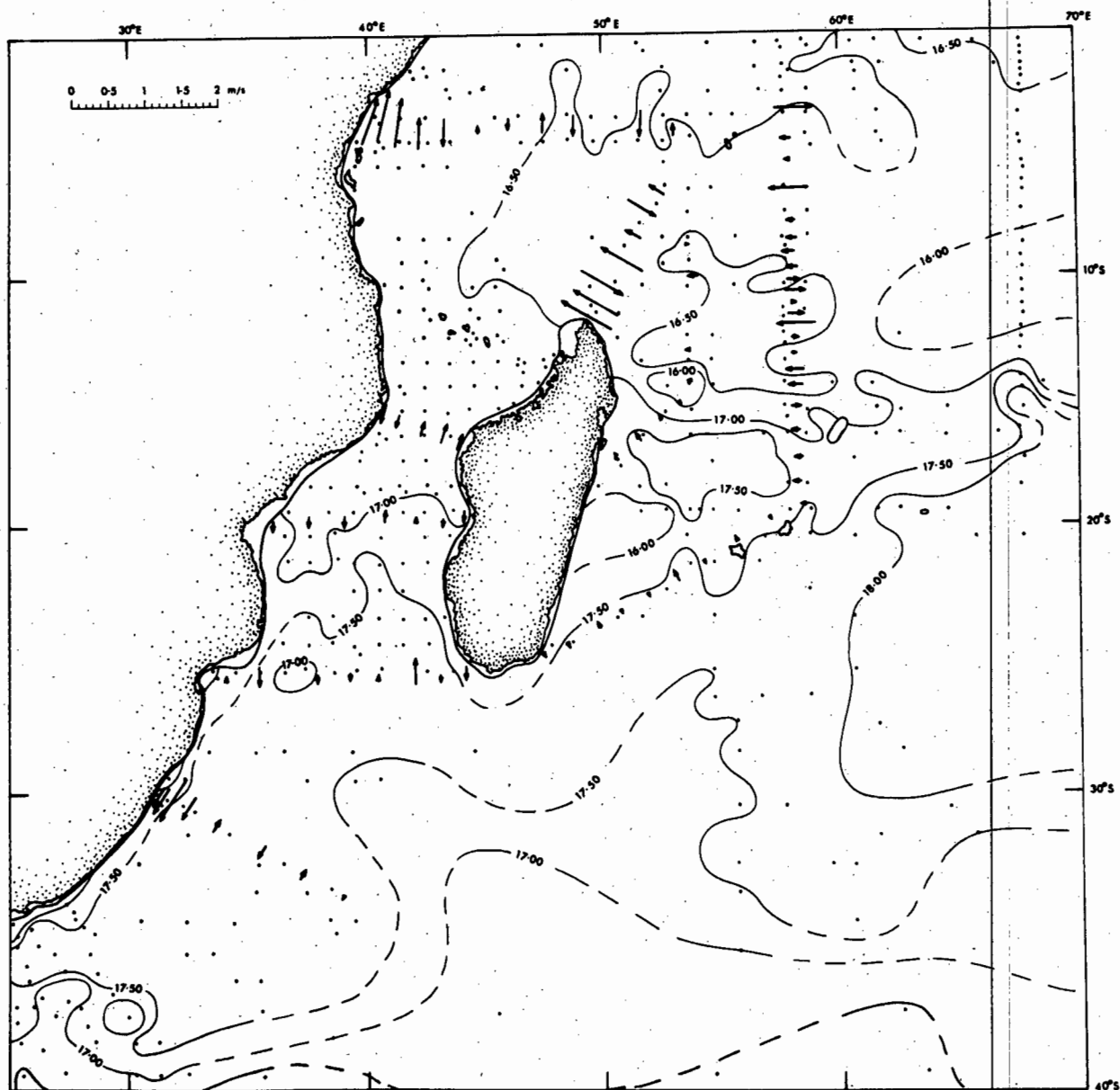


figure 5.16

Distribution of temperature on the σ_t 25.80 level.

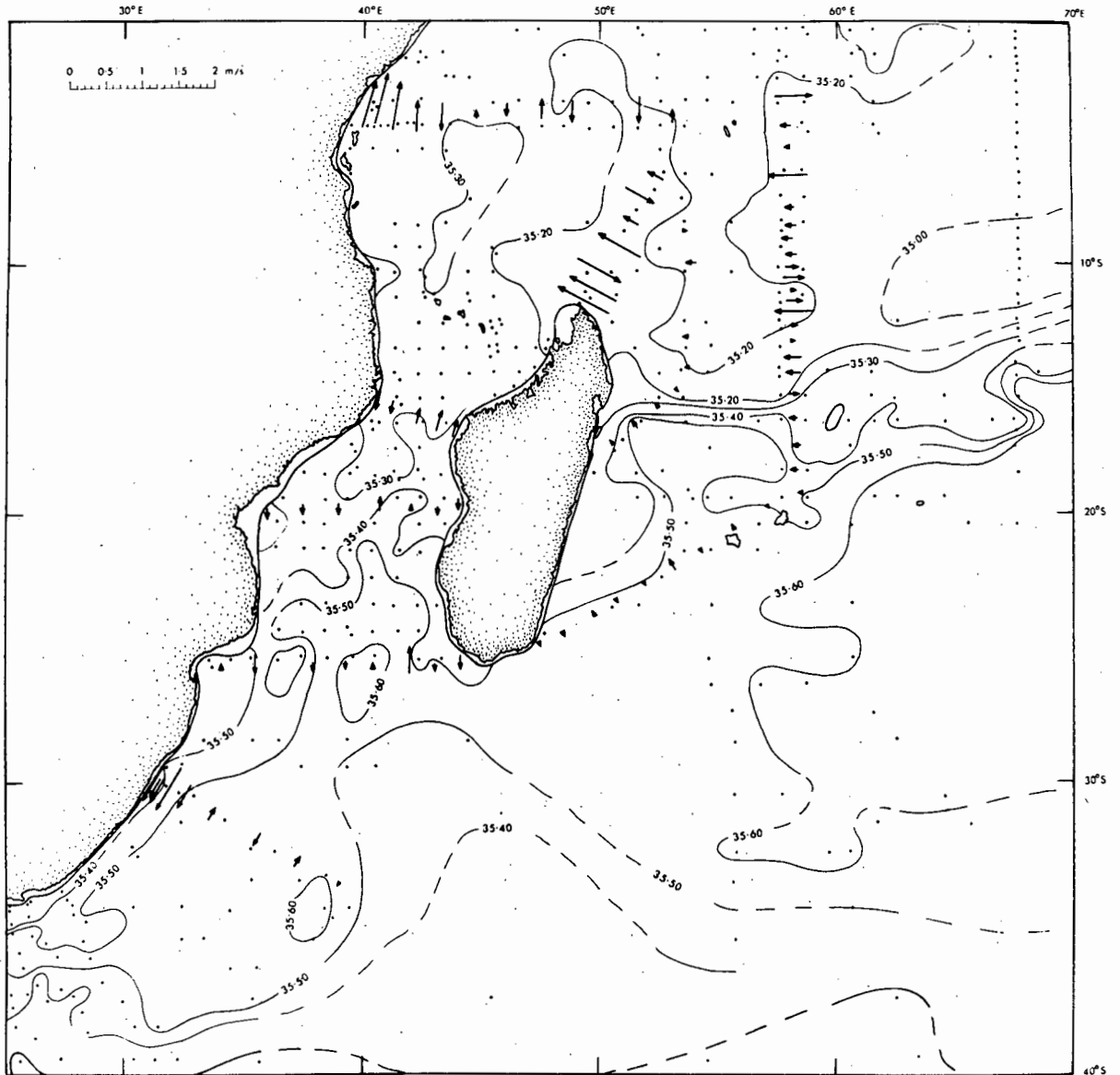


figure 5.17

Distribution of salinity on the σ_t 25.80 level.

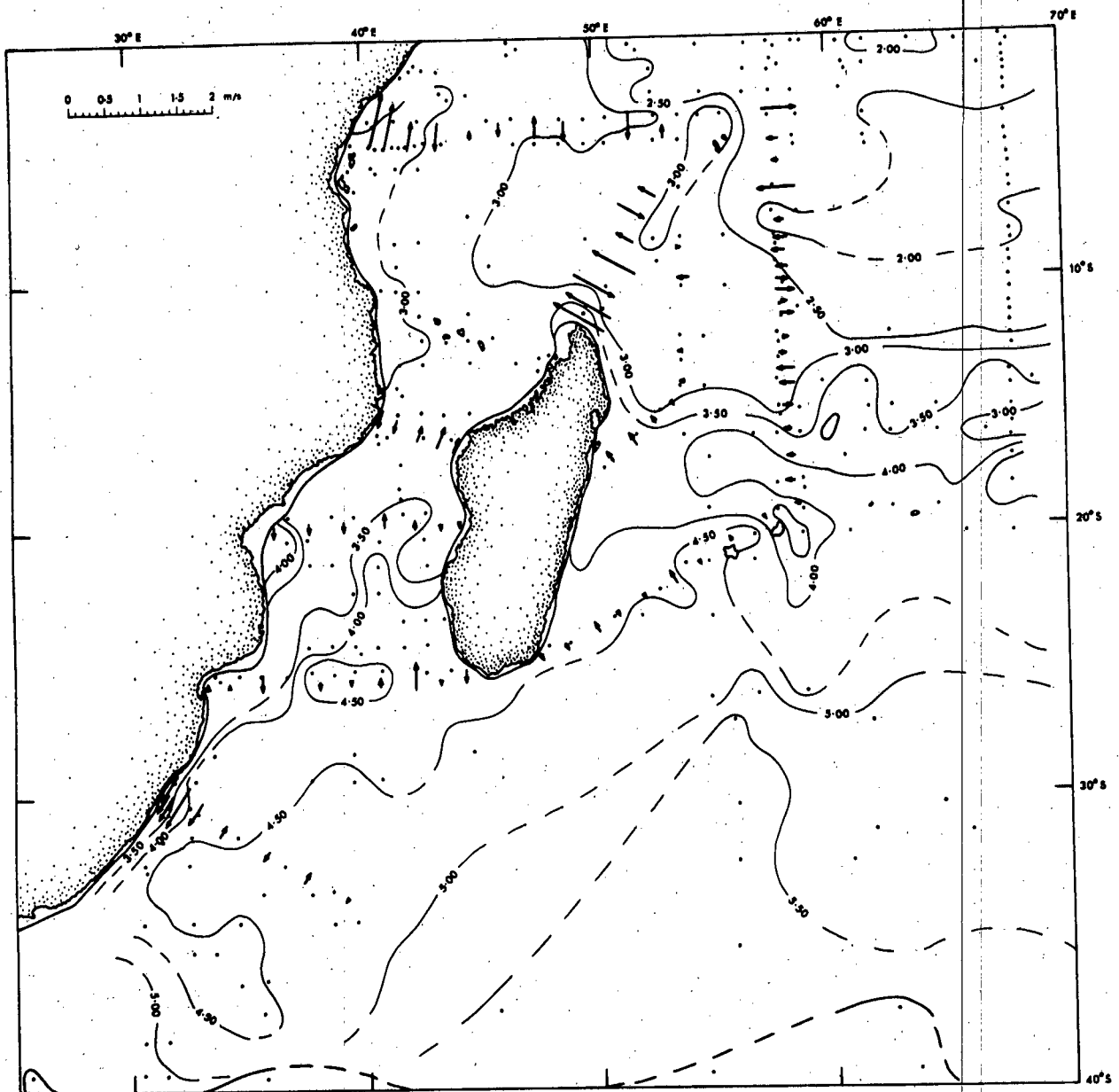


figure 5.18

Distribution of oxygen content on the σ_t 25.80 level.

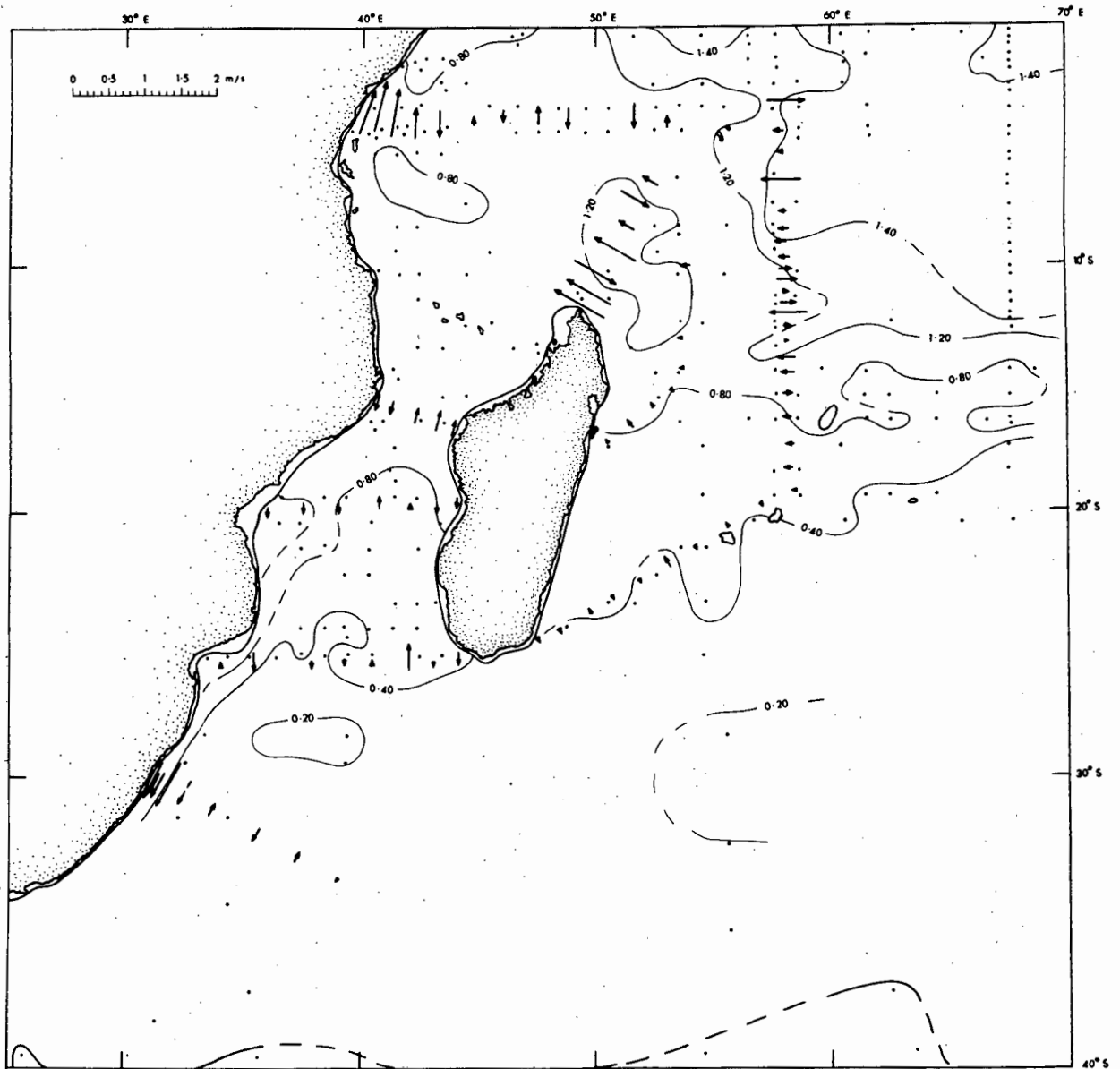


figure 5.19

Distribution of inorganic phosphate on the σ_t 25.80 level.

5.5 THE σ_t 25.80 SURFACE (figures 5.15 - 5.19)

At about 200 m depth a salinity maximum is to be found in this part of the ocean and the σ_t 25.80 surface was chosen to coincide with this maximum. The circulation pattern remains quite distinct on this σ_t surface (figure 5.15), but the support of the identifying properties for this circulation is not very strong.

The South Equatorial Current has its main axis of flow at about 10°S and flows past the Comores Islands before dividing into the Mozambique and East African Coastal Currents. Just seaward of the East African Coastal Current a current setting north is found. The Equatorial Counter Current is also noticeable. The distinctness with which these currents are visible on the depth topography of the σ_t -surface finds no corresponding clarity in the other diagrams. A tongue of cold, low salinity water from the east with low oxygen content corresponds with the South Equatorial Current and the Counter Current is pictured in the salinity and temperature diagrams with an indication of the East African Coastal Current visible in the oxygen isolines, but otherwise the picture is indistinct. What might correspond to a southern boundary to the South Equatorial Current is shown quite vividly at 15°S by the isohalines (figure 5.17). All other diagrams of identifying properties show signs of this. For the first time the East Madagascar Current does appear, but only as part of an anti-cyclonic eddy just west of Mauritius. No sign that it passes south of Cape St. Marie is shown. The oxygen and salinity diagrams support this interpretation. Although the Mozambique

Current stands out clearly and is also shown, in varying degrees, by all the other diagrams, the flow in the middle of the channel is not very coherent. All the identifying properties, especially the salinity and the oxygen clearly show tongues of high oxygen, high salinity water setting north, but the σ_t -surface depth topography shows the current flowing west past the southern mouth of the channel. The Agulhas Current, as continuation of the Mozambique Current, is well defined as is its Return Flow setting northeast. The salinity and temperature distributions (figure 5.17, 5.16) manifest northward deflections as this Return Flow passes over the Madagascar Ridge, which might conceivably be recirculation, but the subjective nature of these contours make interpretation very hazardous. The extremely complicated nature of the Agulhas Current retroflexion area is apparent in figures 5.15 and 5.17; figure 5.15 showing a tongue of water breaking loose.

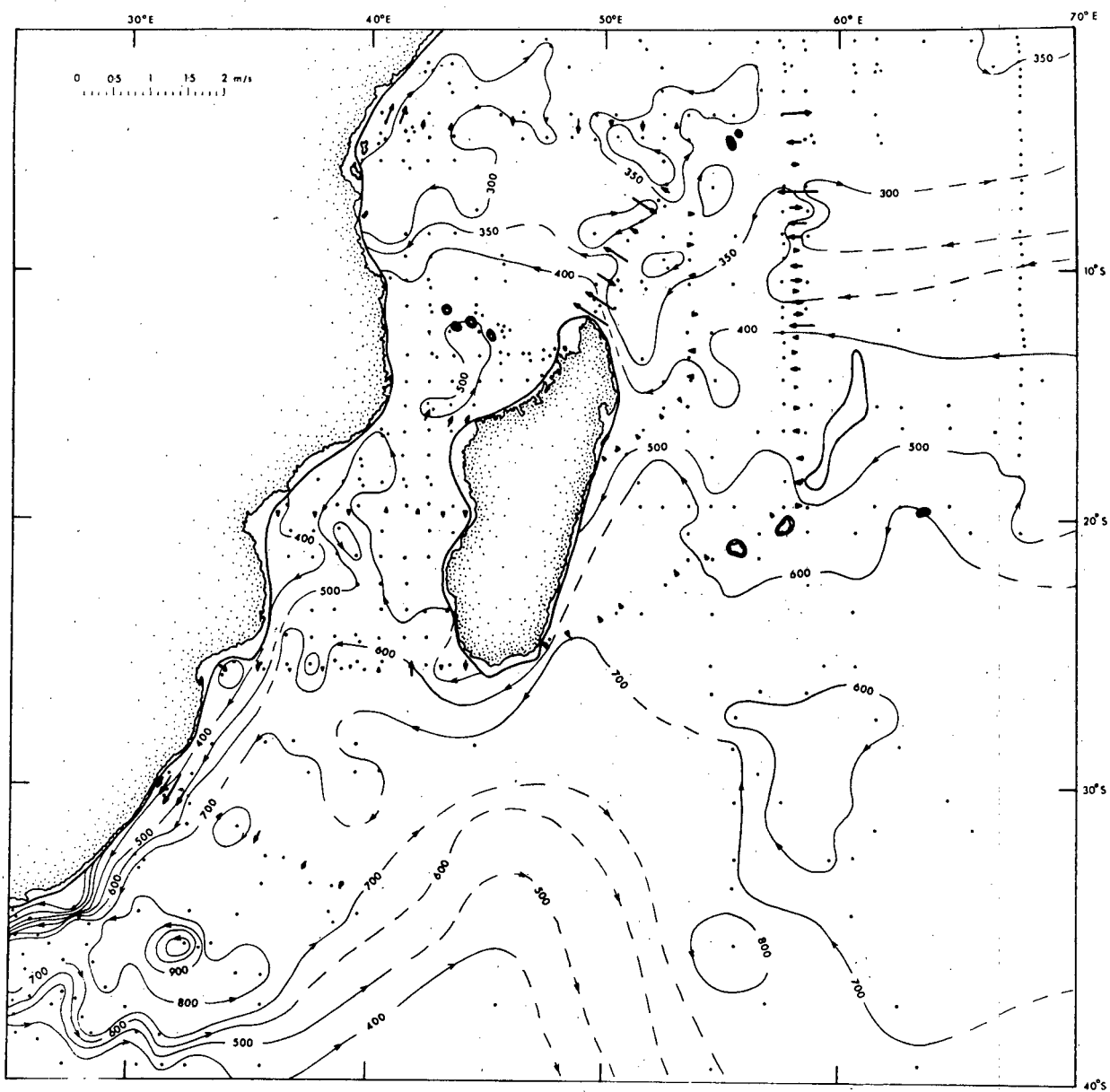


figure 5.20
Depth of the $\sigma_t 26.80$ level.

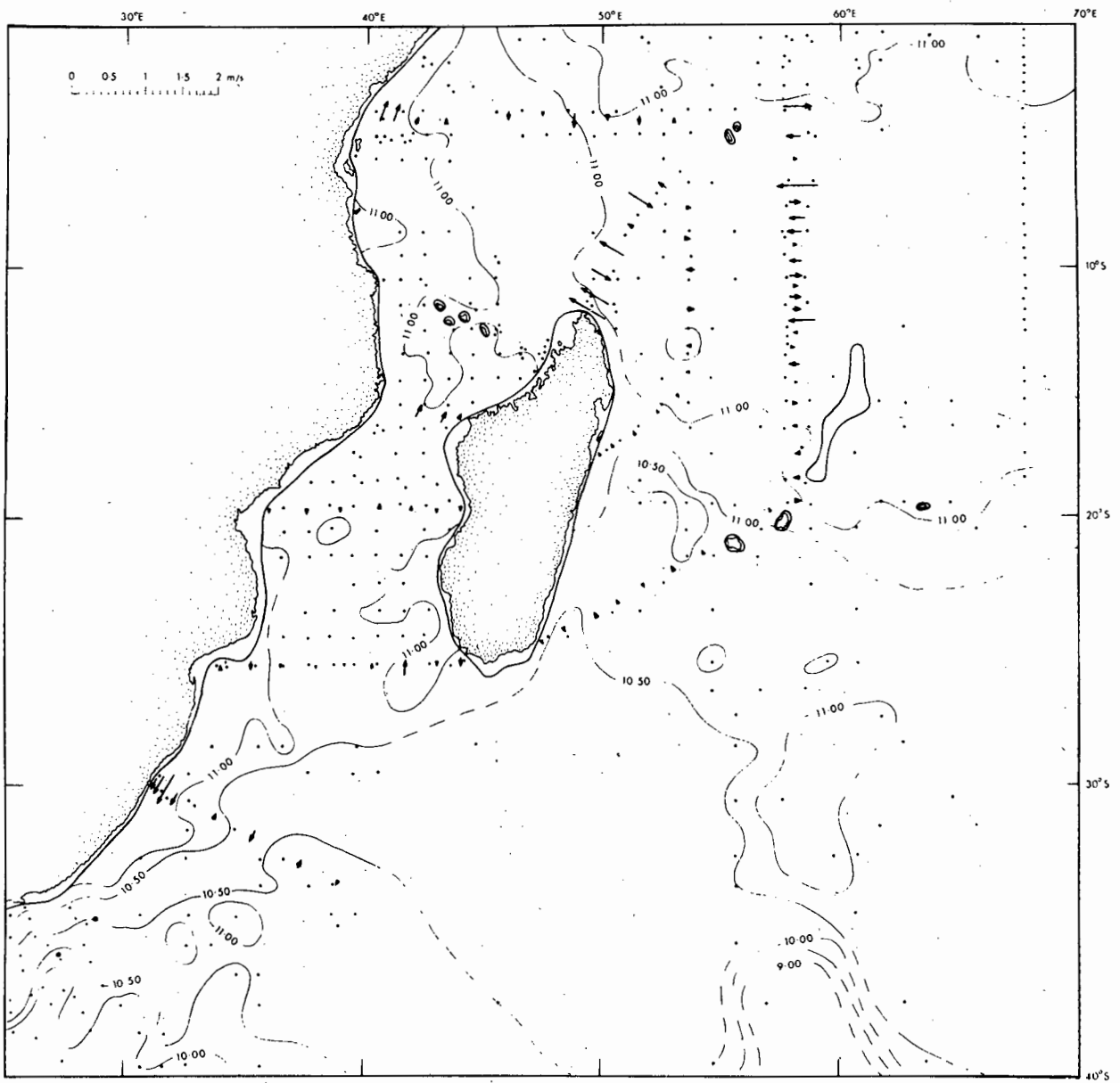


figure 5.21

Distribution of temperature on the σ_t 26.80 level.

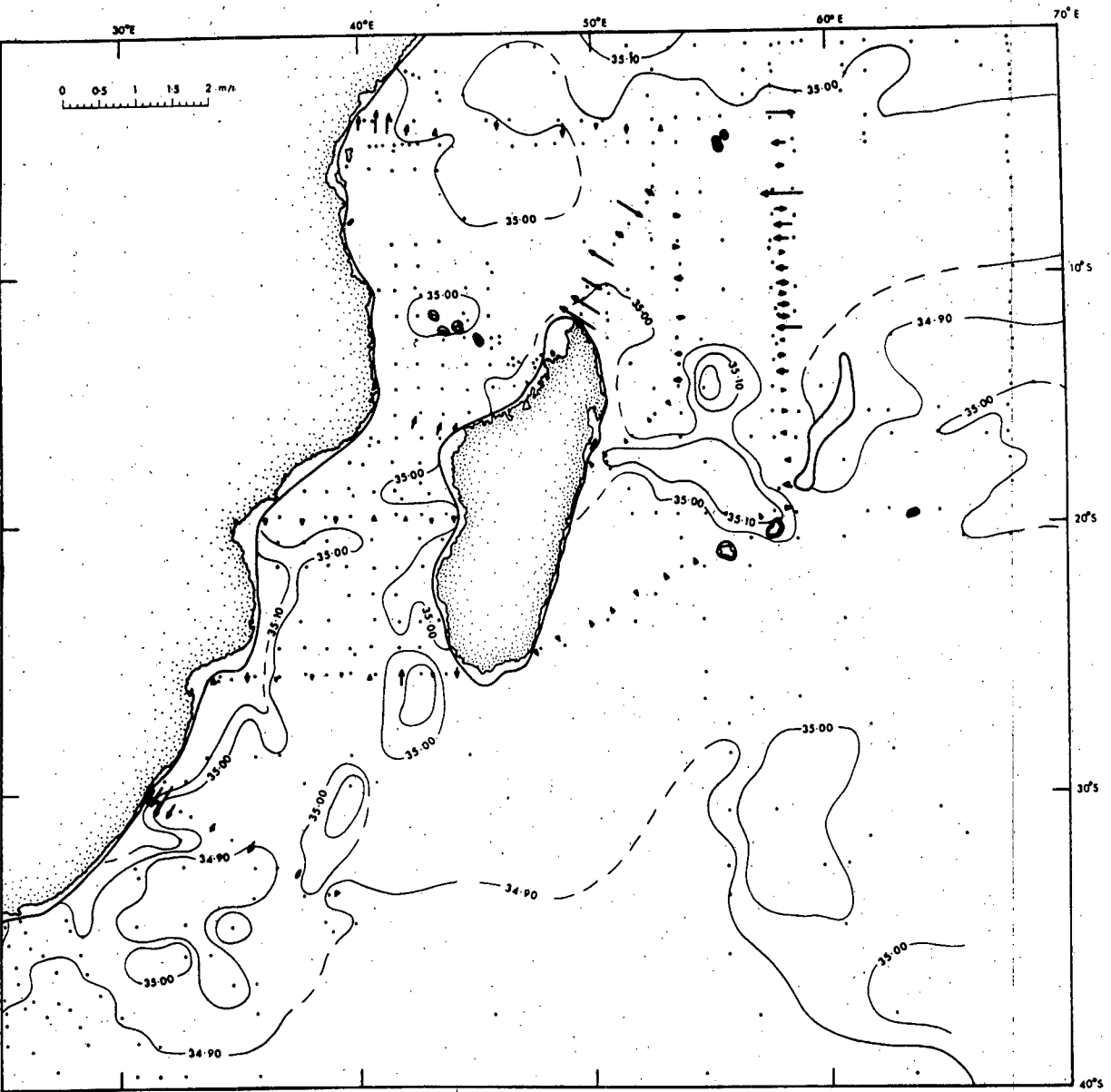


figure 5.22
Distribution of salinity on the $\sigma_t 26.80$ level.

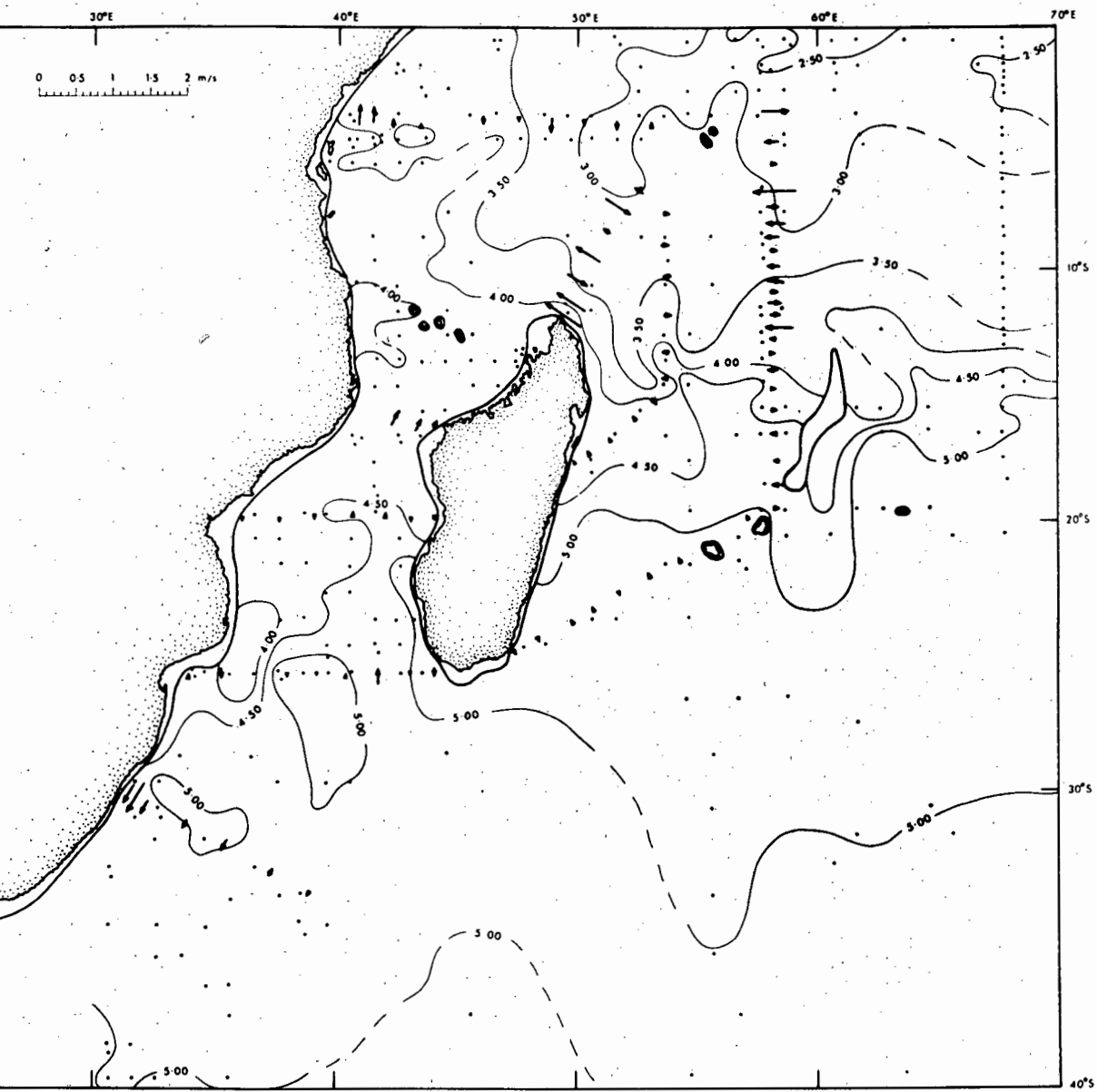


Figure 5.23
Distribution of oxygen content on the $\sigma_t 26.80$ level.

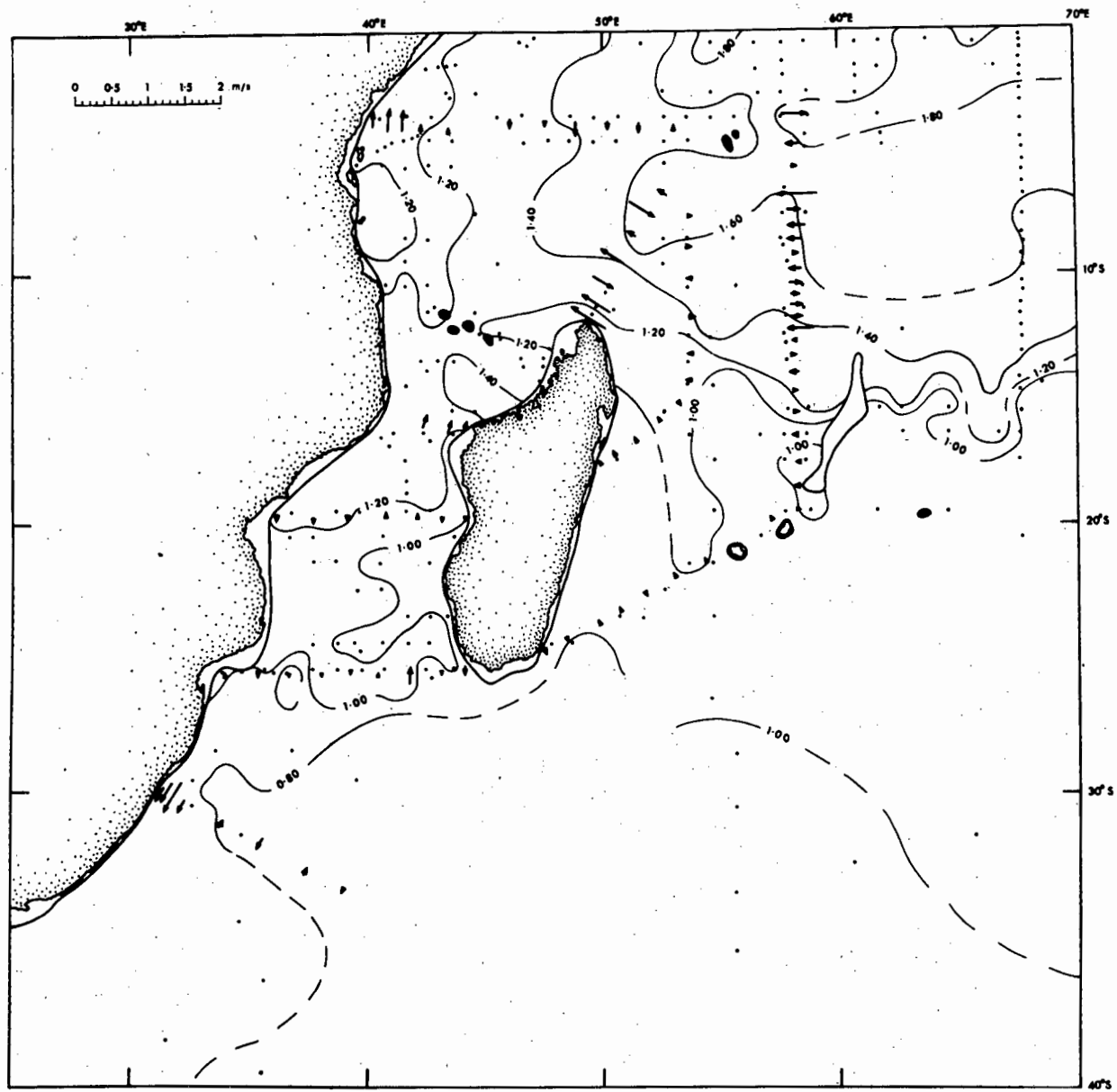


figure 5.24

Distribution of inorganic phosphate on the σ_t 26.80 level.

5.6 THE σ_t 26.80 SURFACE (figures 5.20 - 5.24)

The σ_t 26.80 surface was chosen, as discussed before, for its oxygen maximum and lies, at an average depth of 500 m, in the middle of the Indian Ocean Central Water. The depth topography of this σ_t -surface does show the circulation fairly well, but only the oxygen seems to offer much corroborative evidence.

The South Equatorial Current's axis lies at about 15°S and it divides near the east Madagascar coast, after it has passed the obstruction caused by part of the ridge north of Mauritius, forming the northgoing and the southgoing parts of the East Madagascar Current (figure 5.20). The oxygen distribution (figure 5.23) and the isotherms (figure 5.21) show the same features. The South Equatorial Current then carries straight on towards the African coast branching neither north or south. The circulation to the north of this is a complicated set of eddies. The other diagrams are difficult to interpret. A centre of low oxygen, high phosphate and, to a lesser degree, high salinity, seems to lie in the north-eastern corner of the diagrams. The current arrows would indicate that in this case flow would be parallel to the isolines flowing westward across the ocean and then sweeping northwards along the African coast. The beginning of the Mozambique Current off Cape Delgado is not shown in any diagram. The southflowing East Madagascar Current rounds the southern tip of Madagascar and flows north into the channel (figure 5.20). The oxygen contours and, to a lesser degree, the phosphate isolines also show this. South of latitude 20°S the Mozambique

Current becomes noticeable in the channel and is augmented by water flowing past the south of Madagascar. Figures 5.21 (temperature distribution) and 5.24 give additional evidence for this. The oxygen distribution shows various patches of water of higher oxygen content than 5.00 ml/l in this general direction but no continuous flow. Although the depth topography of this at-surface shows a strongly developed Agulhas Current and Agulhas Return Flow with the possibility of a large deflection north on passing the Madagascar Ridge, only the isotherms are in support of this. The isolines show a perfunctory agreement.

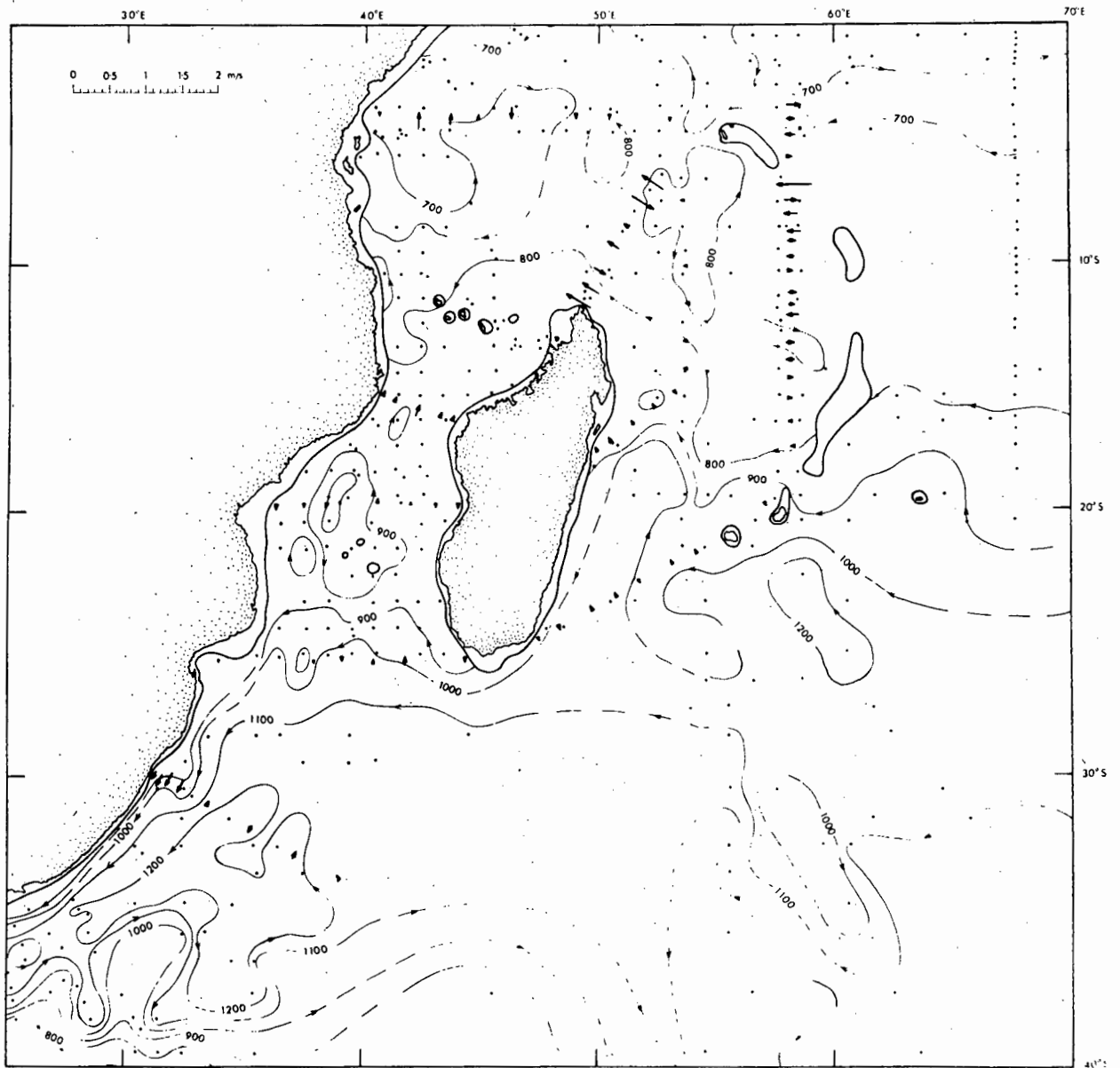


figure 5.25

Depth of the σ_t 27.25 level.

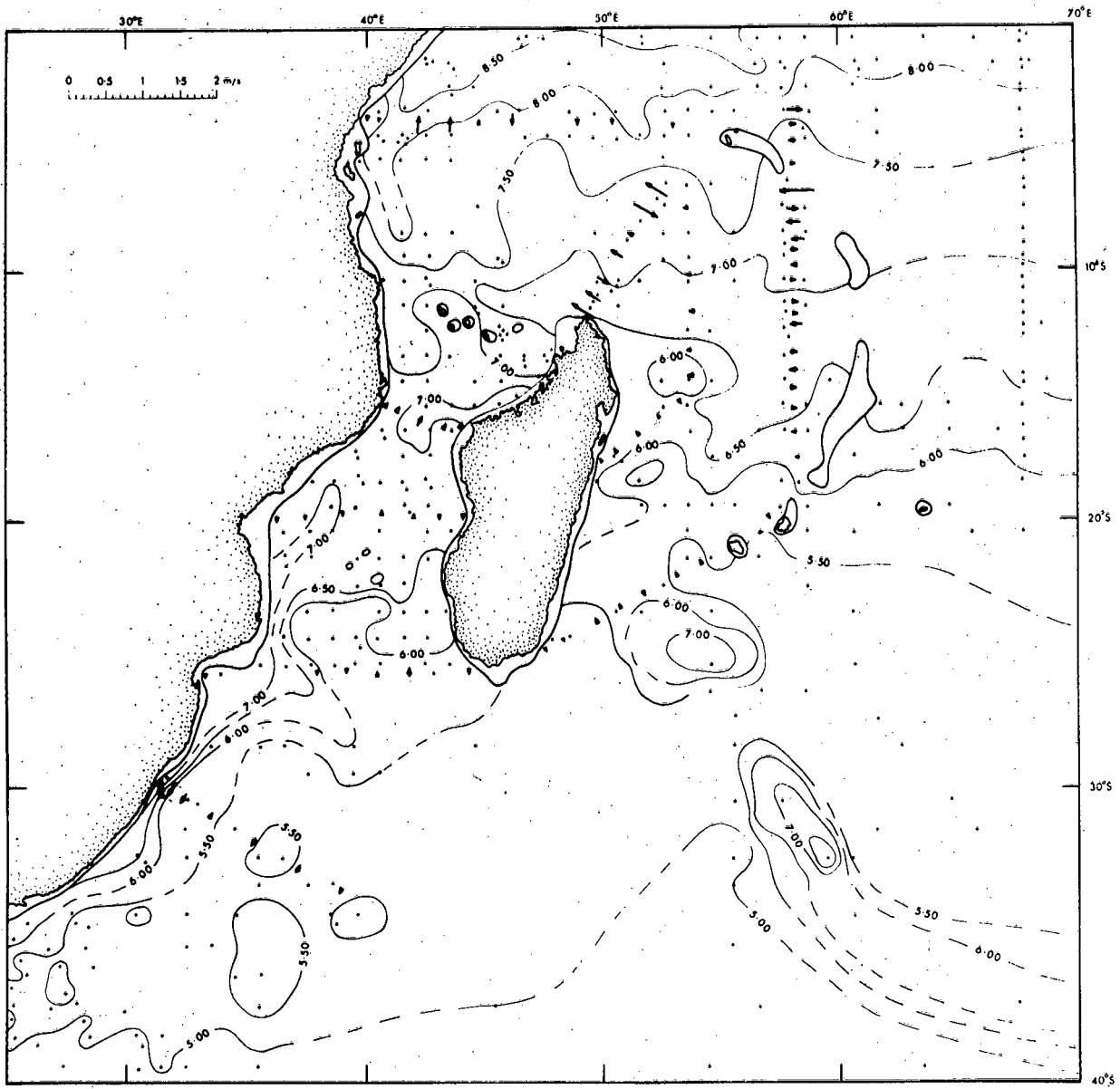


figure 5.26
Distribution of temperature on the $\sigma_t 27.25$ level.

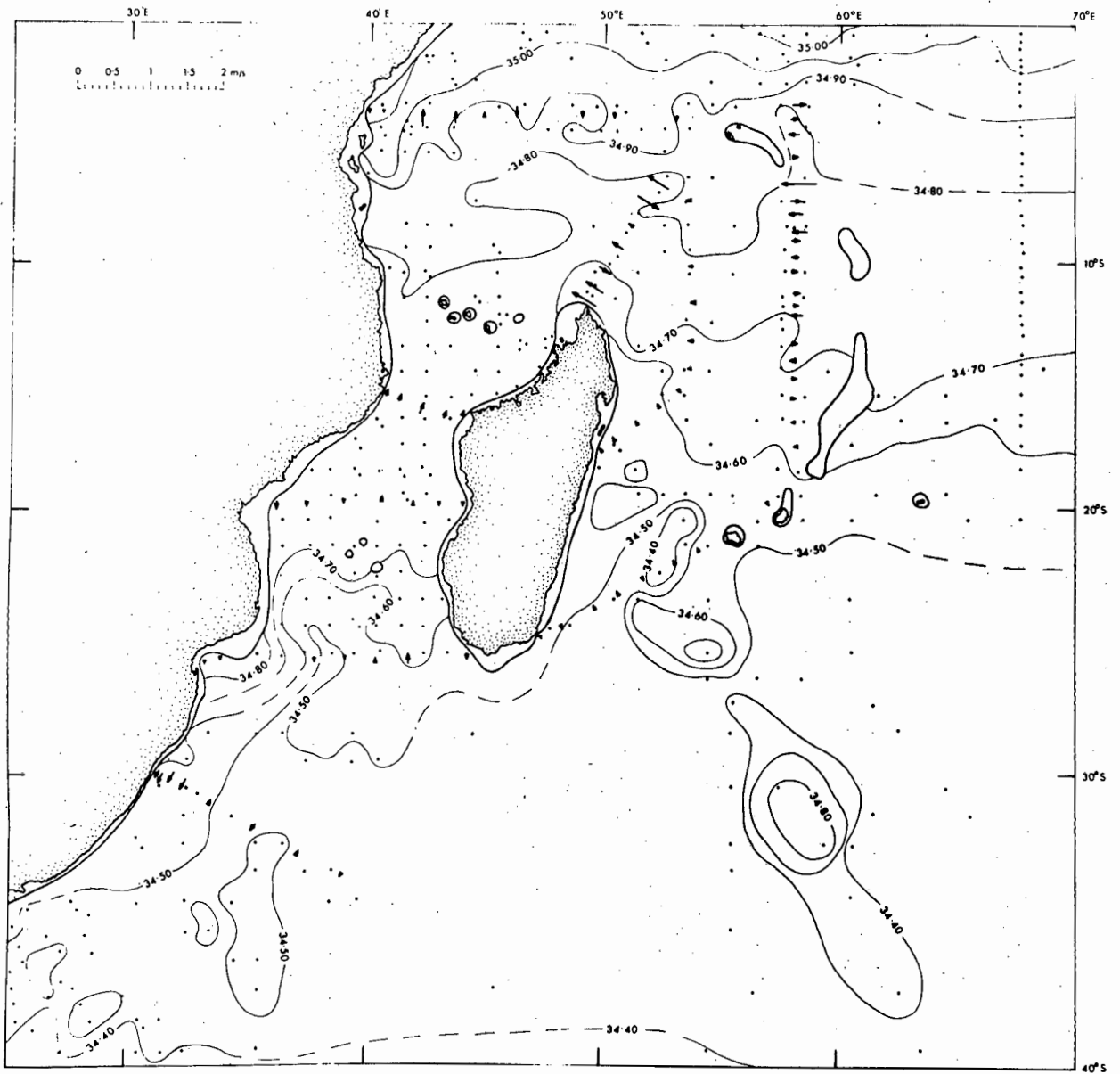


figure 5.27

Distribution of salinity on the $\sigma_t 27.25$ level.

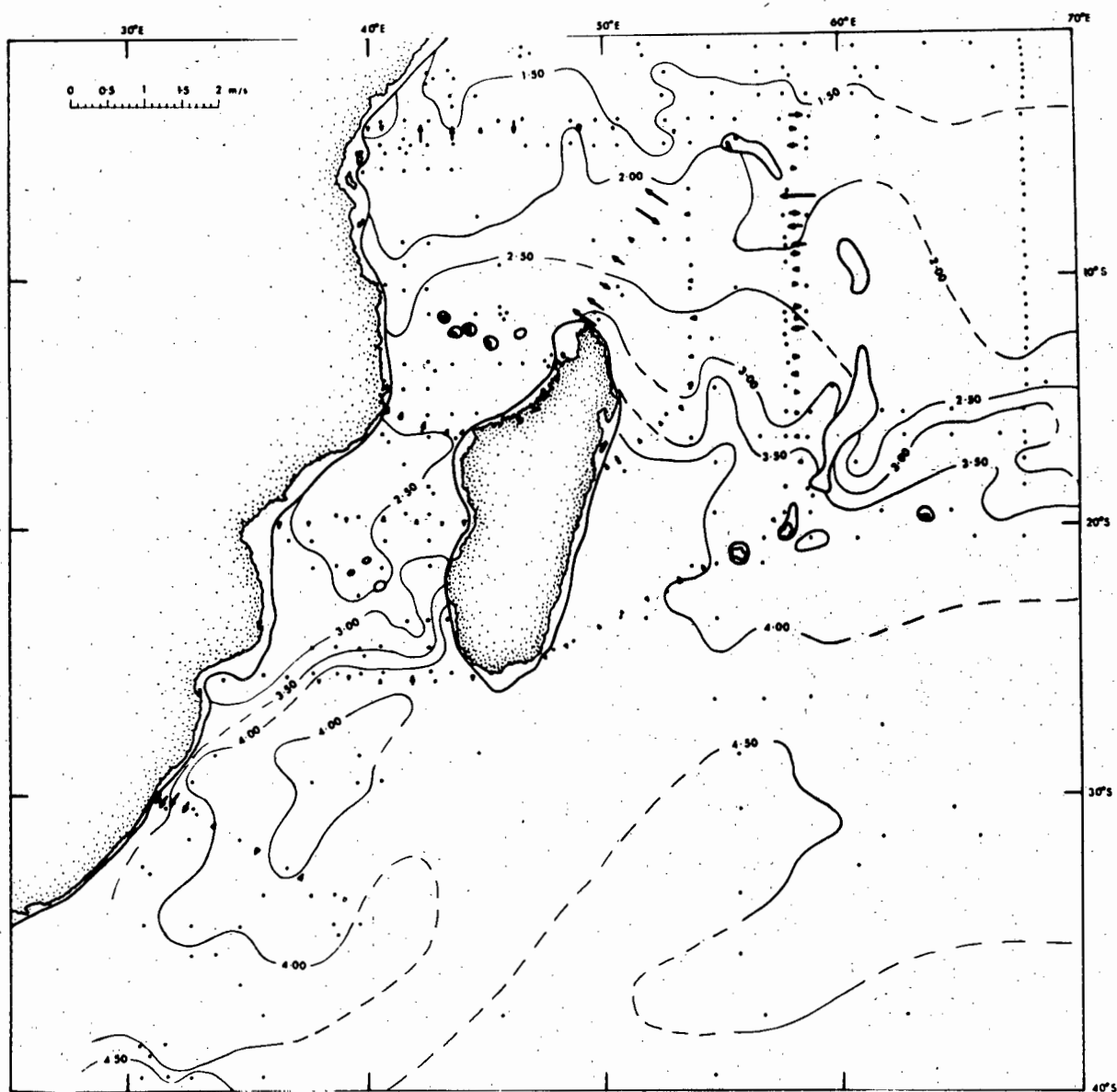


figure 5.28

Distribution of oxygen content on the σ_t 27.25 level.

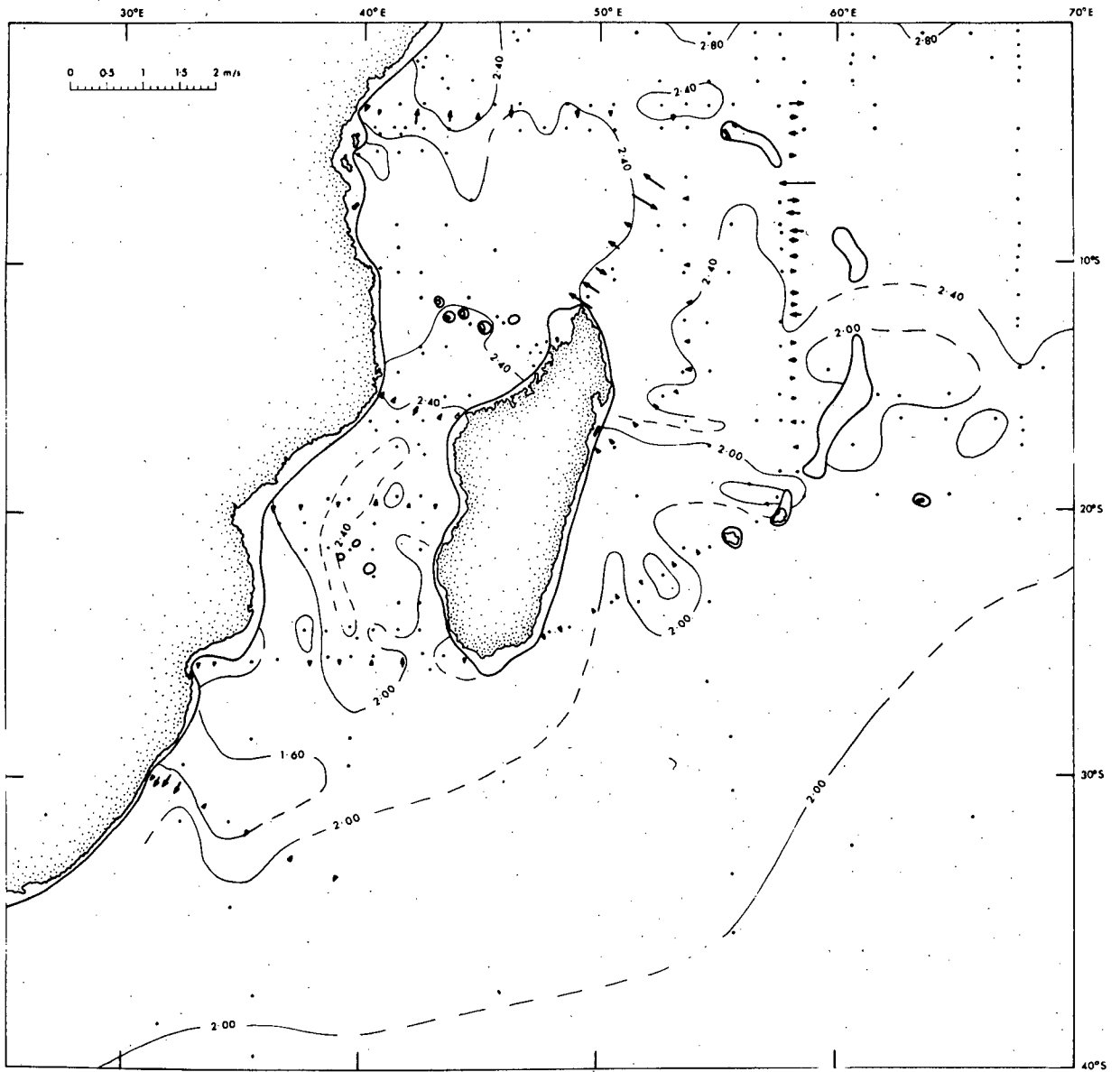


figure 5.29

Distribution of inorganic phosphates on the $\sigma_t 27.25$ level.

5.7 THE σ_t 27.25 SURFACE (figures 5.25 - 5.29)

The salinity minimum of the Antarctic Intermediate Water, lying at about 1000 m depth, corresponds closely to the σ_t 27.25 level. At this depth the topography of the sea-bottom for the first time begins to make an impression and between Mauritius and the Seychelles the ridge penetrates the 27.25 σ_t -surface in places.

The general flow is now beginning to change developing an east to west tendency for the whole area from 5°S to about 30°S . Of the East African Coastal Current little remains except a few eddies. North of 5°S there is a flow to the east. The flow in the Mozambique Channel is indistinct, consisting of a few eddies. The southflowing East Madagascar Current stands out quite clearly and there is good indication of its feeding the Agulhas Current. The Agulhas Current and its return flow are clear and distinct. According to the depth topography of the σ_t -surface (figure 5.25) some re-cycling may take place. The return flow does not, however, carry on north-eastwards but disappears at about 50°E . At this meridian, water from latitude 40°S flows northwestwards into the South West Indian Ocean. The isotherms (figure 5.26) and all the other isolines give very interesting support for this interpretation of the flow. North of about 10°S all the isolines run east-west except for a southward deflection near the African coast. This could be interpreted as a north-south flow, but the current arrows (see figure 5.26) strongly indicate that the flow is east-west. Oxygen, salinity and temperature all indicate a narrow southflowing current parallel

to the African coast. The other features, namely the Agulhas Current, the Agulhas Return Flow, the intrusion of water from the southeast as well as an eddy south of Mauritius, are corroborated very well by all isolines excepting the inorganic phosphate. In this case the scarcity of measuring points now begins to take effect and only the largest of features are still noticeable.

What is very noticeable is that the isotherms and isohalines in the Mozambique Channel have been shifted south relative to the same lines to the eastern side of Madagascar. So also for the oxygen distribution.

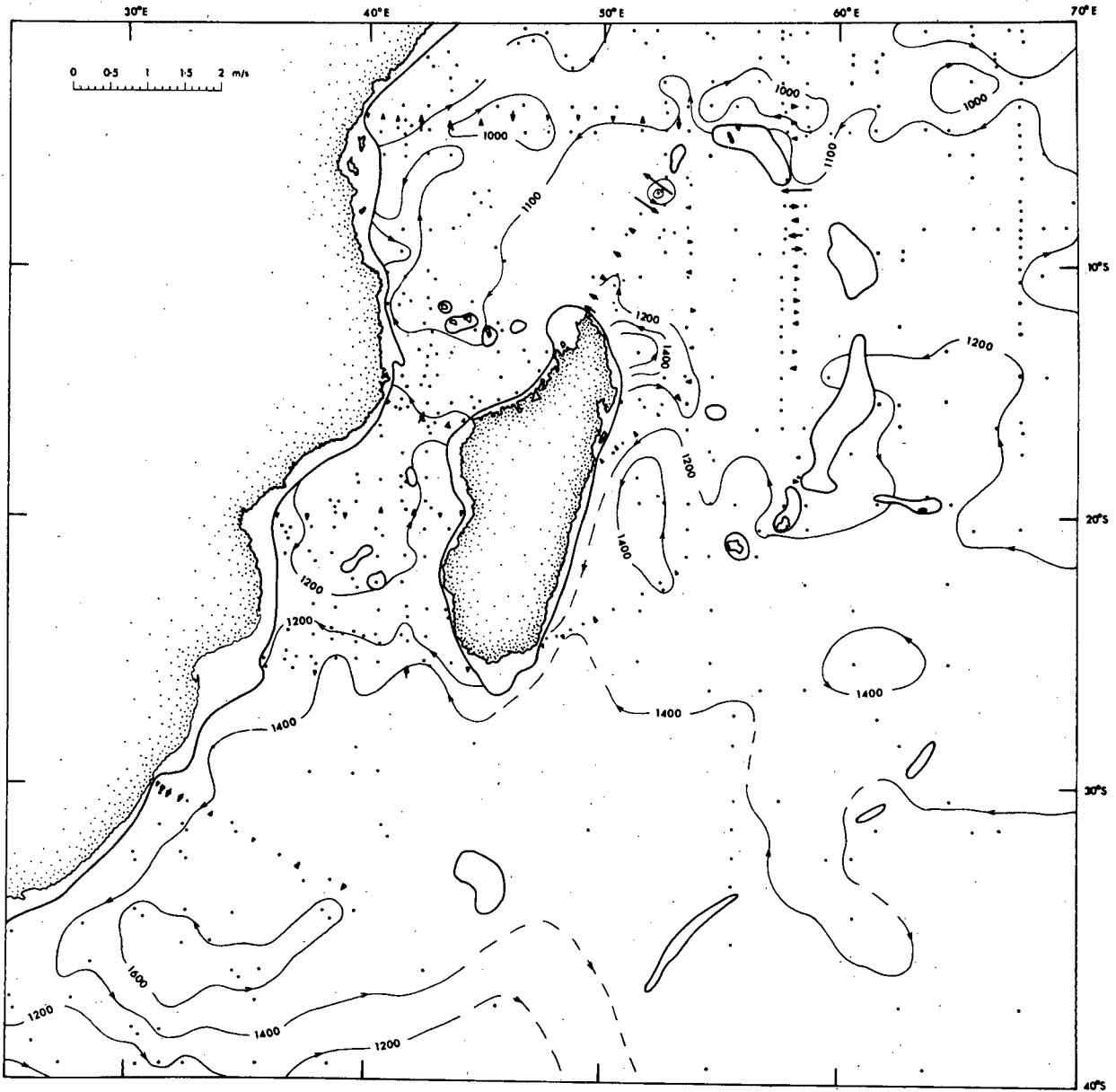


figure 5.30
Depth of the $\sigma_t 27.50$ level.

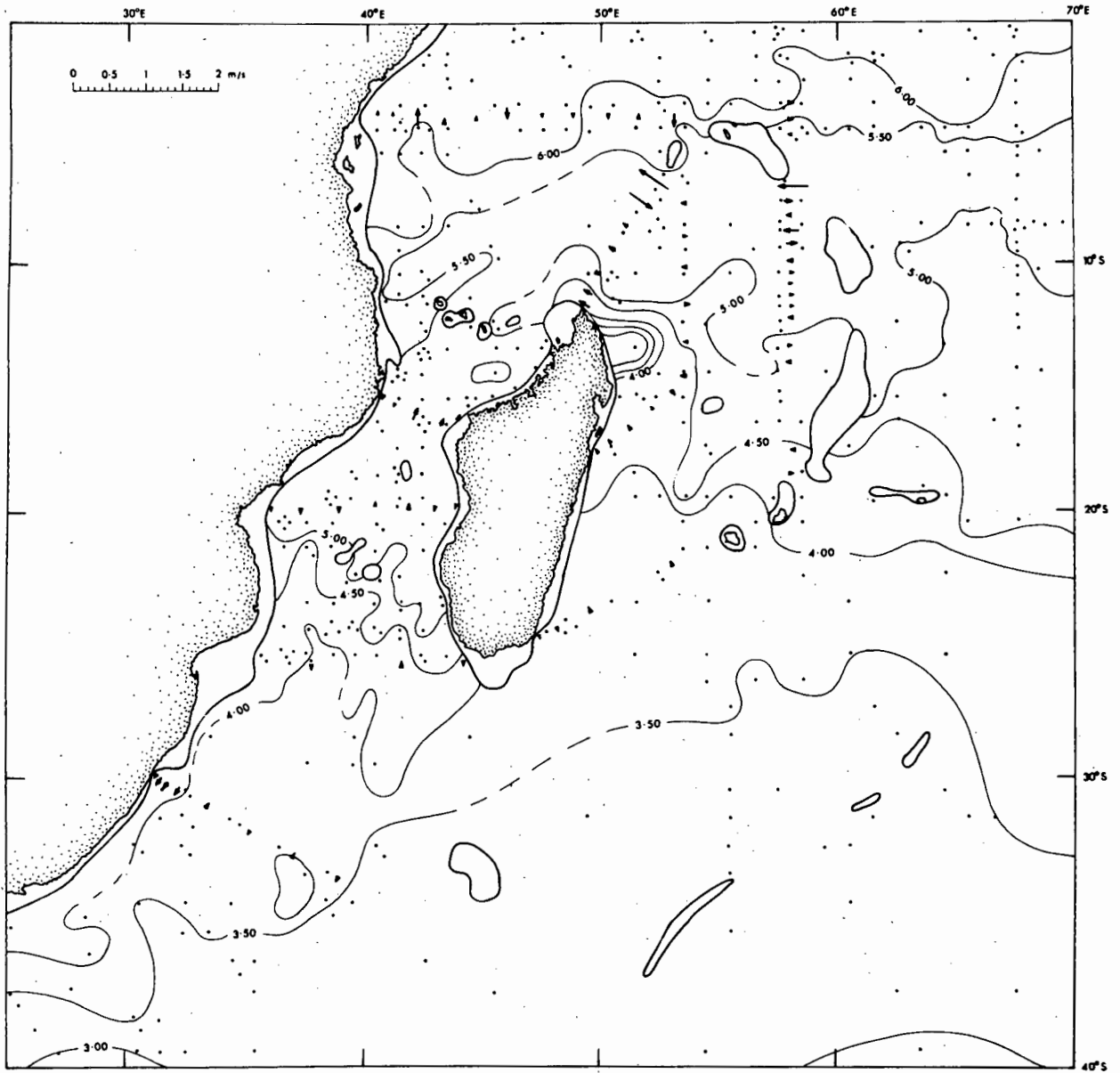


figure 5.31

Distribution of temperature on the σ_t 27.50 level.

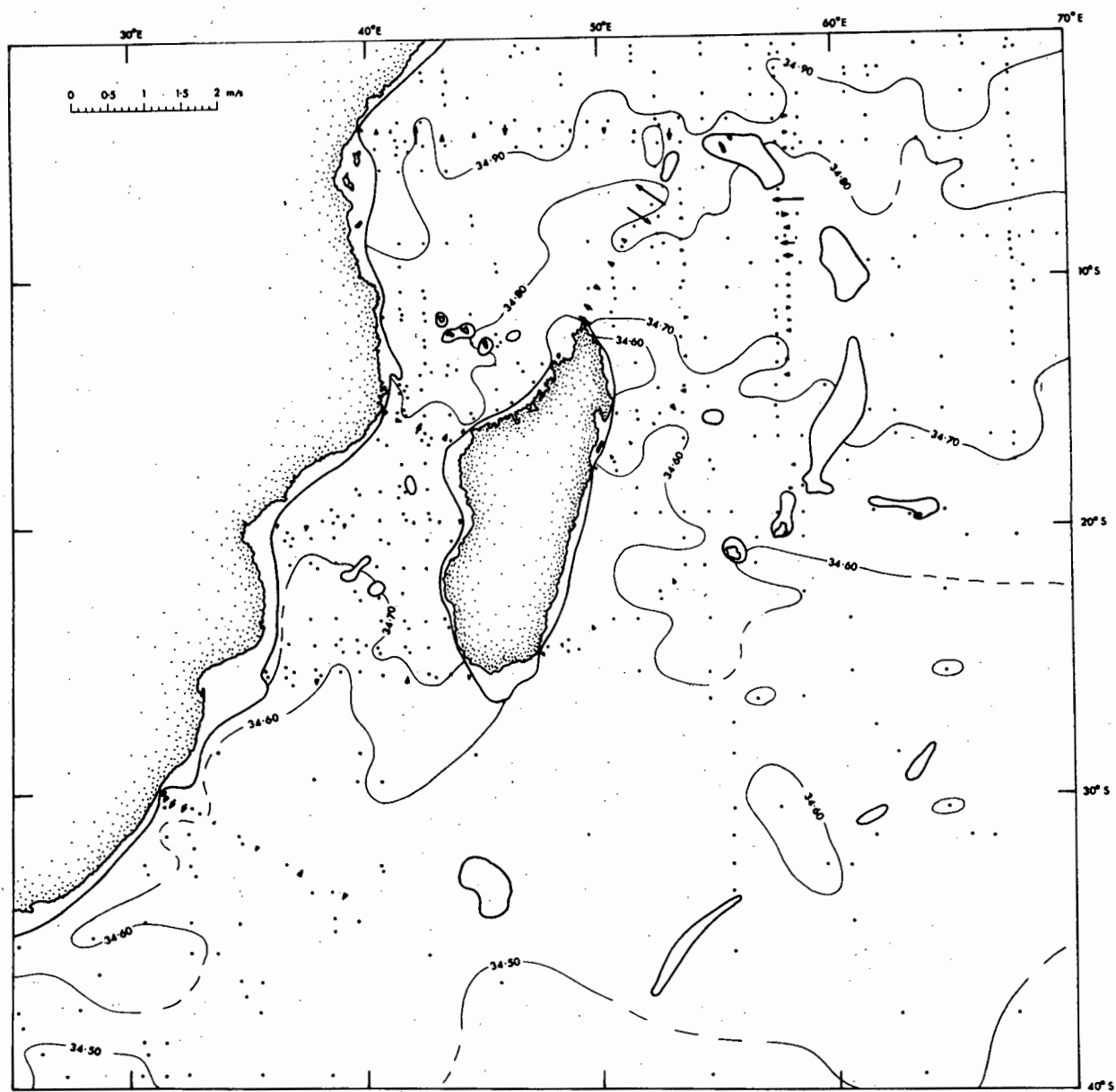


figure 5.32

Distribution of salinity on the $\sigma_t 27.50$ level.

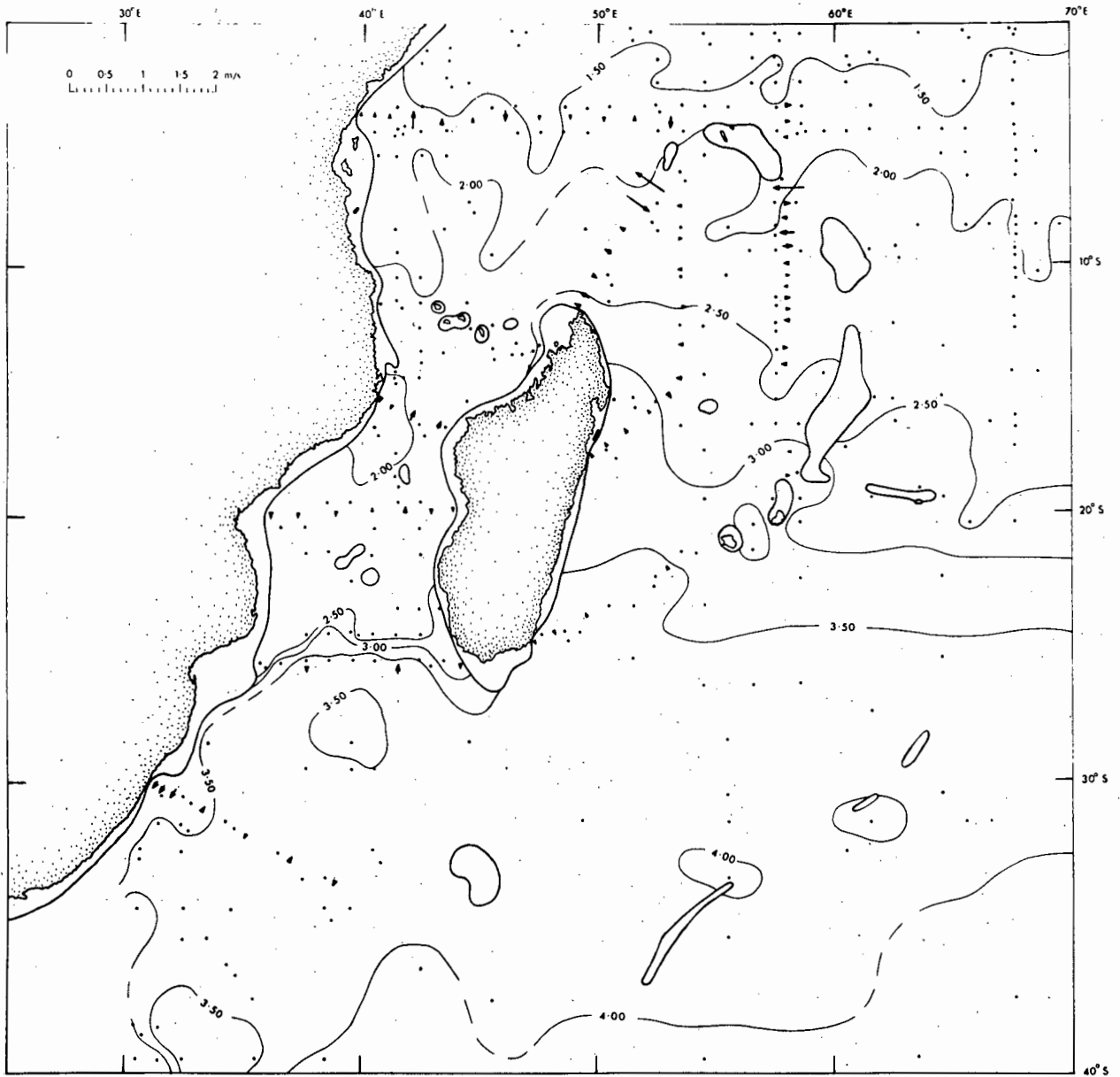


figure 5.33

Distribution of oxygen content on the $\sigma_t 27.50$ level.

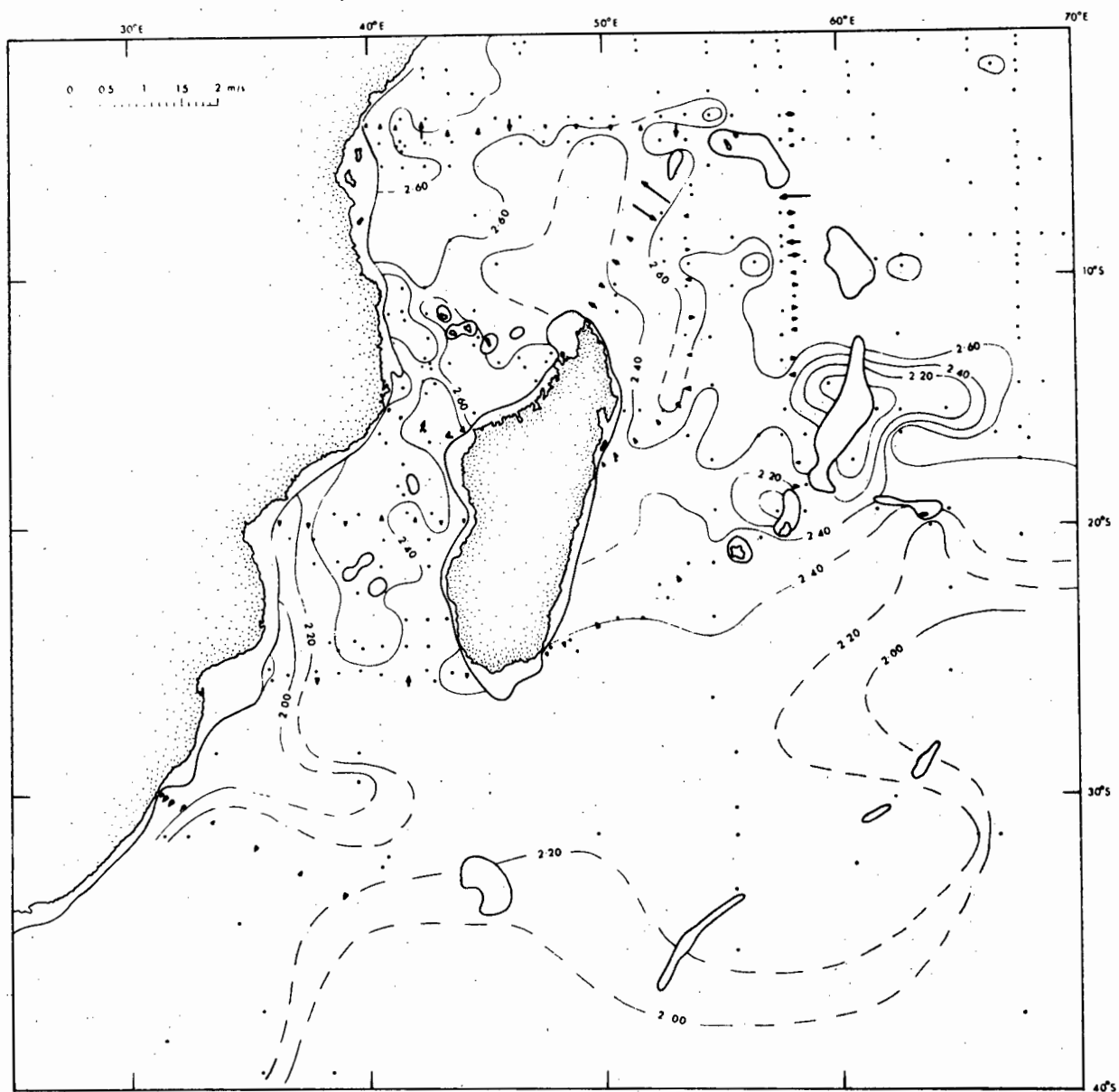


figure 5.34

Distribution of inorganic phosphate on the σ_t 27.50 level.

5.8 THE σ_t 27.50 SURFACE (figures 5.30 - 5.34)

This σ_t -surface lies at about 1200 m and indicates a salinity maximum as well as an oxygen minimum. One can accordingly expect to find North Indian Deep Water present on this surface. For the purpose of this and other diagrams no distinction was attempted between Red Sea Water, Arabian Sea Water etc. but all water showing a salinity maximum and an oxygen minimum with its origin in the north Indian Ocean was called North Indian Deep Water after Clowes & Deacon (1935).

According to the depth of the σ_t -surface (figure 5.30) the flow in the greater part of the ocean is from east to west. Near the equator there are signs of flow eastwards and north of the Mozambique Channel there is also some indication of flow in the same direction. The general westward flow is deflected southward by the land mass of Madagascar, although the interpretation here is very subjective, and it then flows past the southern mouth of the channel in a narrow intense flow. The Agulhas Current and Agulhas Return Flow stand out clearly, but the Return Flow does not seem to flow further east in the area under consideration than 50°E . The flow in the Mozambique Channel consists of a very large anticyclonic circulation with no connection to flow outside the Channel.

Except for the phosphates, the other identifying properties present a very consistent picture. To the north of 15°S all the isolines run east-west, which may indicate a flow in that direction. North of the Mozambique Channel a northerly flow flanked by two southerly flows is shown (especially clear in figure 5.33) as depicted in figure 5.30. The general south-

ward inclination of the $34.80^{\circ}/\text{oo}$ isohaline (figure 5.32) does seem to indicate a general southward flow of high salinity water in this region. The isolines in the Mozambique Channel are displaced southwards on all diagrams forming a veritable boundary at the southern mouth, although the temperature and salinity and, to an even greater degree, the phosphates indicate a flow out from the eastern side of the channel. The strong flow of the Agulhas Current is still parallel to the isolines, but the Return Flow shows only tongues (figure 5.31 and 5.32) protruding eastwards.

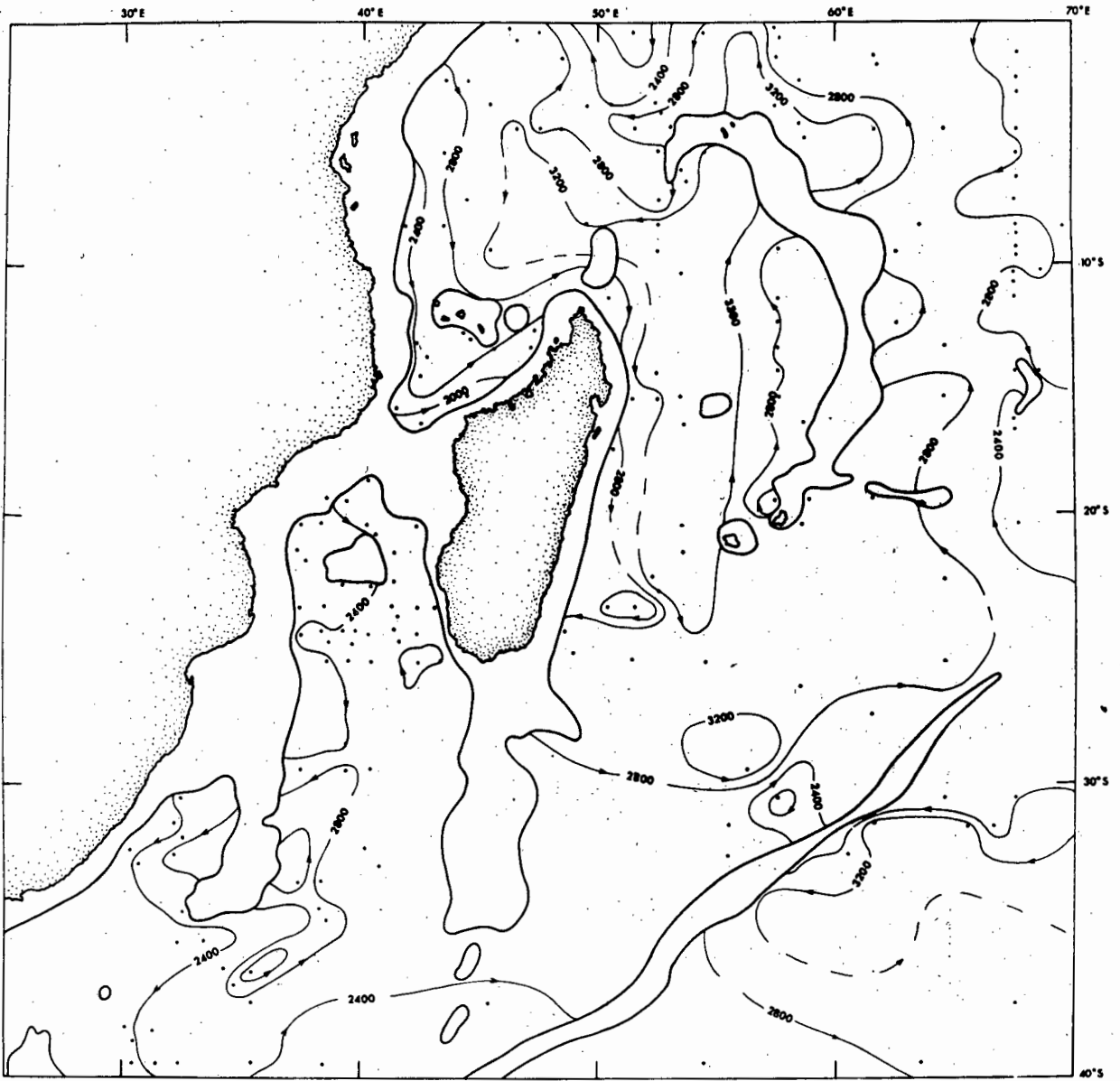


figure 5.35
Depth of the σ_t 27.80 level.

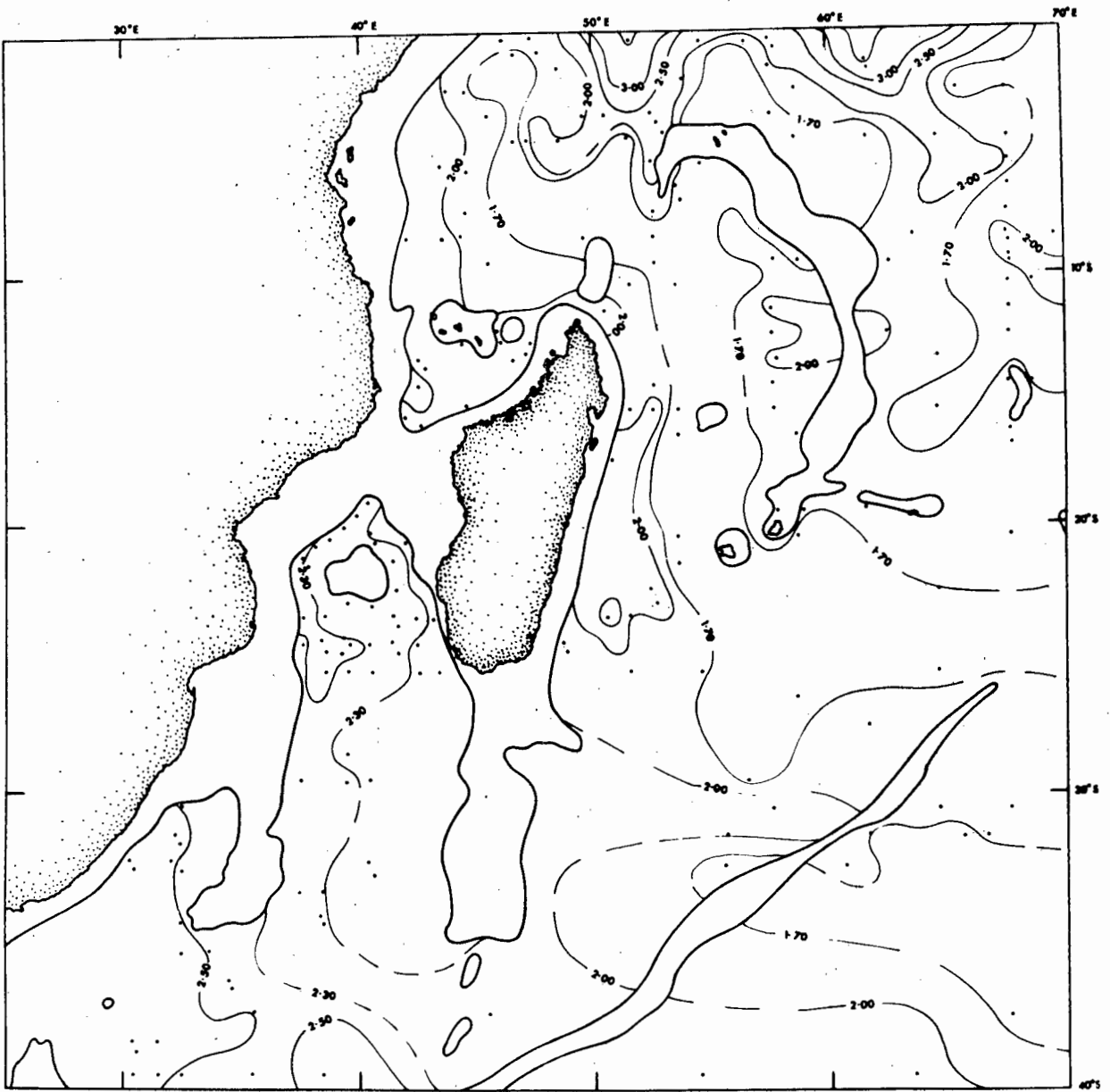


figure 5.36

Distribution of temperature on the σ_t 27.80 level.

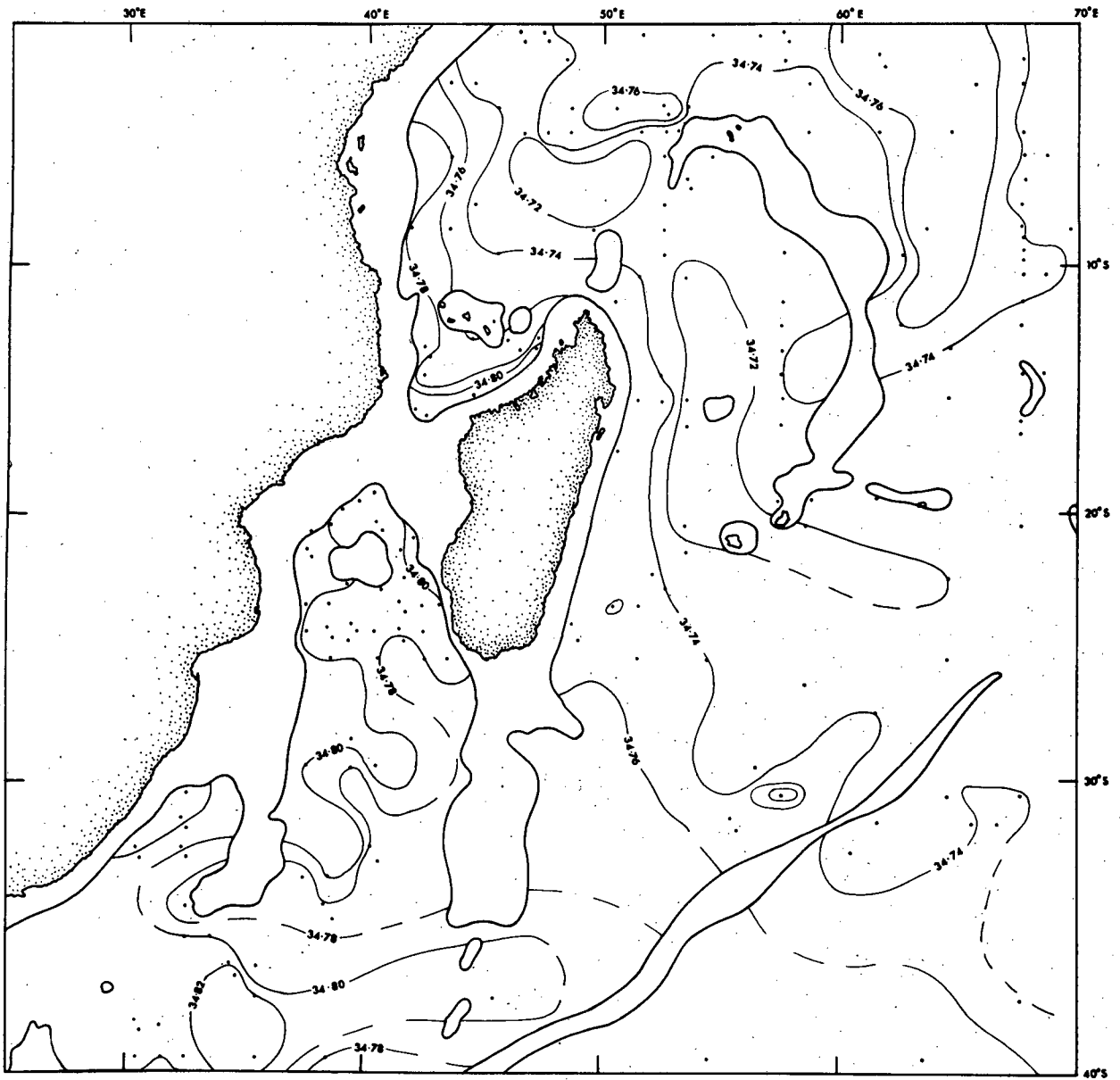


figure 5.37

Distribution of salinity on the $\sigma_t 27.80$ level.

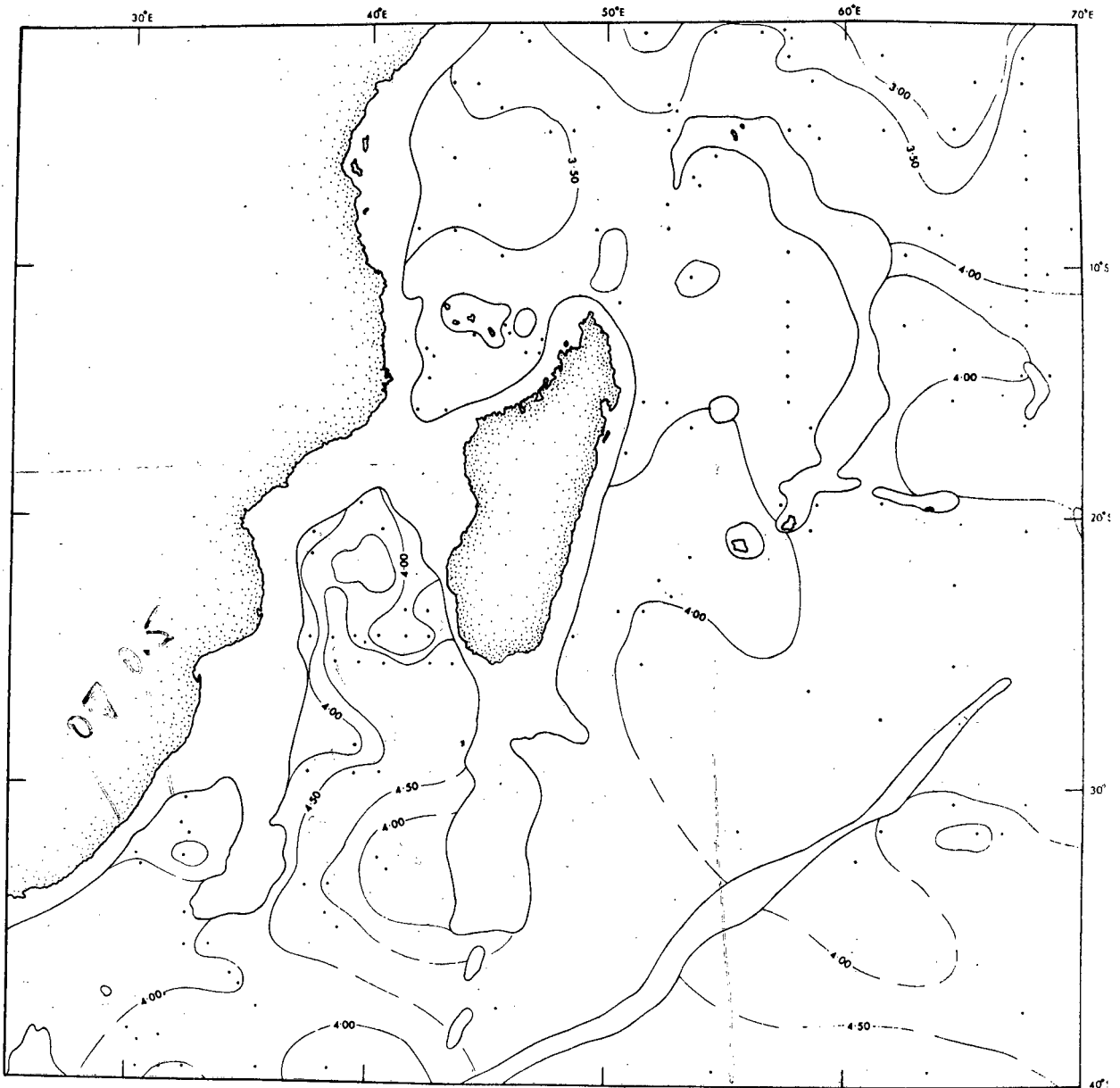


figure 5.38

Distribution of oxygen content on the σ_t 27.80 level.

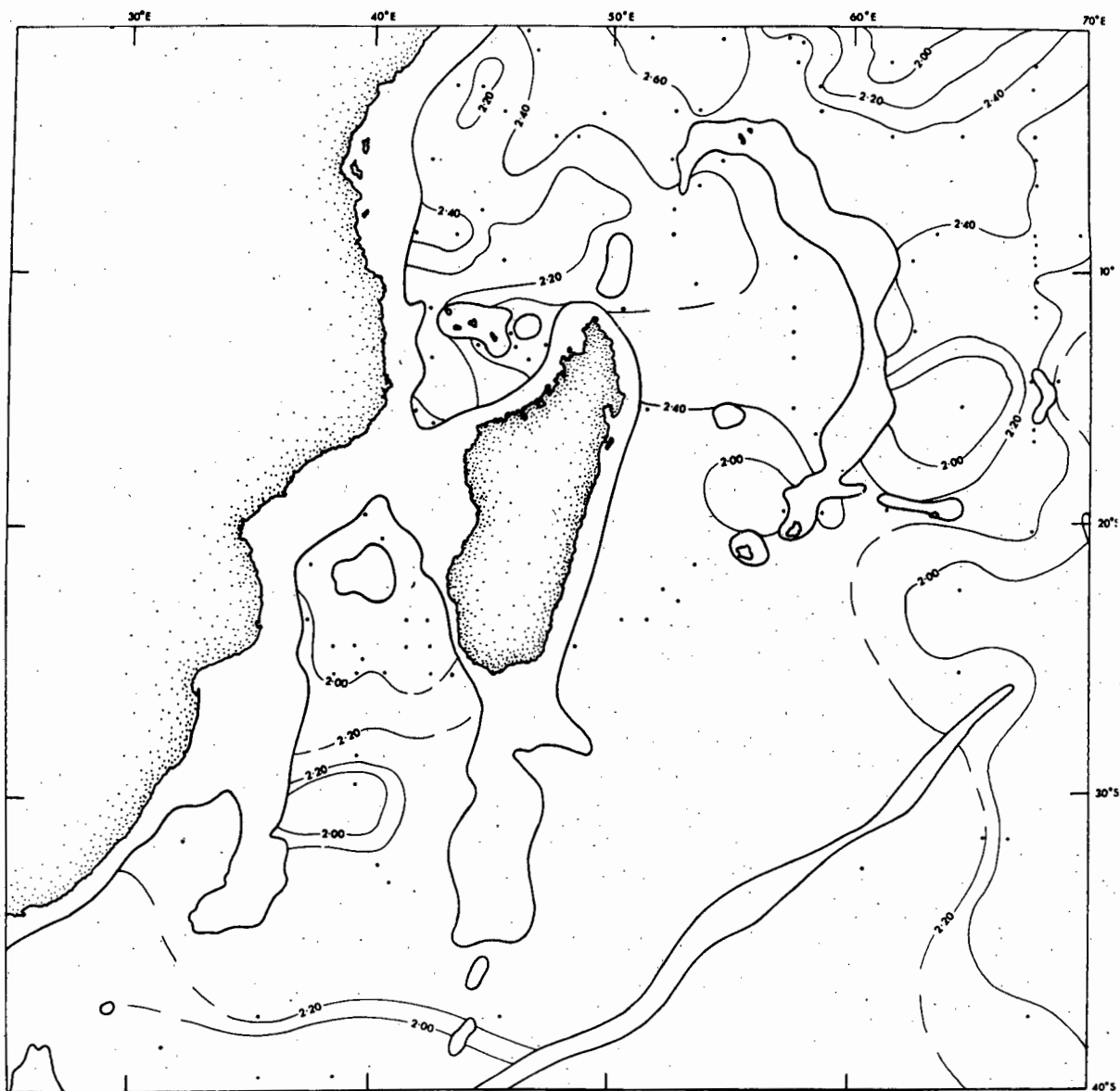


figure 5.39

Distribution of inorganic phosphate on the σ_t 27.80 level.

5.9 THE σ_t 27.80 SURFACE (figures 5.35 - 5.39)

The deepest σ_t -surface chosen for this analysis is the 27.80 surface at an average depth of 2380 m. This is related to a weakly developed salinity maximum that is probably due to North Atlantic Deep Water but that does not occur at all stations. At this depth the very variable bottom topography (figures 5.1 and 6.2) manifests itself as can be seen in the σ_t -diagrams. This surface is also very near to the chosen level-of-no-motion for the velocity calculations so that no velocity arrows are shown. The depths are also approaching those at which the limits of the isentropic methods application are reached. An extra complication is the dearth of stations at this depth which makes interpretation very difficult.

In the southern part of the ocean there would seem to be a good indication of high salinity water entering the ocean from the west and spreading eastwards on the northern side of the Atlantic-Indian Ridge (figure 5.37). The topography of the σ_t -surface (figure 5.35) shows a similar circulation. In the cul-de-sac formed between the Mozambique and the Madagascar Ridge there is a higher station density, but the flow remains obscure. A highly oxygenated, low salinity and high temperature tongue stretching up this area might indicate a flow parallel to the sides of this enclave, but the isobaths do not show this. Near the equator and roughly parallel to it there is a bunching of isolines that might indicate strong flow or a hydrological barrier. All diagrams show this except the salinity distribution. An indentation in this "barrier" at about 63°E shown in all figures and depicted as a tongue of high salinity water (figure 5.37) may be in line

with the 2800 m isobath which shows a flow southwards. Otherwise the diagrams are open to various interpretations.

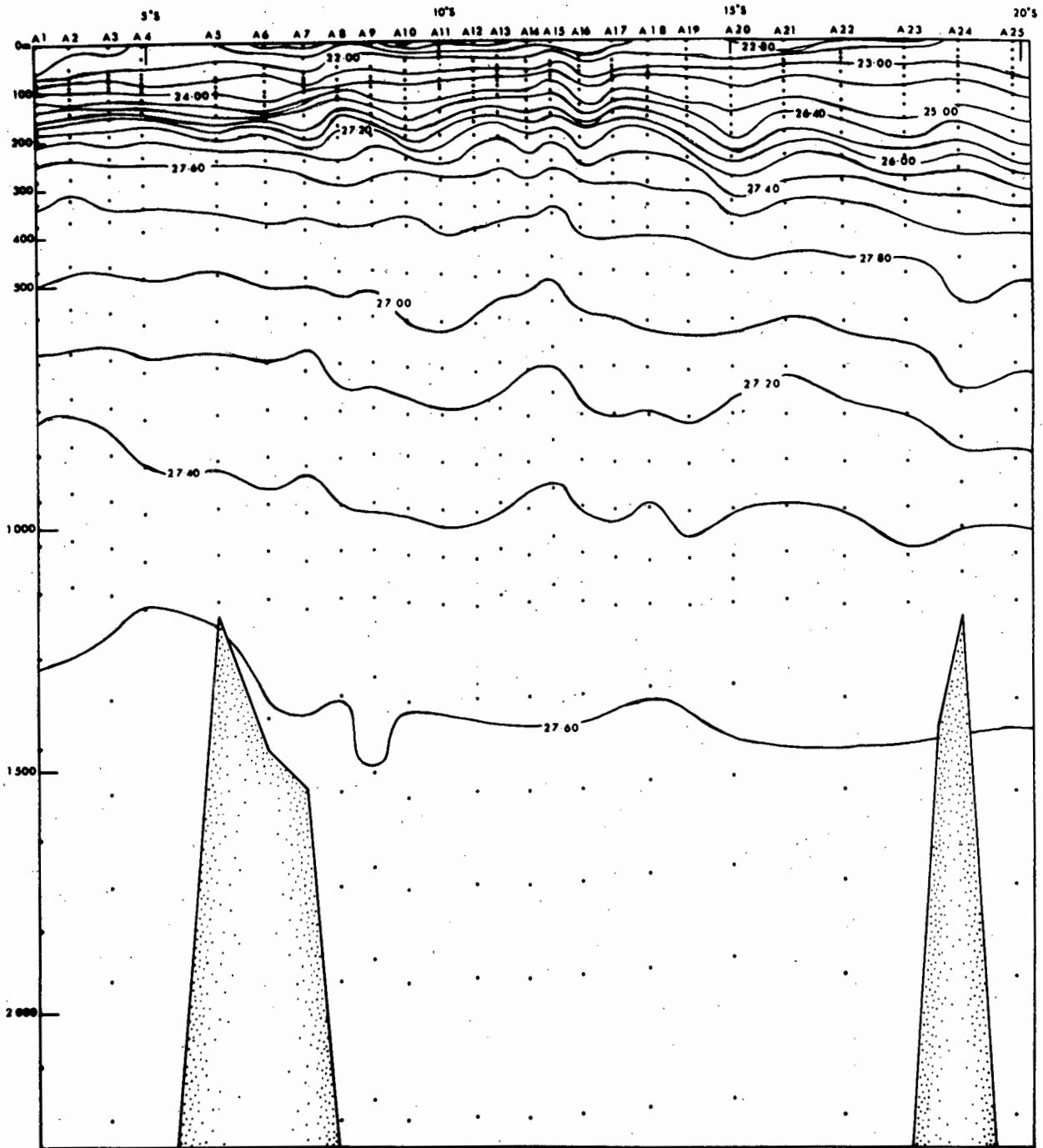


figure 5.40
Density distribution in vertical section A.

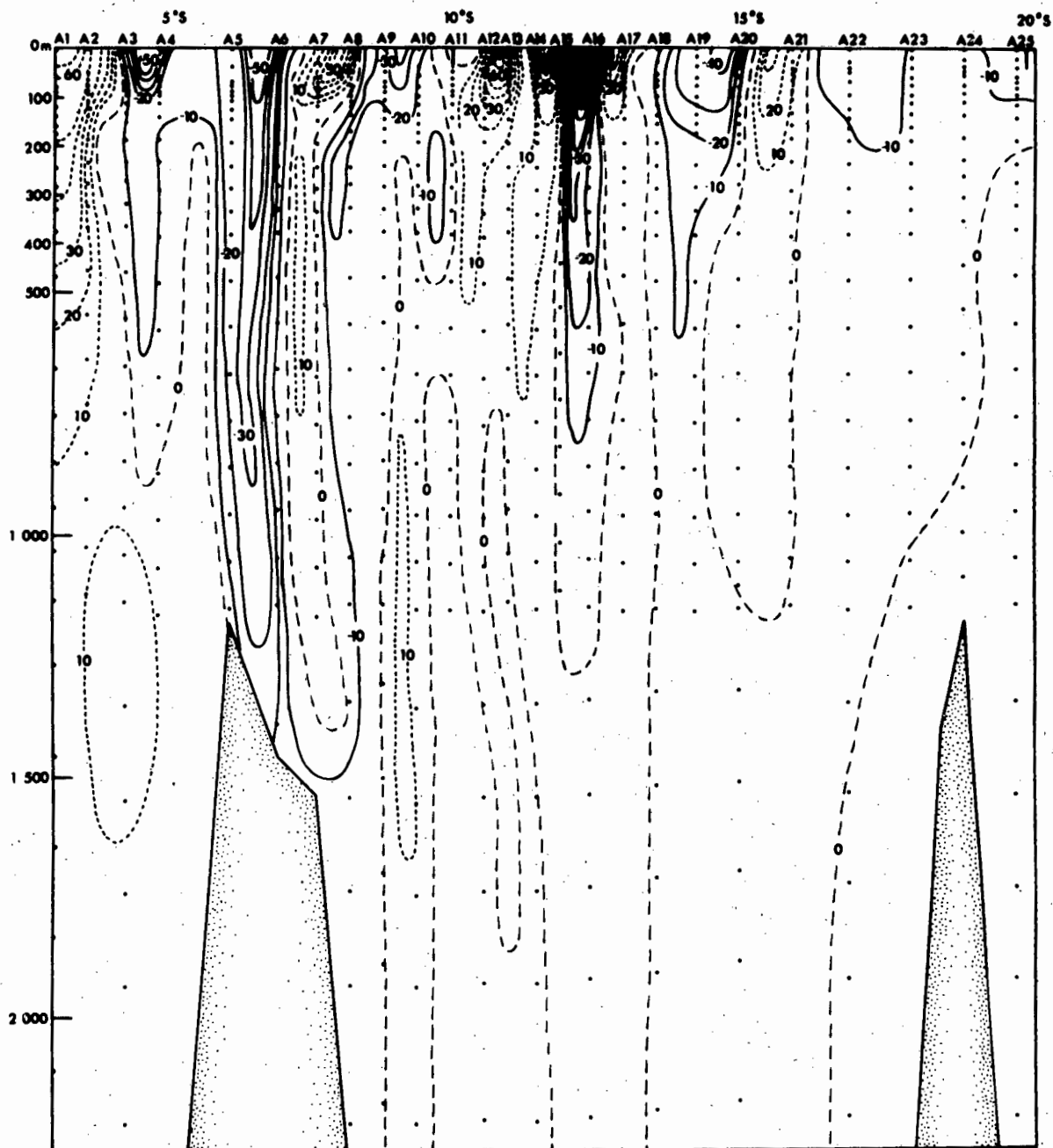


figure 5.41

Velocity profile for vertical section A.

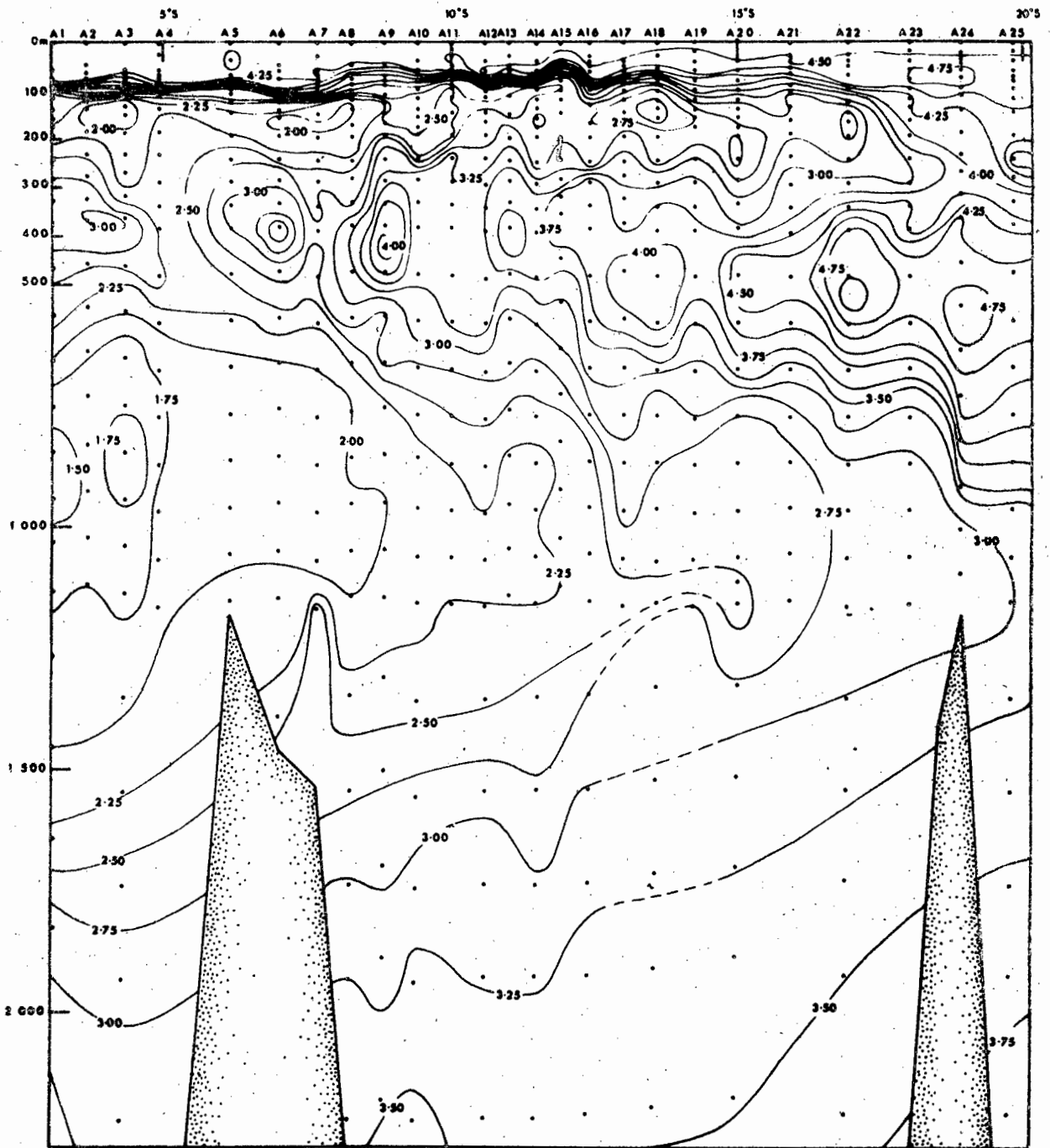


figure 5.42

Distribution of oxygen content in vertical section A.

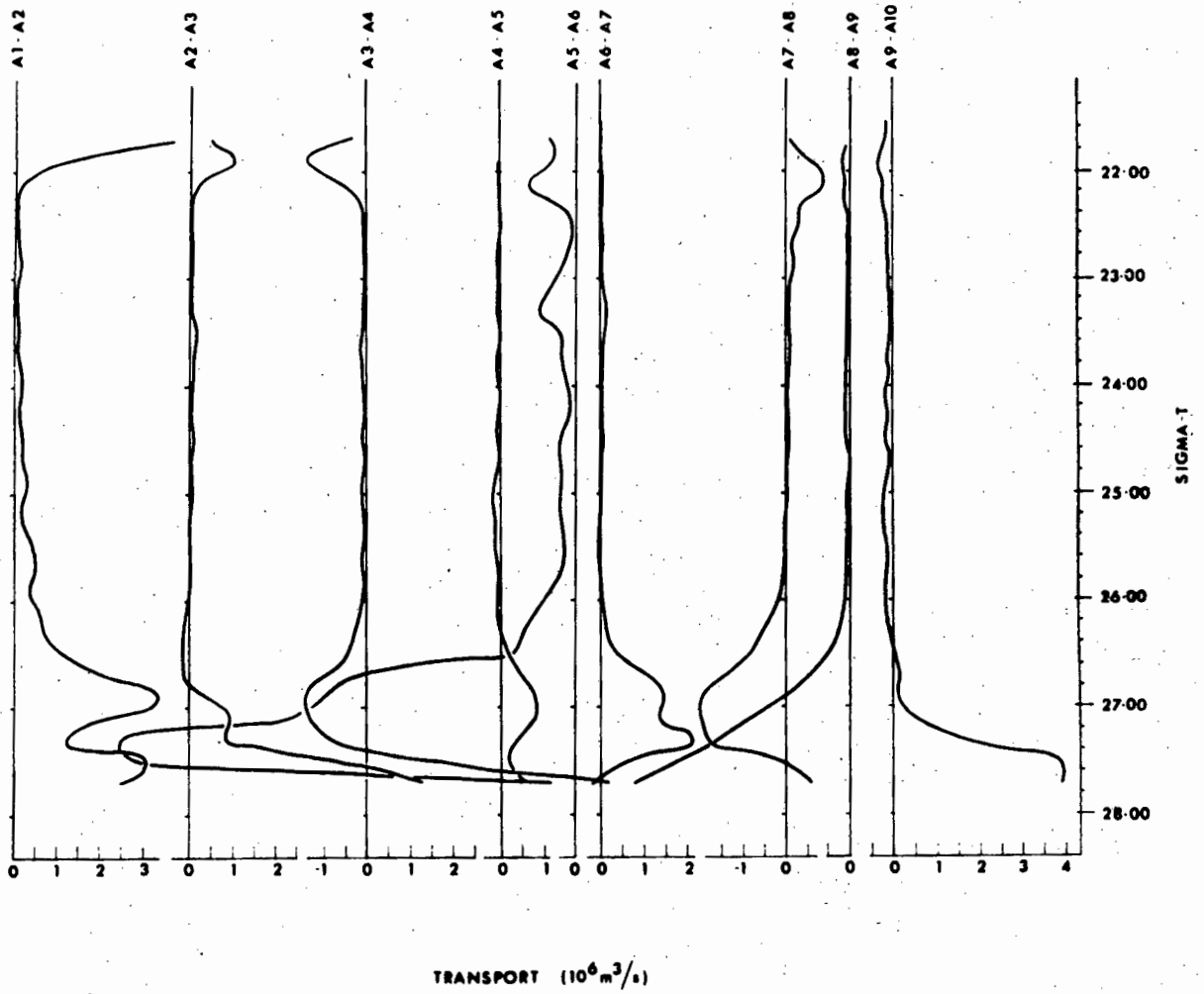


figure 5.43

Graphs of volume transport according to σ_t between stations for vertical section A (stations A 1 to A 10).

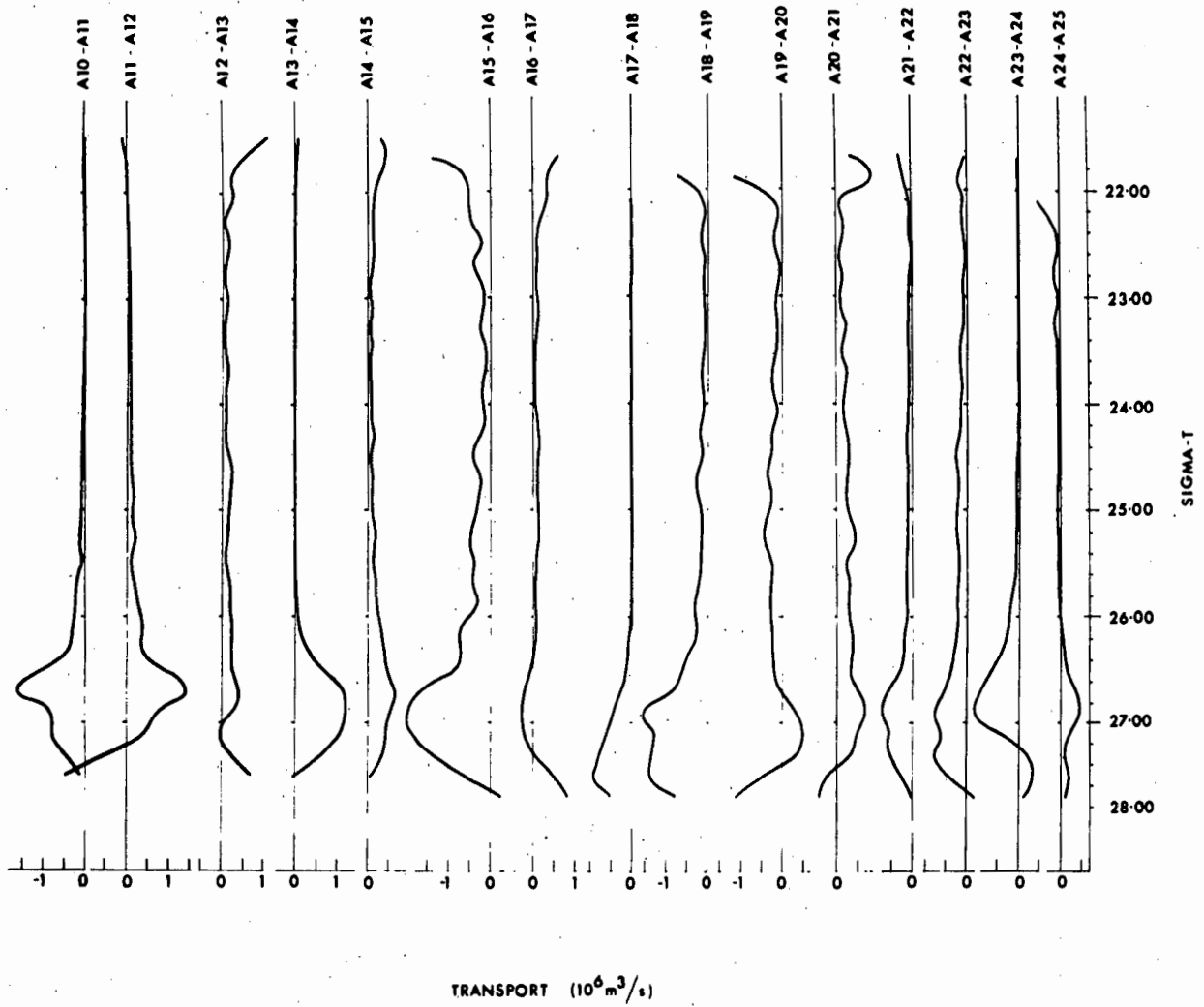


figure 5.44

Graphs of volume transport between stations according to σ_t for vertical section A (stations A 10 to A 25).

5.10. THE VERTICAL SECTION A (figures 5.40 - 5.44)

This section consists of stations occupied by the Discovery in March and April of 1964 and measurements have been taken along the 58°E meridian from about 3°S to 20°S (see figure 4.18). The station numbers are those as used in figure 4.18. The ships own nomenclature for the stations is given in table IV.2 in the appendices. Latitude positions have been marked and dots, as is usual, denote actual depths at which measurements were taken. The depth is in meters and the bottom topography was derived from the bathymetries by Simpson & Forder (1969) and the Carte Général Bathymétrique des Océans (— 1938).

The general trend of the σ_t lines is to slope up from south to north indicating a general flow from east to west. The changes in slope from the general trend in certain localities are reflected in the velocity profiles (figure 5.41). The negative velocities denote east-west flow, i.e. out of the page. The general flow westwards is clear as well as the various currents and counter-currents (or eddies) near the surface. In places the surface currents are strong and deep. The velocity at the surface between stations A 15 and A 16 is 135 cm/s and the velocity at 1200 m for the flow between stations A 5 and A 6 is still 20 cm/s. An interesting feature is also the "undercurrents" where parcels of water are moving, at depth, in the opposite direction than the surface flow. An example is the current of more than 10 cm/s below 1000 m between stations A 2 and A 3.

The lines of equal oxygen show, very distinctly, a meridional flow of considerable vertical extent (figure 5.42). Near the surface the water is highly oxygenated. A low oxygen core moves south flowing from 150 m at 5°S to about 300 m at 18°S. A high oxygen core lies below this. This core starts with an oxygen value of 4.75 ml/l at 20°S (at 600 m) that is depleted to about 2.50 ml/l at 5°S (at 350 m). Below this, stretching deeper than 2000 m is a core of very low oxygen water that passes the equator having a value of 1.50 ml/l.

The volume transports across the whole section as measured between stations are very small for most of the water above σ_t 26.00, excepting the very surface water (figures 5.43 and 5.44). For currents that show a sustained velocity below 300 m there is a slight peak at about 27.00 σ_t . Between stations A 5 and A 6 the current flows so deep that the major part of its transport falls in the 27.40 σ_t region. The "undercurrents" are shown in the sharp rise of the curves for the stations A 2 - A 3 and A 3 - A 4 at about 27.60 σ_t .

It is clear from this section why it was not possible to combine the transports of those station pairs that show transport in any one direction. If stations had formed distinct groups denoting clearly different currents this would have been possible, but with the fragmentary nature of the currents any grouping would have been artificial. To lesser or greater degrees this argument also holds true for other vertical sections to be considered.

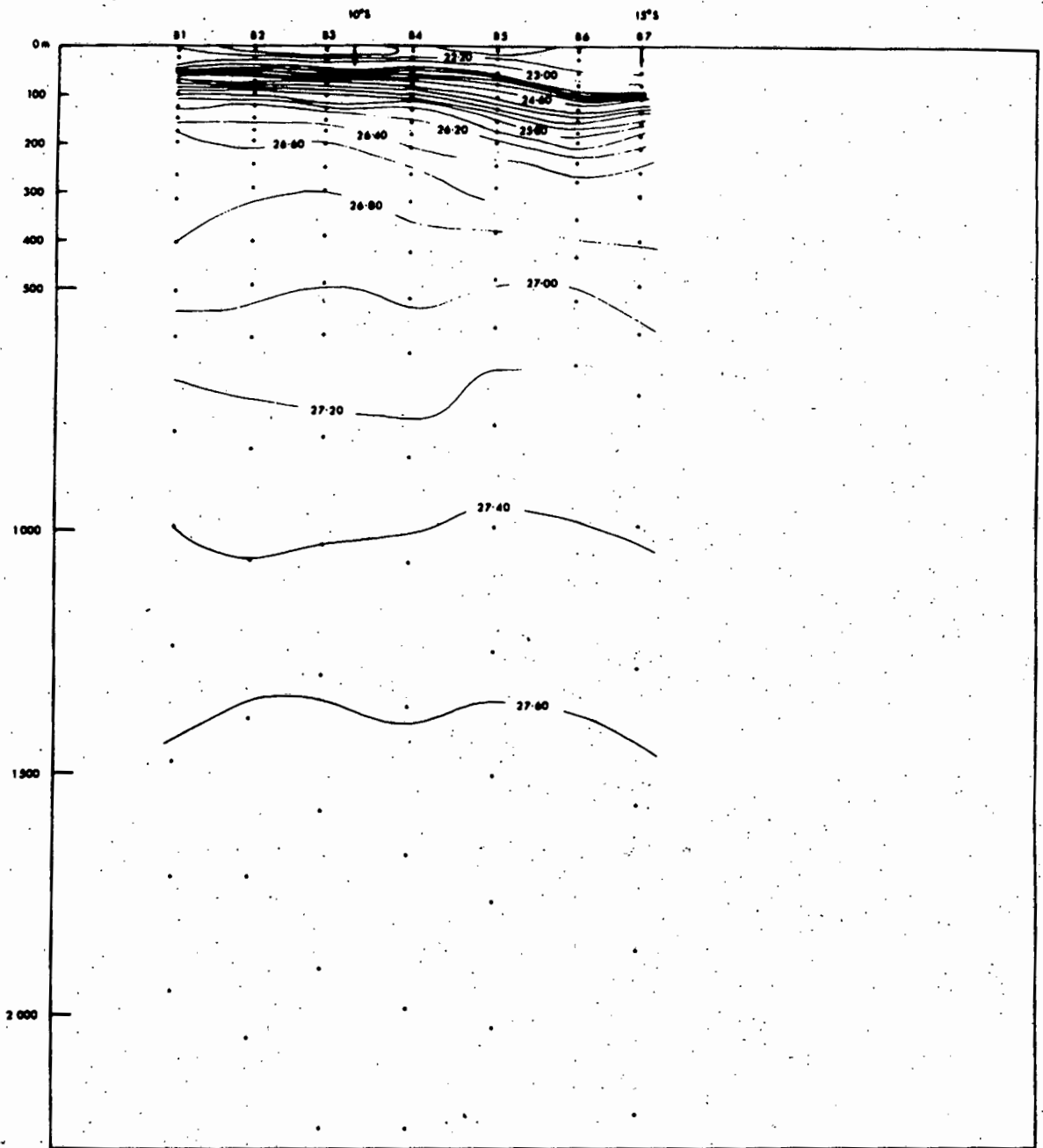


figure 5.45
Density distribution in vertical section B.

figure 5.47
Distribution of oxygen content in vertical section B.

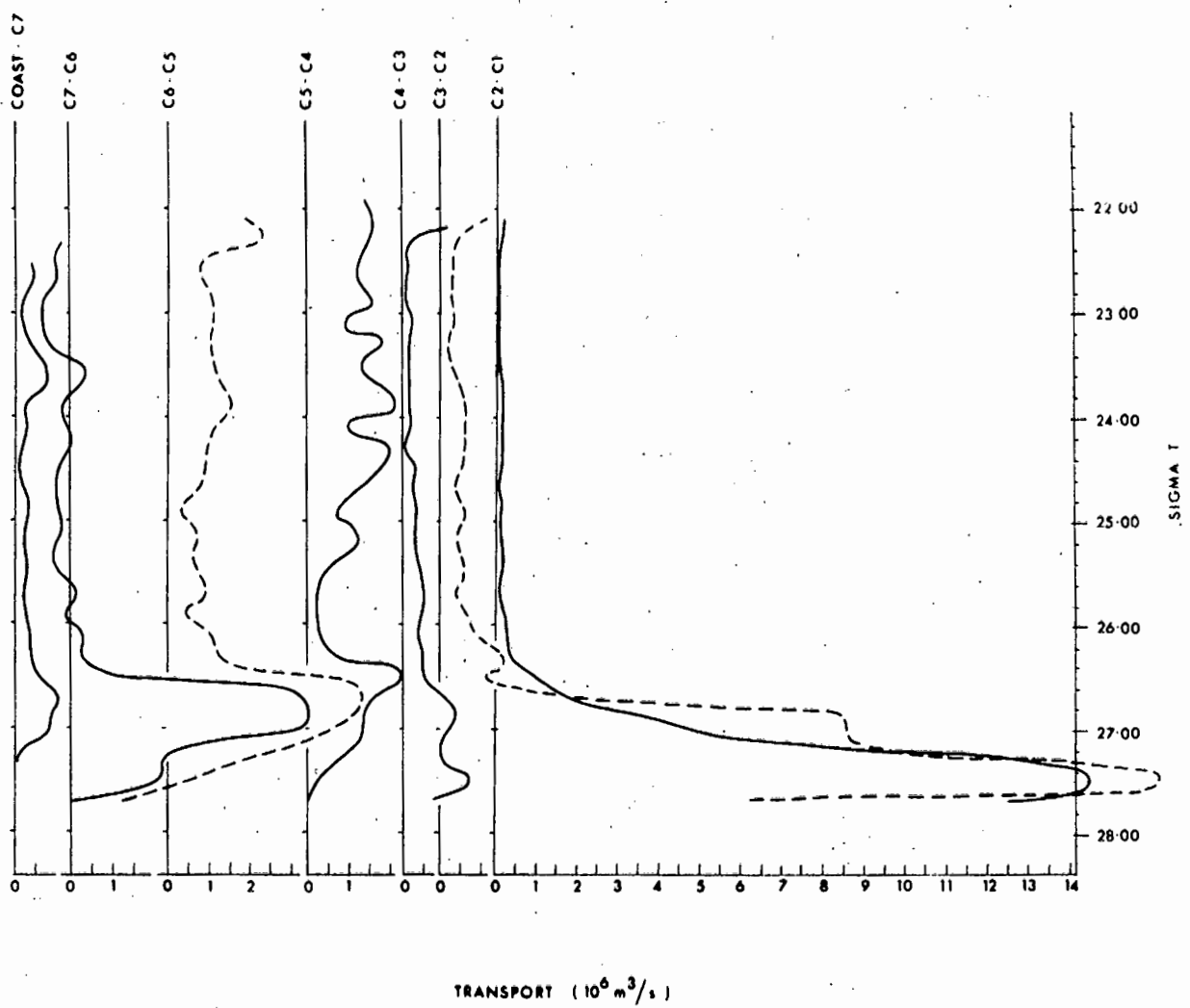


figure 5.51

Graphs of volume transport according to σ_t between stations for vertical section C.

5.12 THE VERTICAL SECTION C (figures 5.49 - 5.51)

This section runs from Cape d'Ambre north-northeast to the Seychelles (figure 4.18) and was occupied by the Laperouse in March 1957. The bottom topography shows that it covers what might be termed a channel to the north of Madagascar. The slopes of the σ_t -surfaces are coherent with depth (figure 5.49) and the resulting currents are strong and extremely deep. The current closest inshore, proceeding from Cape d'Ambre, reaches a velocity of 128 cm/s which is the same as the velocity of the countercurrent north of this. Currents alternating in directions follow on proceeding further north until at station C 1 the highest velocity is 40 cm/s at 1100 m. The curves relating volume transport to σ_t show up the current structure very clearly. Since many of the currents depicted have very sustained velocities at depth the transport for higher σ_t -values is very large. To facilitate the drawing of the diagram some of the curves are inverted. These have been drawn as broken lines. A combination of the first two curves give an indication of the transport of the current just off-shore which is nearly the same as that for the countercurrent. The transport between stations C 5 - C 4 and C 4 - C 3 give a sustained transport with by far the largest transport in the upper layers. Between C 3 and C 2 there is also some transport in the upper layers, but the largest peak, as in C 2 - C 1, is at 27.50 σ_t at about 1500 m.

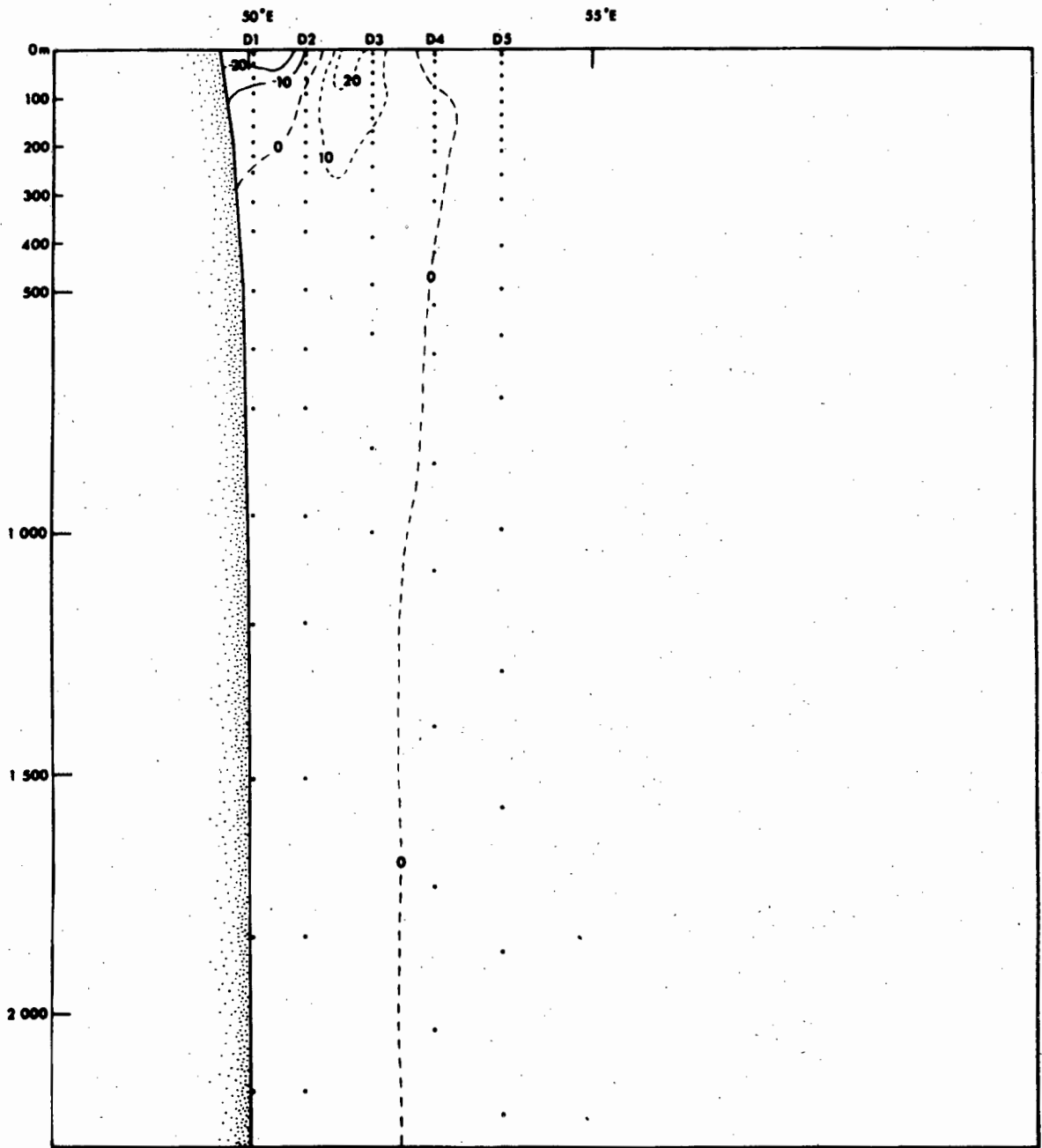


figure 5.53
Velocity profile for vertical section D.

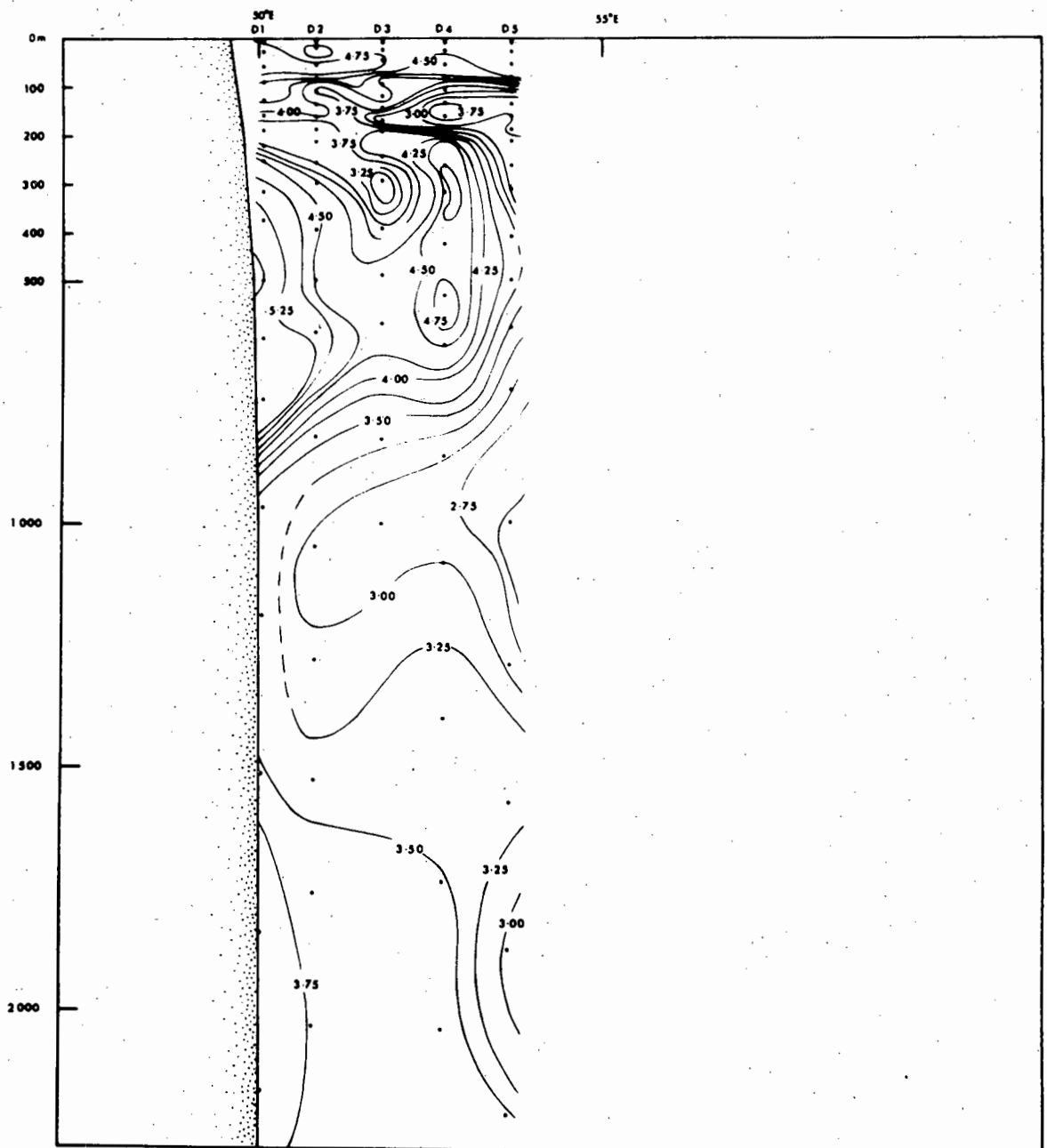


figure 5.54

Distribution of oxygen content in vertical section D.

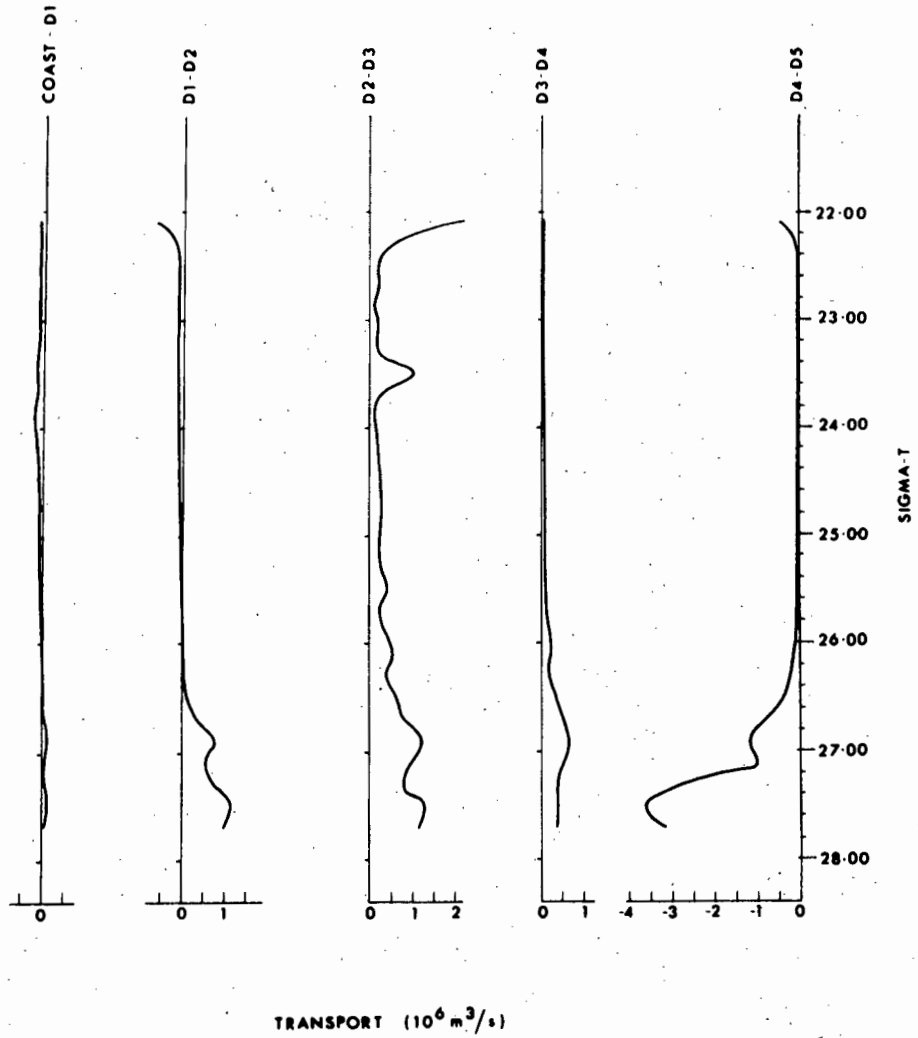


figure 5.55

Graphs of volume transport according to σ_t between stations for vertical section D.

5.13 THE VERTICAL SECTION D (figures 5.52 - 5.55)

This section is a continuation of the Vityaz cruise of February, March 1960 as portrayed by section B and extends from Tamatave in a northeasterly direction as shown in figure 4.18. The slopes of the σ_t -surfaces are weak and not very coherent in their direction (figure 5.52) with the result that the currents are weak and sometimes shallow. Just offshore there is a current flowing southwards but its extent is no further than 300 m in depth. Most of the flow is north except seaward of station D 4 there is a slow flow south (figure 5.53). This is also quite marked in the transport curves (figure 5.55) that show very little transport except that going north (D 2 to D 3) and that going south between D 4 and D 5, but then only noticeable at about 27.60 σ_t . The oxygen distribution (figure 5.54) shows very sharp contrasts. A thin oxygen core at 150 m, a highly oxygenated water mass at 500 m and a low oxygen water mass at 1000 m are the main features. That part of the core which lies nearest the coast has the highest oxygen. It might be borne in mind at this stage that this line is not zonal but runs to the northeast and would thus be at an angle to any meridional flow of high or low oxygen water.

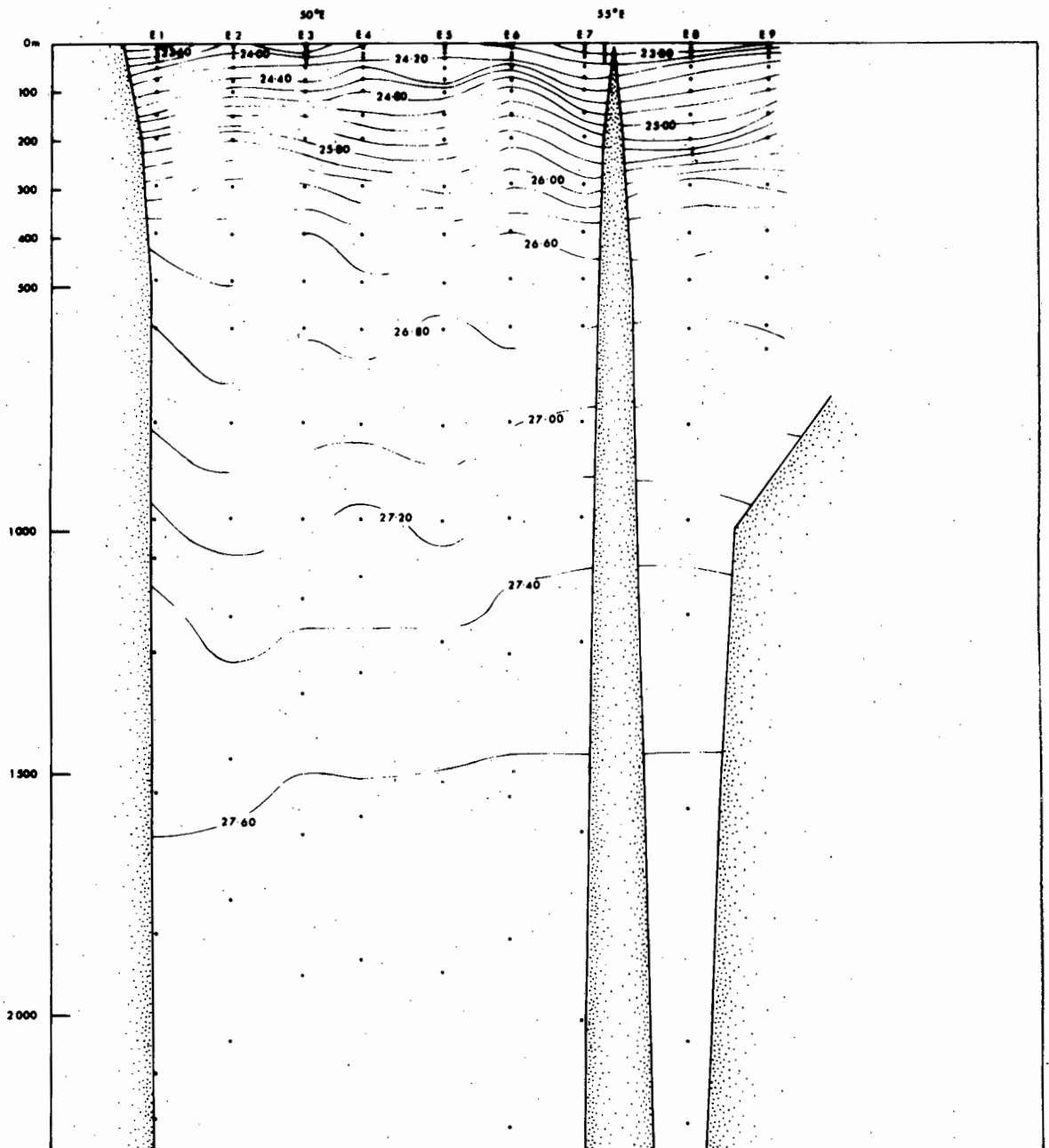


figure 5.56

Density distribution in vertical section E.

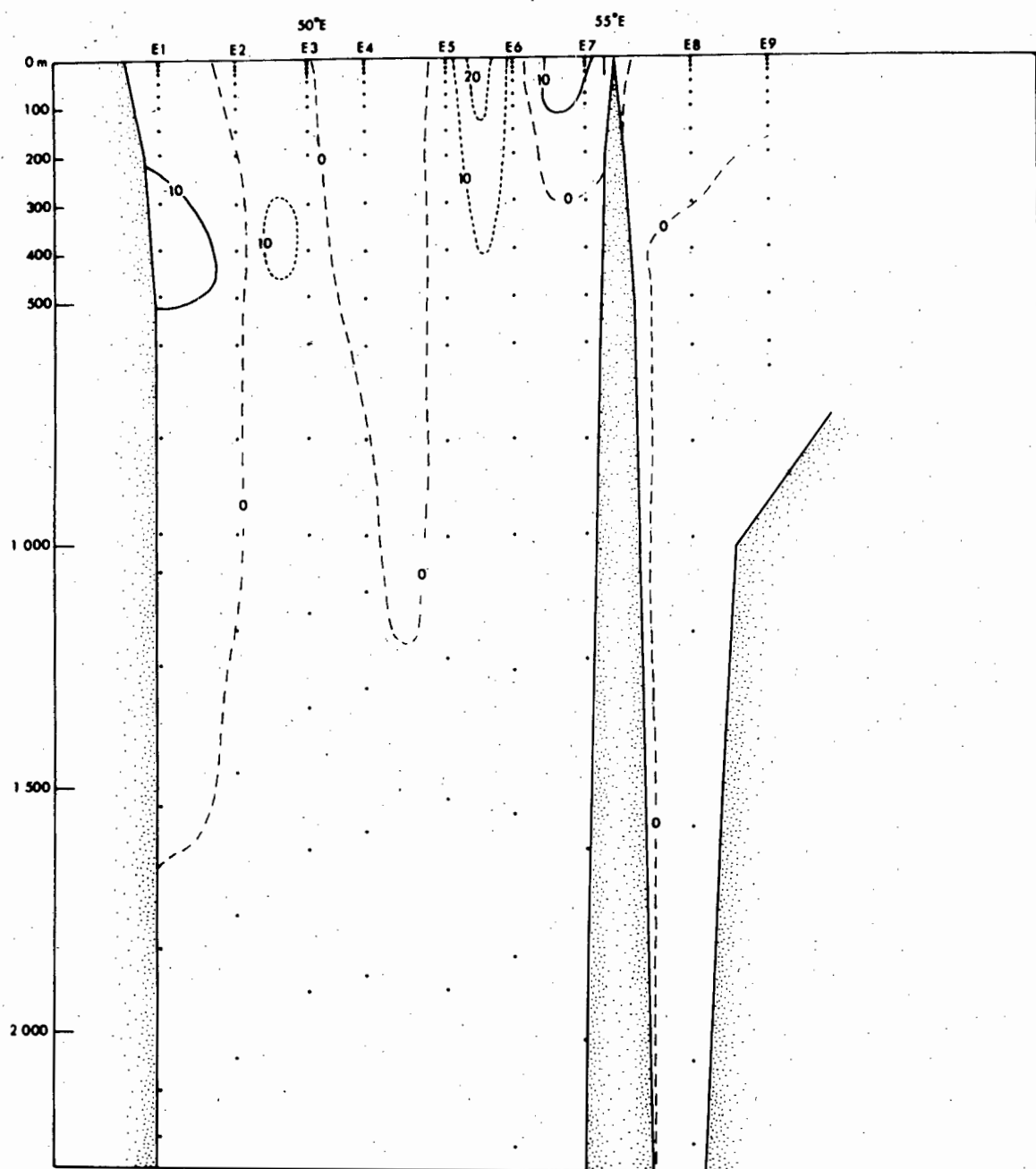


figure 5.57

Velocity profile for vertical section E.

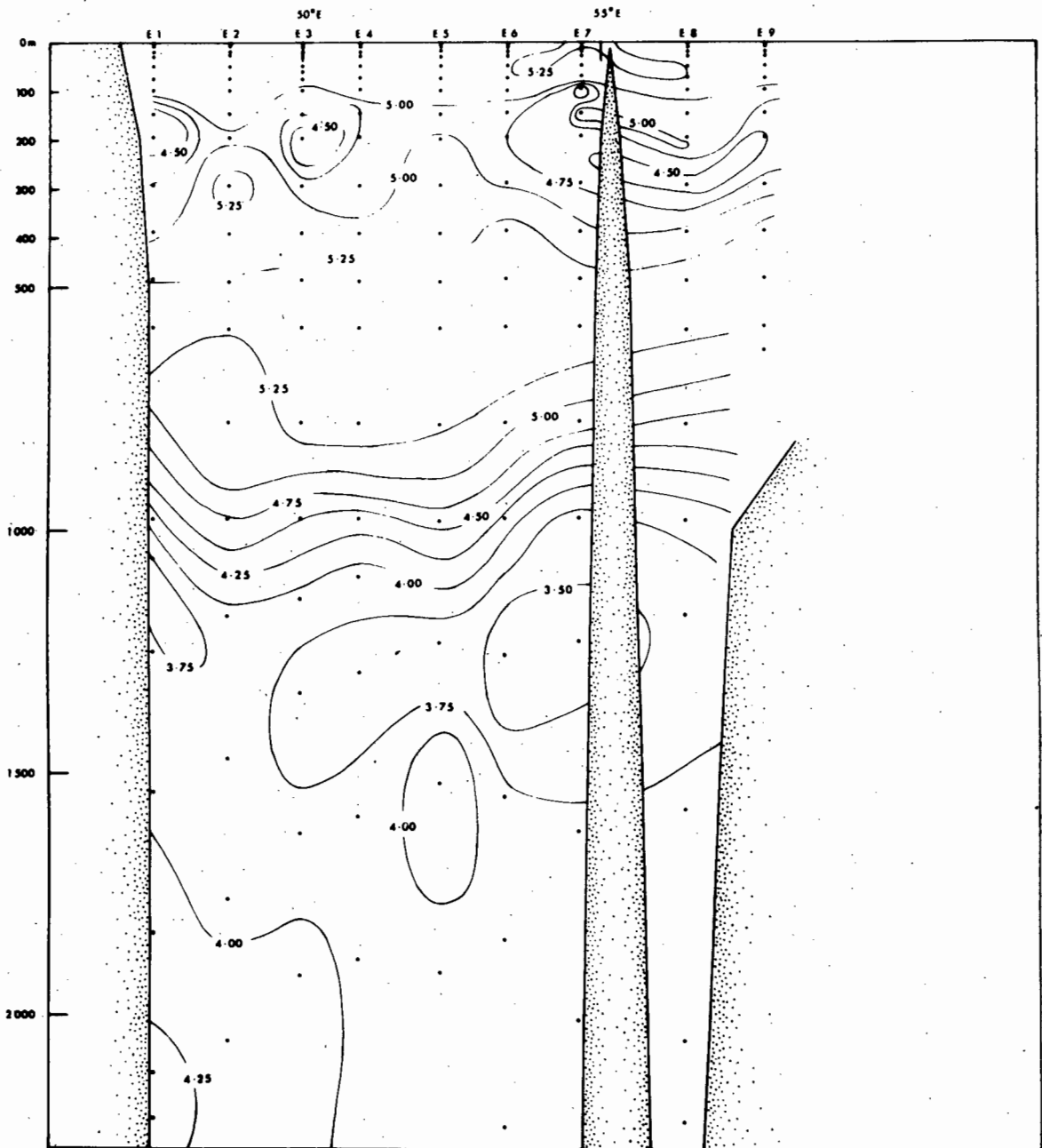


figure 5.58

Distribution of oxygen in vertical section E.

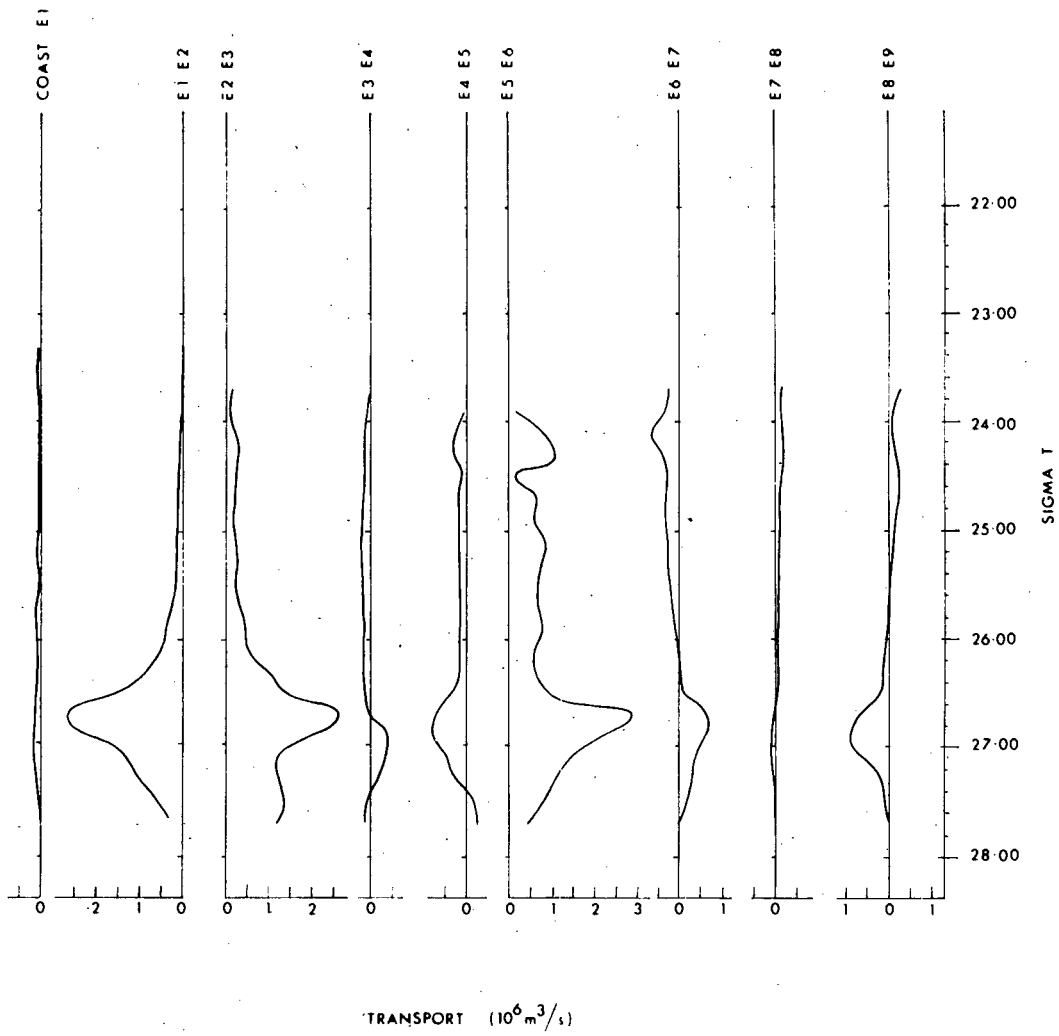


figure 5.59

Graphs of volume transport according to σ_t between stations for vertical section E.

5.14 THE VERTICAL SECTION E (figures 5.56 - 5.59)

The vertical section E (see figure 4.18) is a continuation of the section done by the Atlantis in April 1965 from Lourenço Marques to Cape St. Marie. It runs from Cape St. Marie to Mauritius and is nearly parallel to section D. Figure 5.56 shows the varying slopes of the σ_t -levels. Near the coast the slopes are sustained up to about 350 m from where they change direction. This distribution results in the subsurface velocity maximum close inshore at about this depth. The velocities are small and the currents shallow, most of the water moving slowly north. The only deeper southsetting current is between the Madagascar Coast and station E 2. This is depicted in the greater transport at about σ_t 27.00 for stations E 1 - E 2. Except for two other stations showing this same transport peak for flow northward, the transports on the whole are very small. Although this line is approximately parallel to vertical section D, the cores of the high and low oxygen masses do not show a similar variation across the section. The high oxygen core of about 5.25 ml/l was found at about 600 m and the lowest values (3.50 ml/l) at 1300 m.

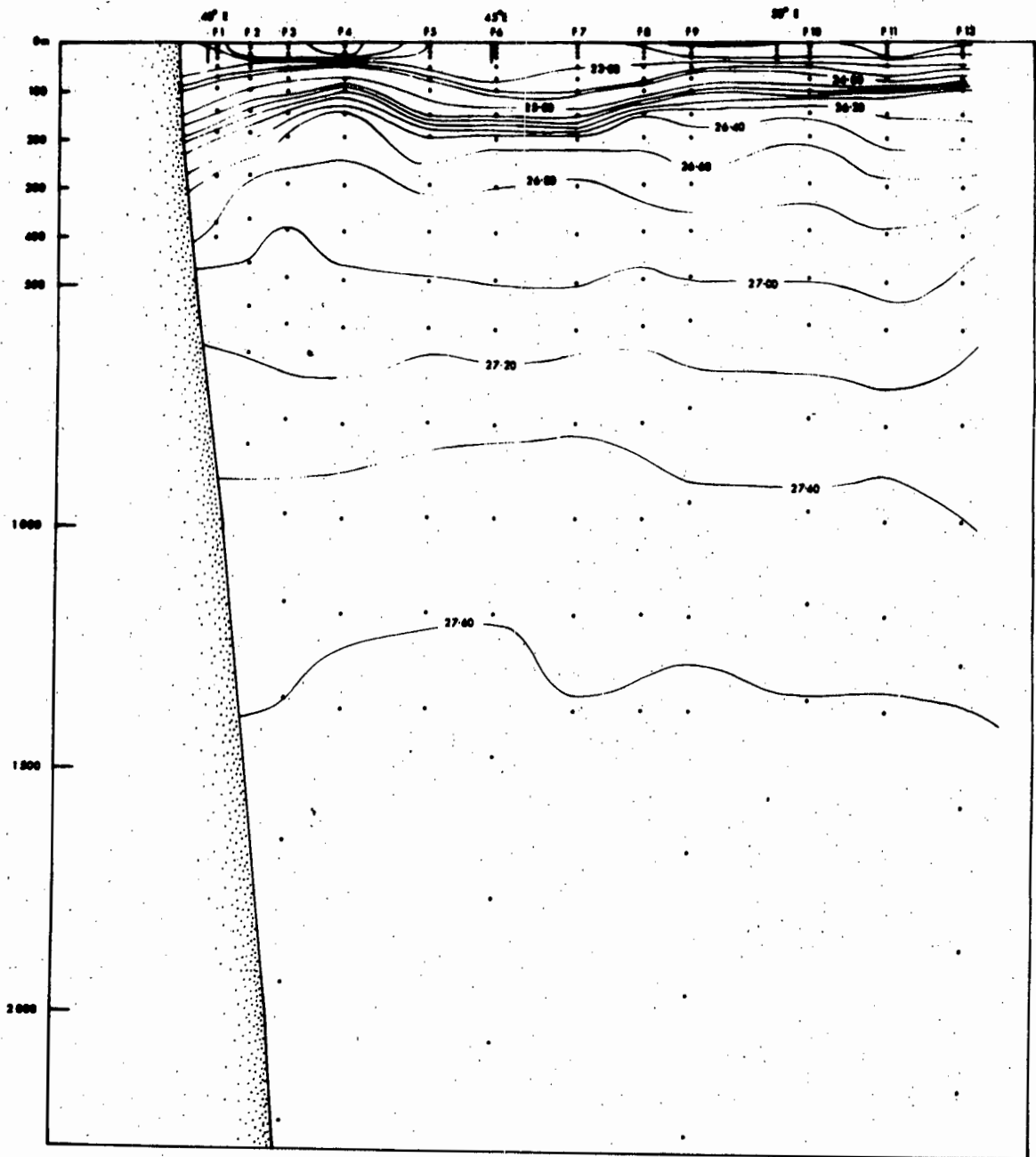


figure 5.60

Density distribution in vertical section F.

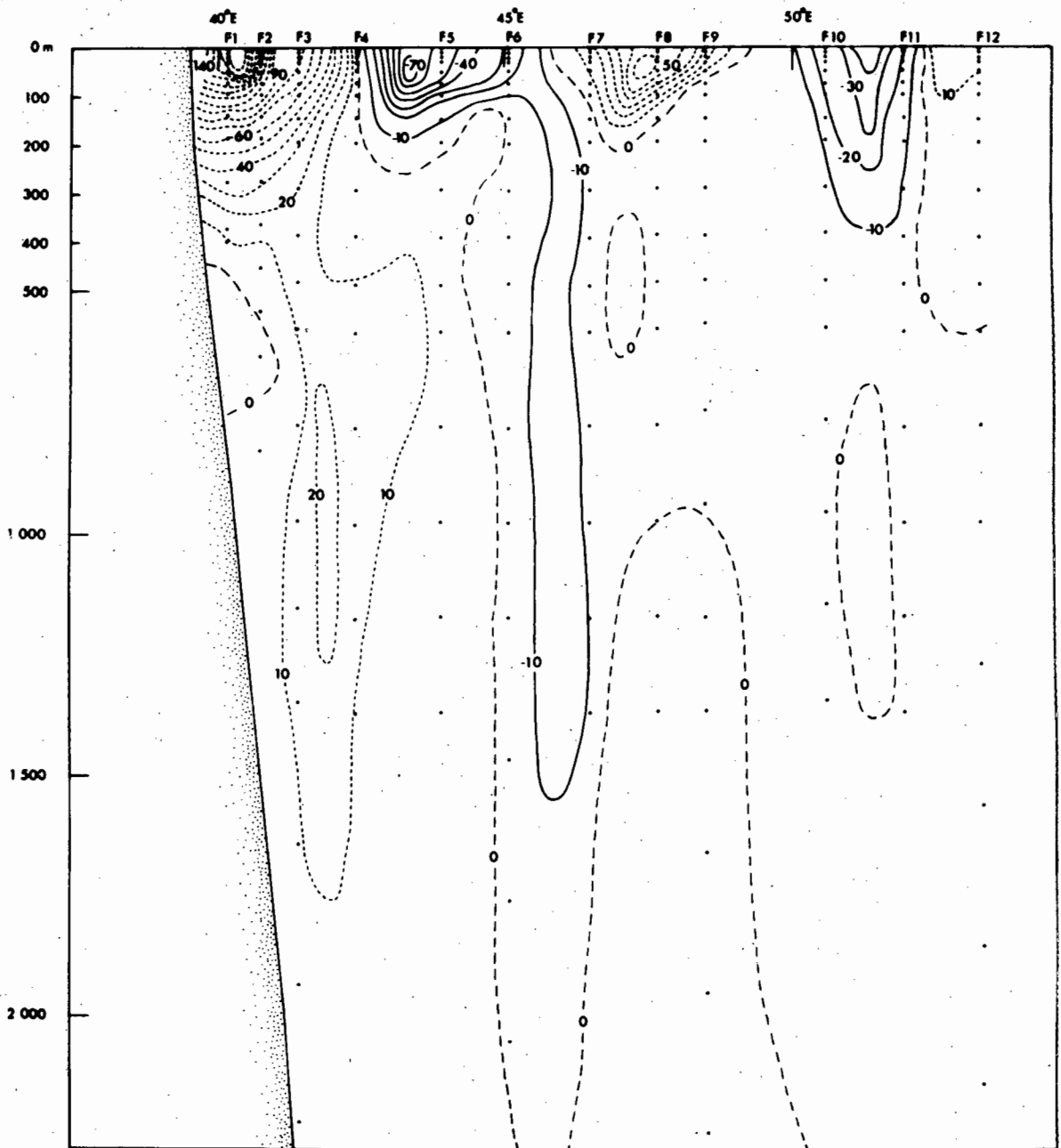


figure 5.61

Velocity profile for vertical section F.

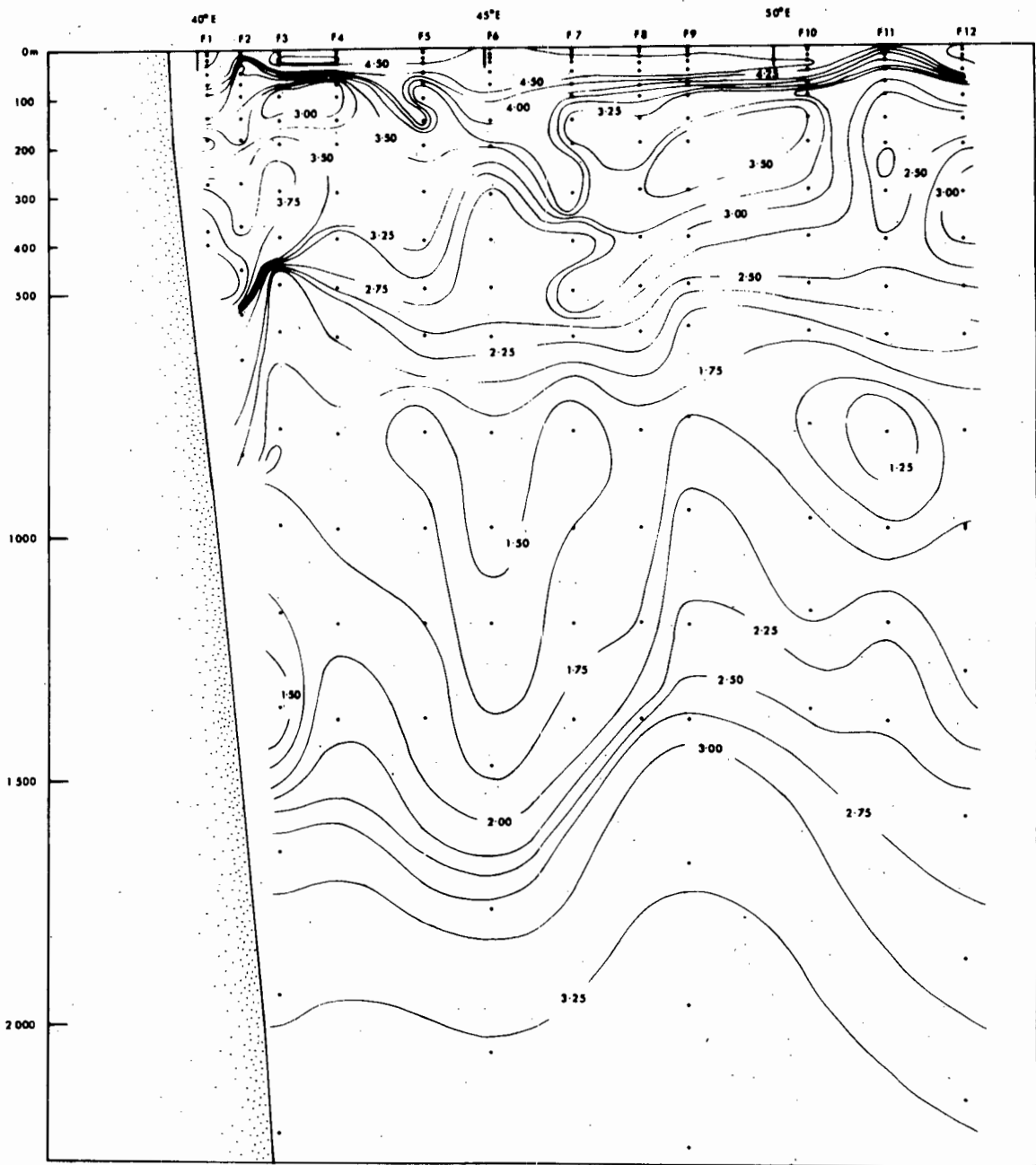


figure 5.62

Distribution of oxygen content in vertical section F.

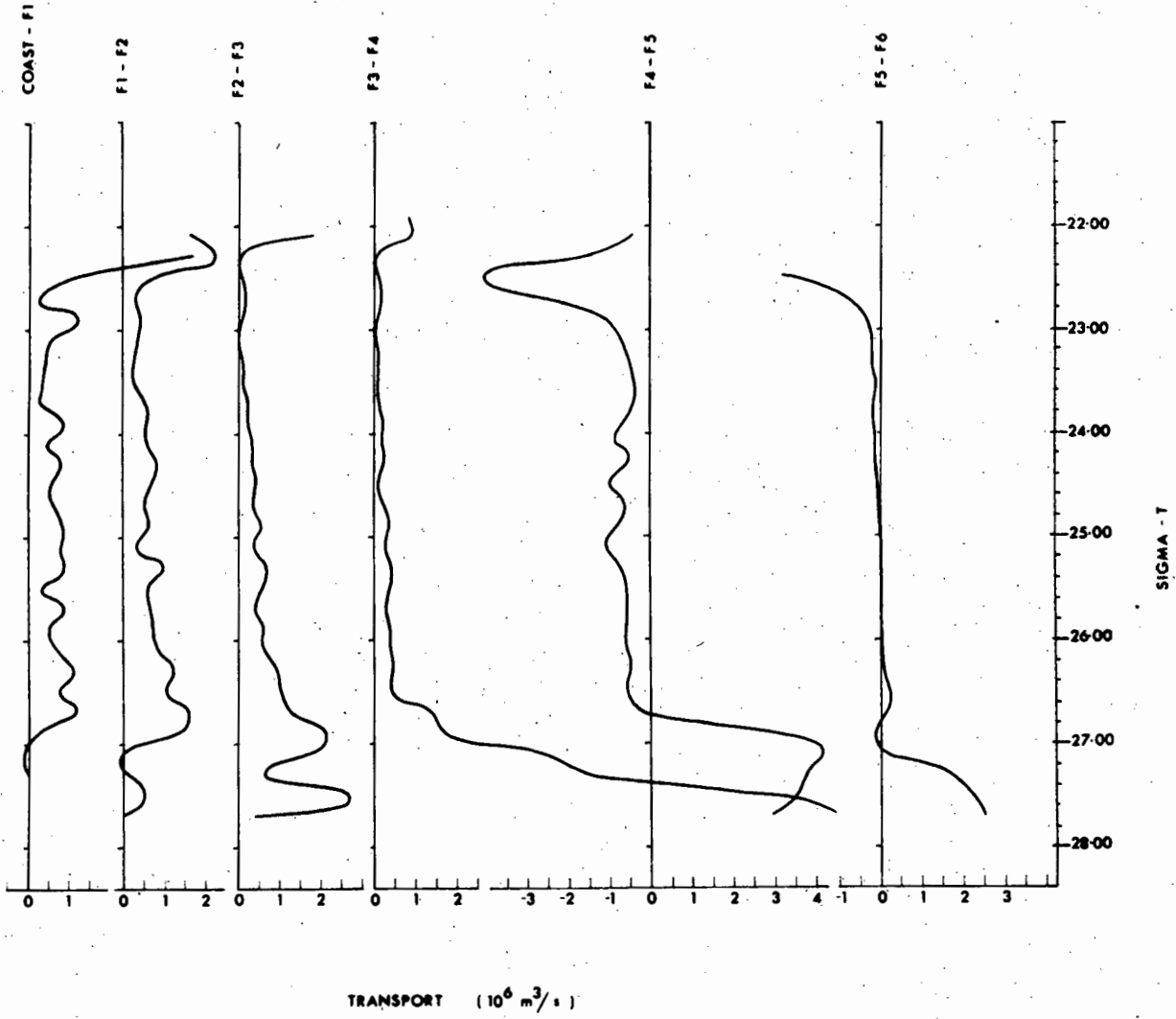


figure 5.63

Graphs of volume transport according to σ_t between stations for vertical section F (coast to station F 6).

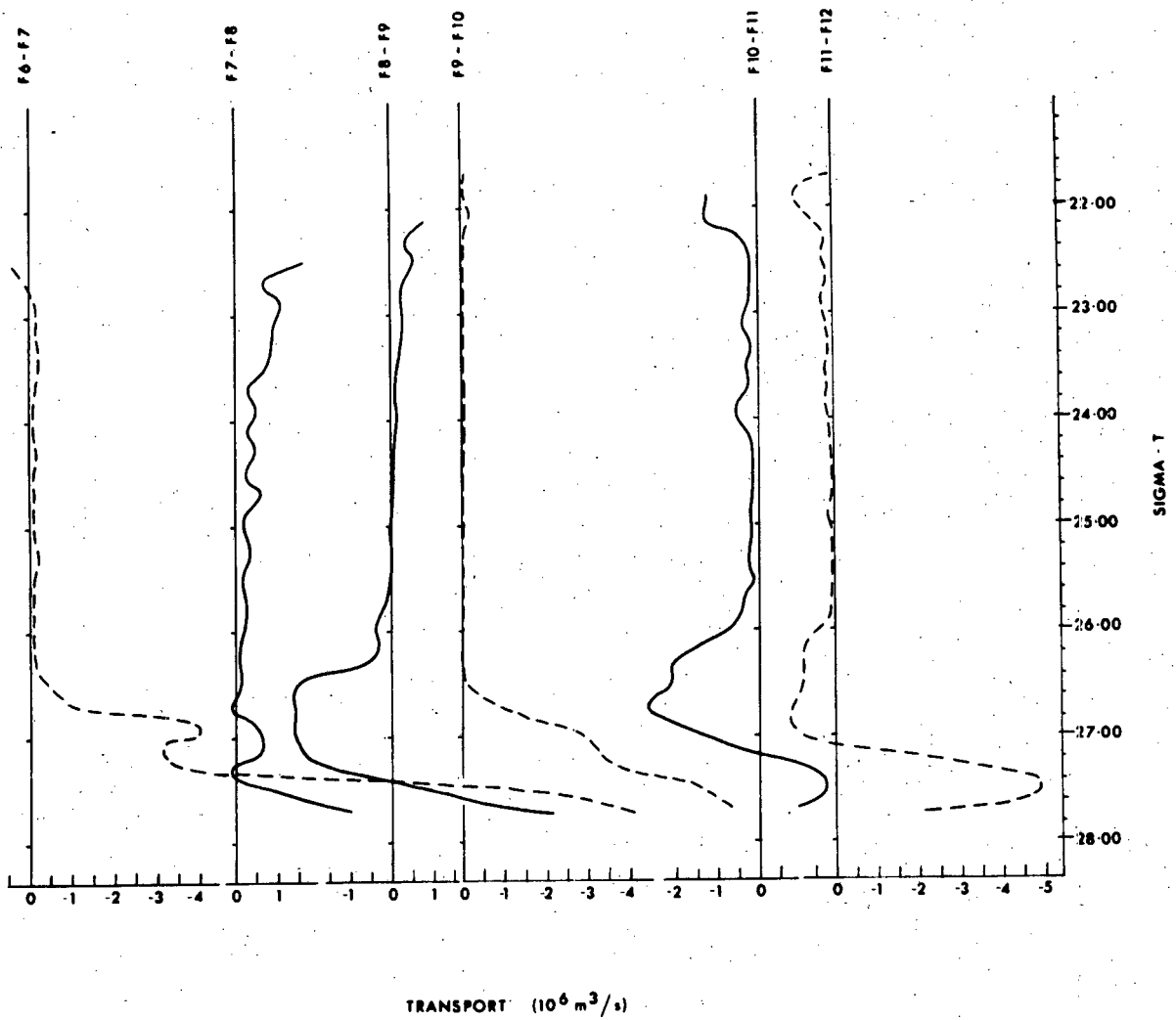


figure 5.64

Graphs of volume transport according to σ_t between stations for vertical section F (stations F6 to F12).

5.15 THE VERTICAL SECTION F (figures 5.60 - 5.64)

The last five vertical sections are more nearly zonal and section F lies at about 4°S running from the African coast to the Seychelles. It was occupied by the Atlantis in April 1965. In this section the sharpest slopes in the σ_t -surfaces are closer inshore as shown by figure 5.60. This is reflected in the strong East African Coastal Current with its axis at about 40°E and reaching velocities of 181 cm/s, the highest found for all the sections in this work. Between stations F 4 and F 5 a current flows south at about half this speed although to the same depth. This is represented by the very high peak in the volume transport at σ_t 27.40 for stations F 6 - F 7 as compared to a similar peak for the stations F 3 - F 4. The major surface flow across this section also lies in these two currents as can be noted from the peaks at about σ_t 22.40 for the stations coast - F 1, F 1 - F 2 and F 4 - F 5, as well as the general higher transport for the lower density water. To the east of station F 7 there is an extensive flow of water in the opposite direction to that nearer the surface (figure 5.61) a fact which also emerges from figure 5.64 as peaks of volume transport on both the negative and positive transport sides.

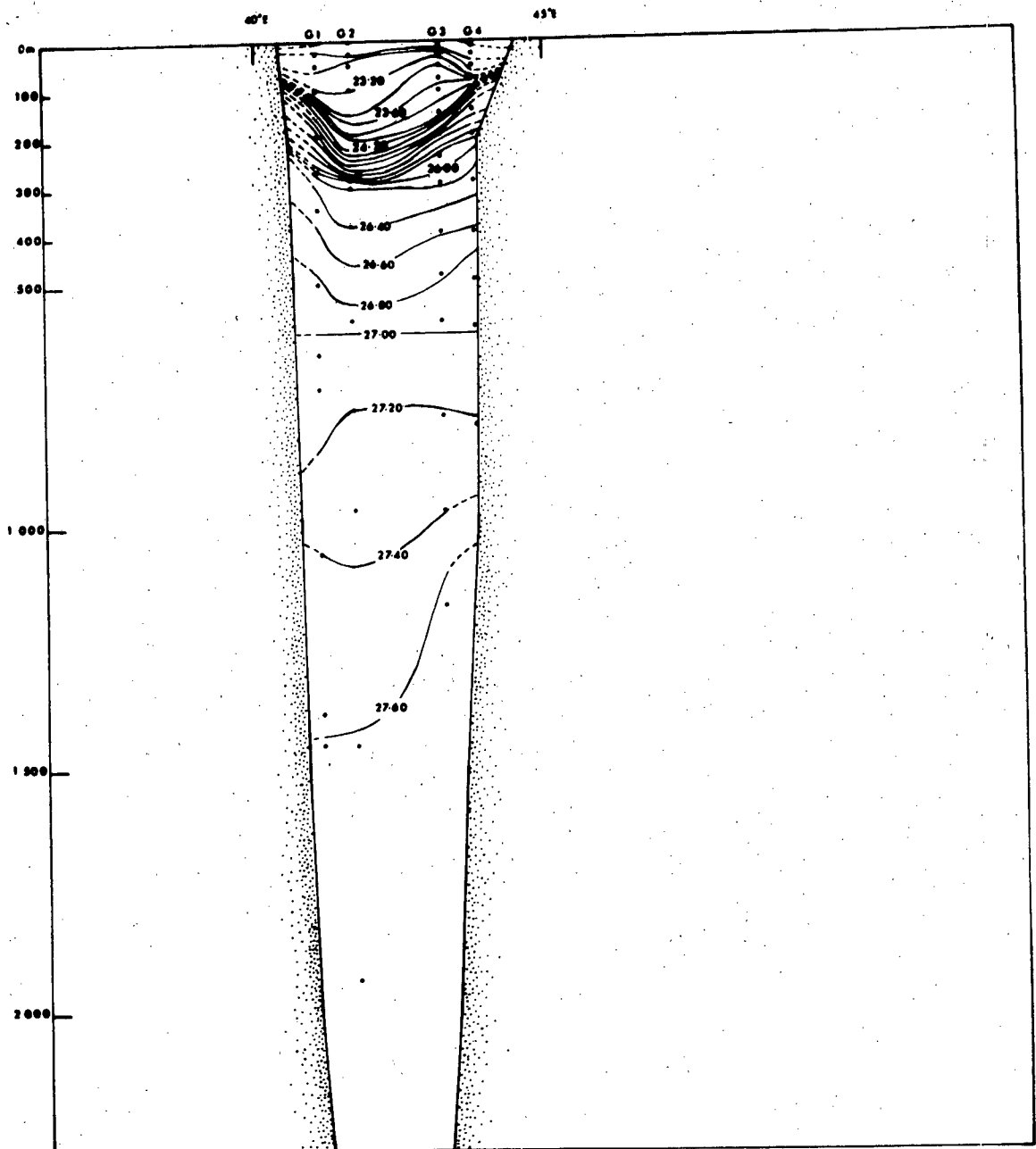


figure 5.65

Density distribution in vertical section G.

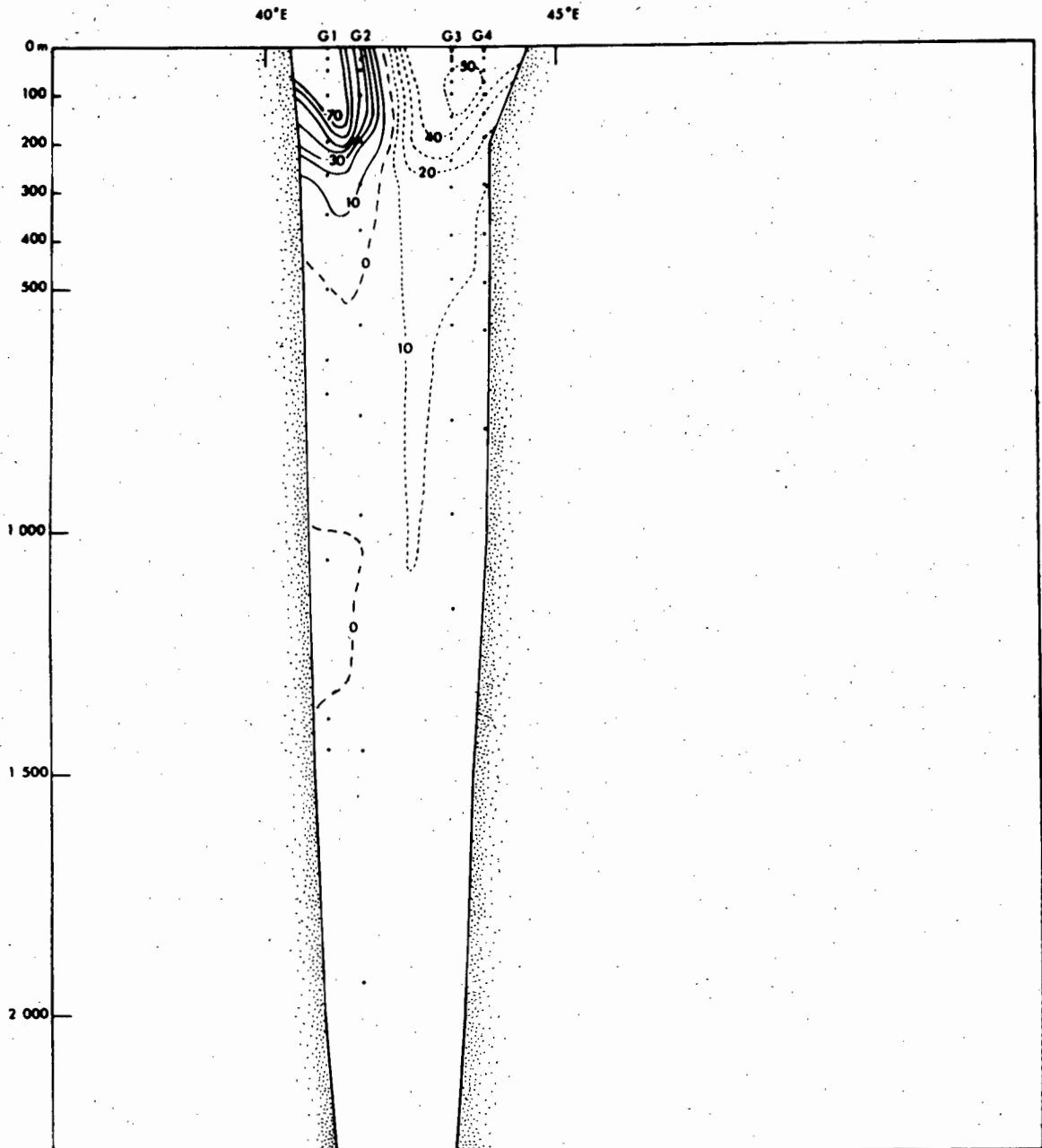


figure 5.66

Vertical profile for vertical section G.

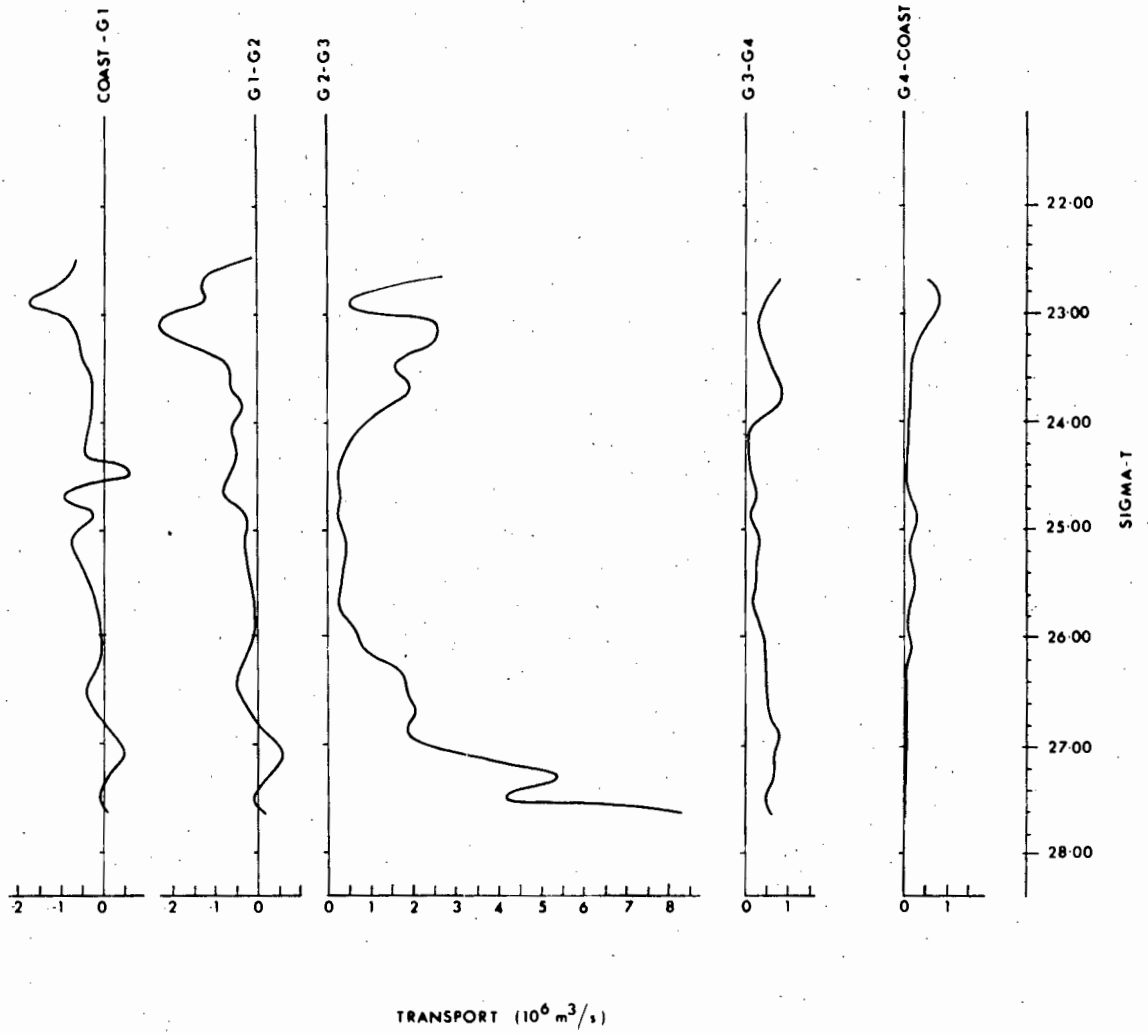


figure 5.67
Graphs of volume transport according to σ_t between stations
for vertical section G.

5.16 THE VERTICAL SECTION G (figures 5.65 - 5.67)

The vertical section G lies in the narrowest part of the Mozambique Channel, the bottom topography of which is shown in figure 6.2 depicting the deepest part as lying at 2500 m. It is the only section where non-synoptic stations were used although both cruises made their measurements in the same month. Stations G 1 and G 2 were occupied in November 1952 by the Alidade and stations G 3 and G 4 by the Giraud in November 1957 (table IV.2).

The slopes of the σ_t -surfaces (figure 5.65) show that the 27.00 σ_t surface is remarkably level but that above this all σ_t -surfaces slope upwards towards both coasts. At depth the 27.60 σ_t -surface slopes very steeply downwards from Madagascar to the African coast. The resulting flow (figure 5.66) is predominantly northwards with a current of up to 50 cm/s between station G 3 and G 4. The southflowing current on the western side of the channel, the Mozambique Current, is strictly a surface current going no deeper than 500 m. A subsurface current of limited cross-section flows south at 1100 m. Between the stations closest to the shore and the shore itself extrapolation for the σ_t -surfaces was done which is depicted by broken lines in figure 5.65. The volume transport with σ_t shows a considerable transport of surface water for the southflowing current (figure 5.67) and a very large transport for water of σ_t higher than 27.00 in the middle of the channel.

No oxygen was measured on these cruises.

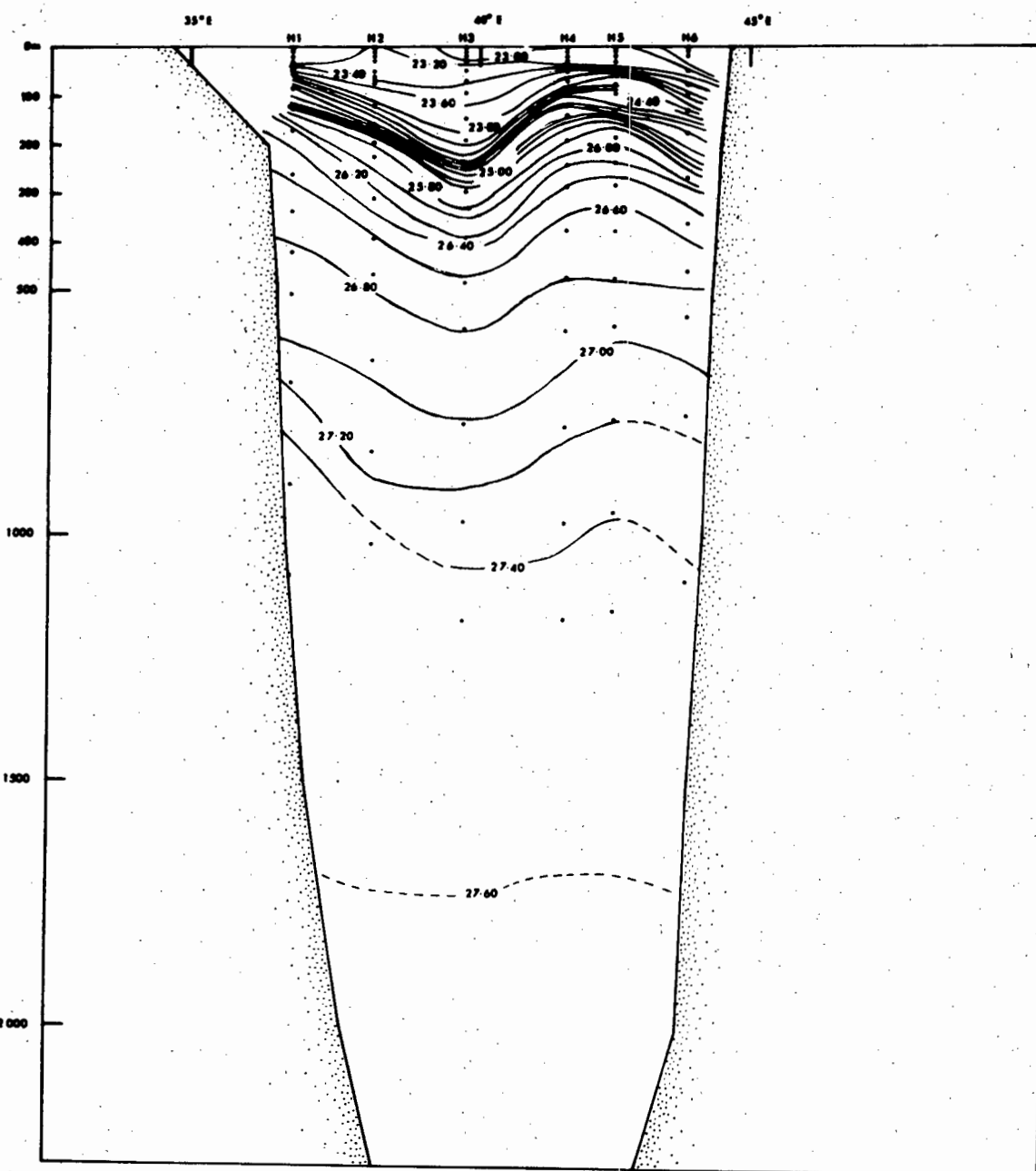


figure 5.68

Density distribution in vertical section H.

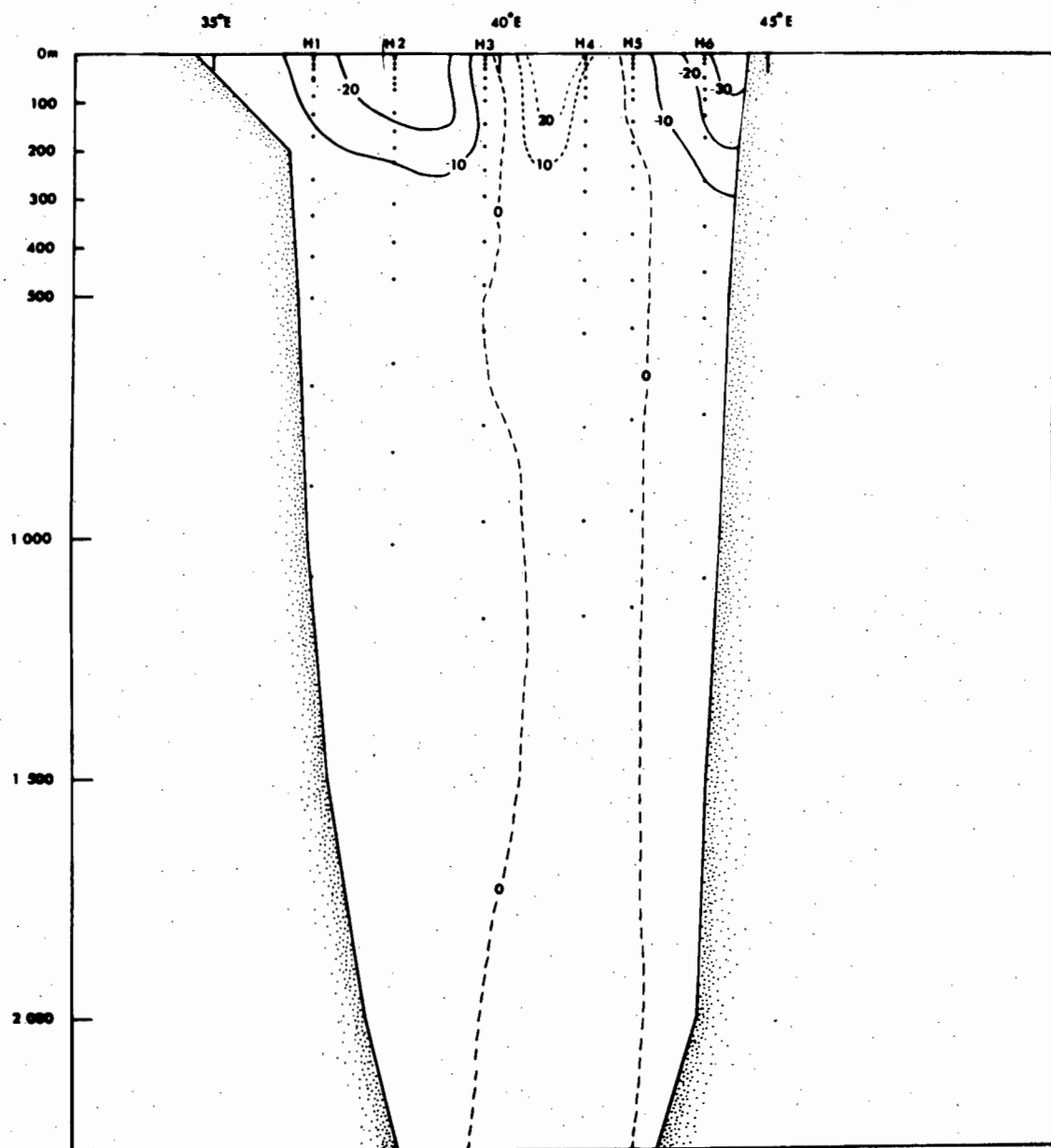


figure 5.69

Velocity profile for vertical section H.

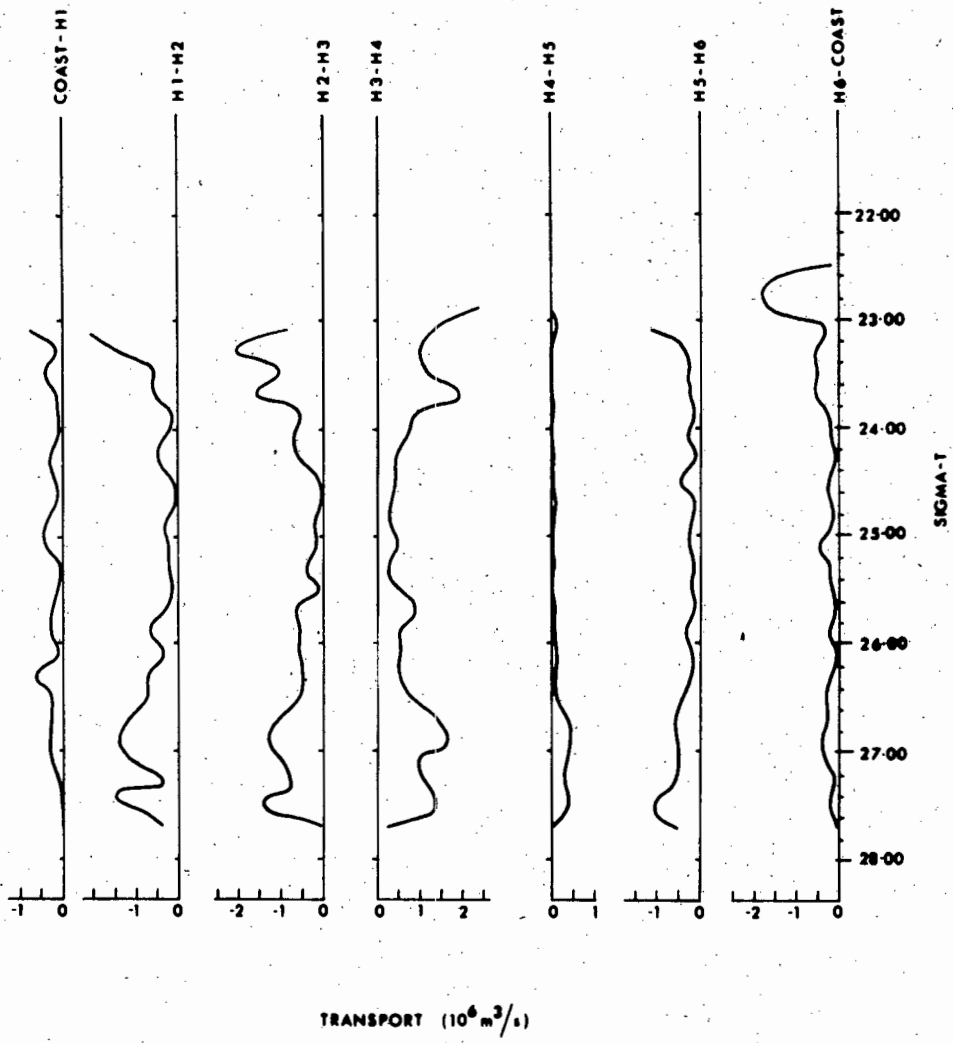


figure 5.70

Graphs of volume transport according to σ_t between stations for vertical section H.

5.17 THE VERTICAL SECTION H (figure 5.68 - 5.70)

The second vertical section across the middle of the Mozambique Channel has no oxygen measurements since it was also occupied by the Giraud in November 1957, a cruise during which no oxygen measurements were made. The same cruise being used, there is a measure of synopticity between section G and section H. Section H is identical to the line CC' on figure 6.2. Line CC' shows that the channel has now widened, but not become much deeper than at section G.

The slopes of the σ_t -surfaces are coherent throughout, showing a slope down from the African coast to the middle of the channel, a sharp slope up between stations H 3 and H 4 and then again a slope down to meet the Madagascar coast. Unfortunately the measurements were not made to a depth greater than 1200 m and the 27.60 σ_t -line was drawn in quite subjectively as a broken line on figure 5.68. The coherence of the slopes of the σ_t -surfaces is reflected in the current profiles showing the currents as deep. A north flowing current, flanked on both sides by southward flowing currents all shallow and of low velocity, is shown by figure 5.69. The volume transport diagram in figure 5.70 describes clearly that the first three curves belong to the same current. The near mirror image of the H 3 - H 4 transport curve to the H 2 - H 3 transport curve is conspicuous. The other station pairs show very little transport except for the high transport of low density water on the surface just off the west coast of Madagascar.

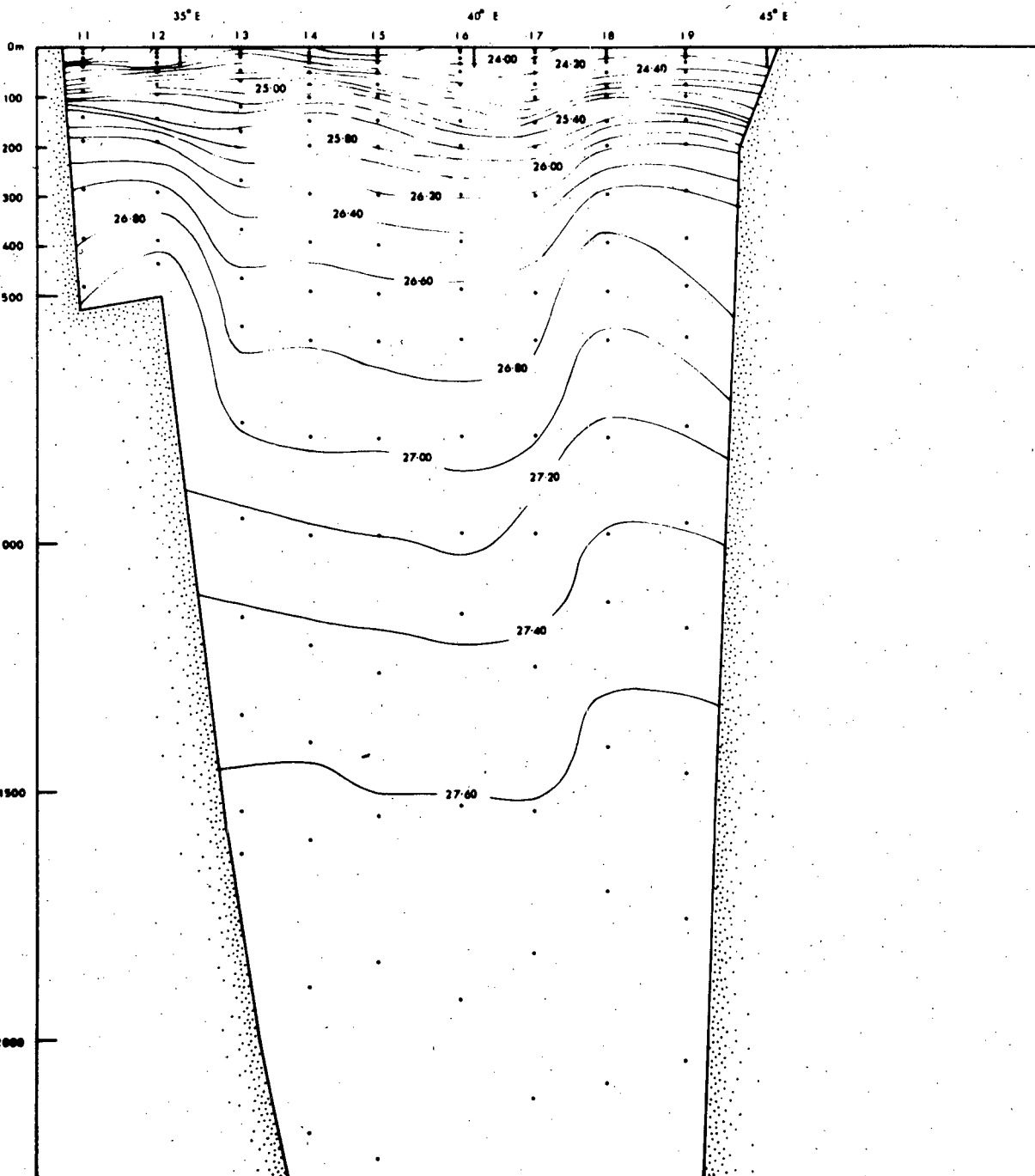


figure 5.71
Density distribution in vertical section I.

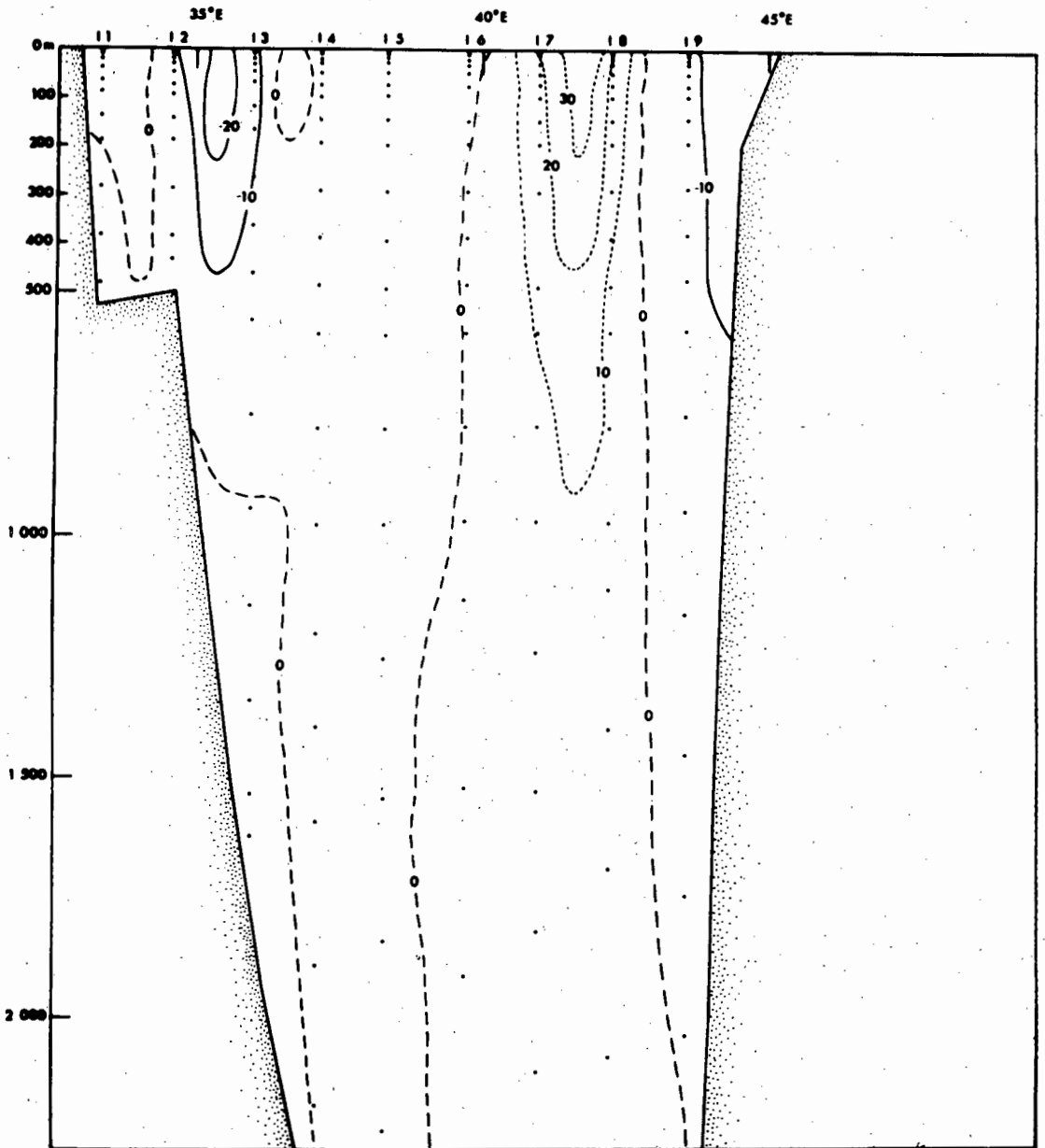


figure 5.72

Velocity profile for vertical section I.

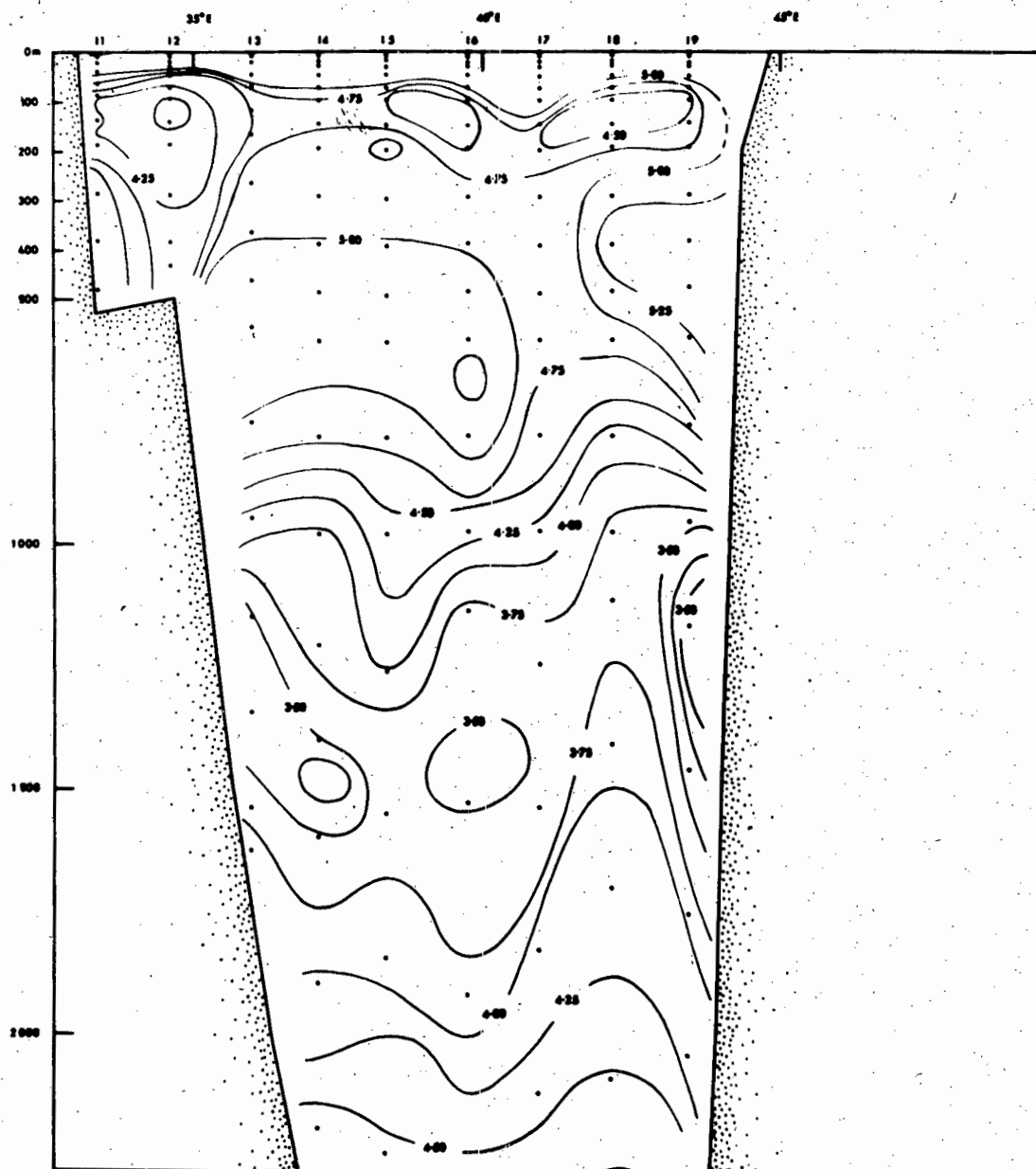


figure 5.73

Distribution of oxygen content in vertical section I.

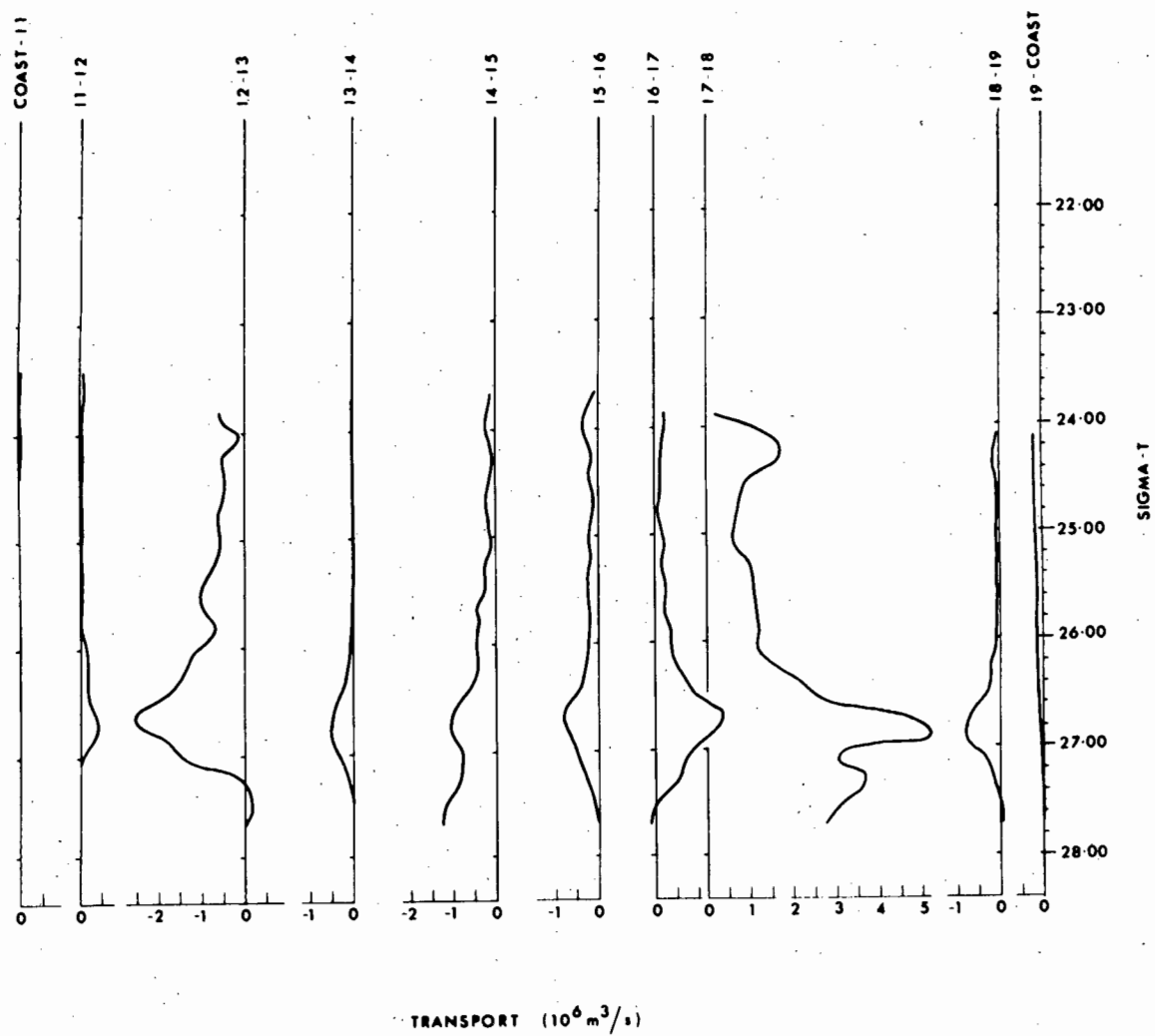


figure 5.74

Graphs of volume transport according to σ_t between stations for vertical section I.

5.18 THE VERTICAL SECTION I (figure 5.71 - 5.74)

The two station lines I and E were occupied consecutively by the Atlantis in November 1963. The depth measurements of this cruise were combined with maps of bathymetry to construct the bottom topography as portrayed in figure 6.2. This profile shows the Mozambique Channel mouth to be wide and deep (4000 m) except for the shallow shelf on the African coast that is also depicted in figure 5.71.

Figure 5.71 shows no sharp slopes of the σ_t -surfaces above 200 m, but below this there are a few features which are prominent. Between stations I 7 and I 8 there is a very steep slope on all σ_t -surfaces right down to 1500 m. A steep slope in the opposite direction between stations I 2 and I 3 does not go deeper than 800 m. Next to the coasts the slopes are again downwards. The general flow across the section is southwards with a close inshore current off Lourenzo Marques and the more strongly developed current between stations I 6 and I 8 flowing north. The highest velocity reached on this section is 30 cm/s between stations I 7 and I 8. On the whole the currents are sluggish and the volume transport small. As is to be expected, the only two station pairs showing some measure of higher transports are the southward flow between I 2 and I 3 representing the Mozambique Current and the stronger northward flow between I 7 and I 8. Both of these (figure 5.74) show very distinct transports at 27.00 σ_t . The oxygen distribution (figure 5.73) shows an oxygen maximum at about 500 m and an oxygen minimum at about 1400 m.

Although these layers are nearly horizontal, there is some disruption between stations I 7 and I 8 which may be connected to the northward flowing current at these stations.

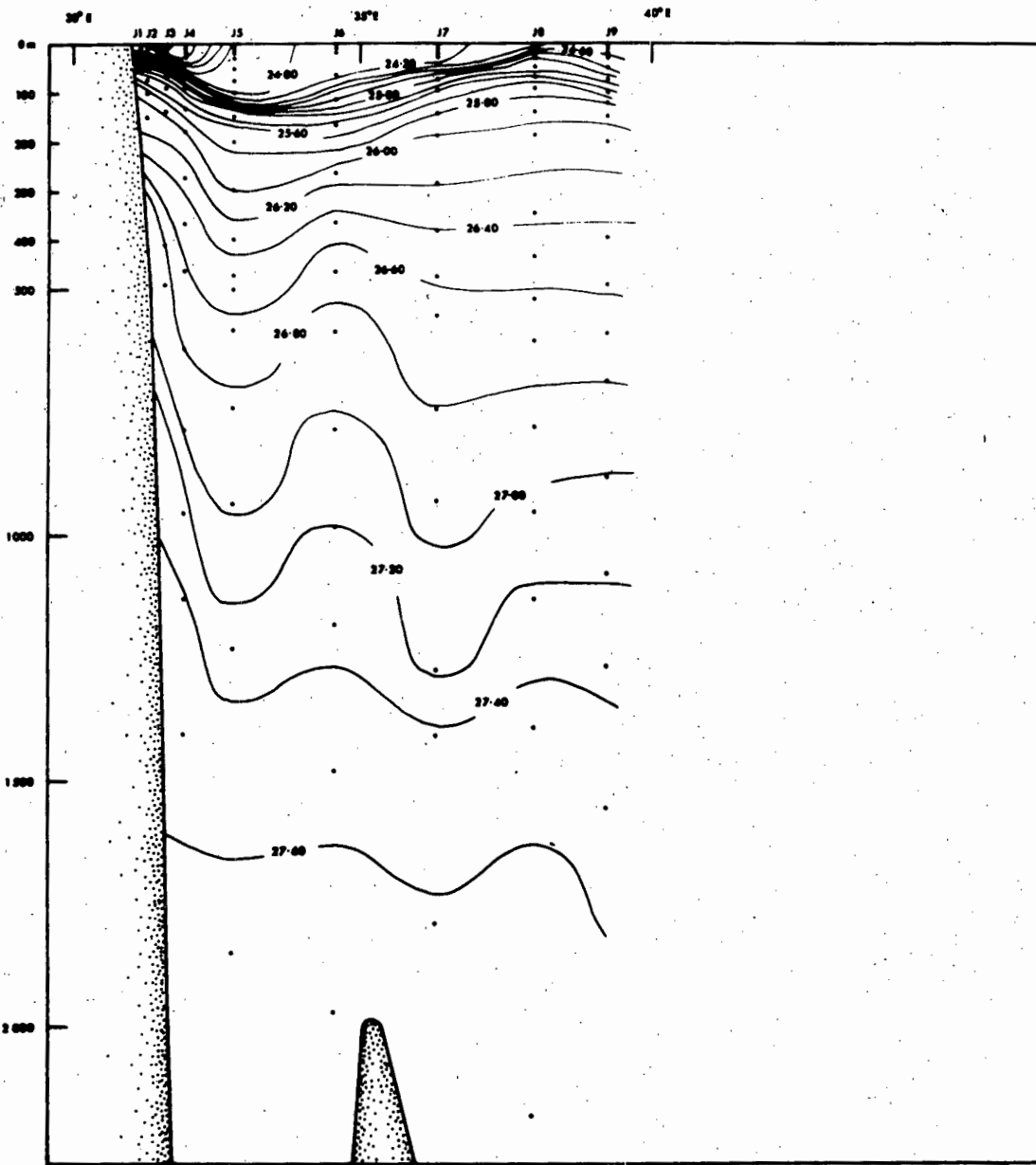


figure 5.75

Density distribution in vertical section J.

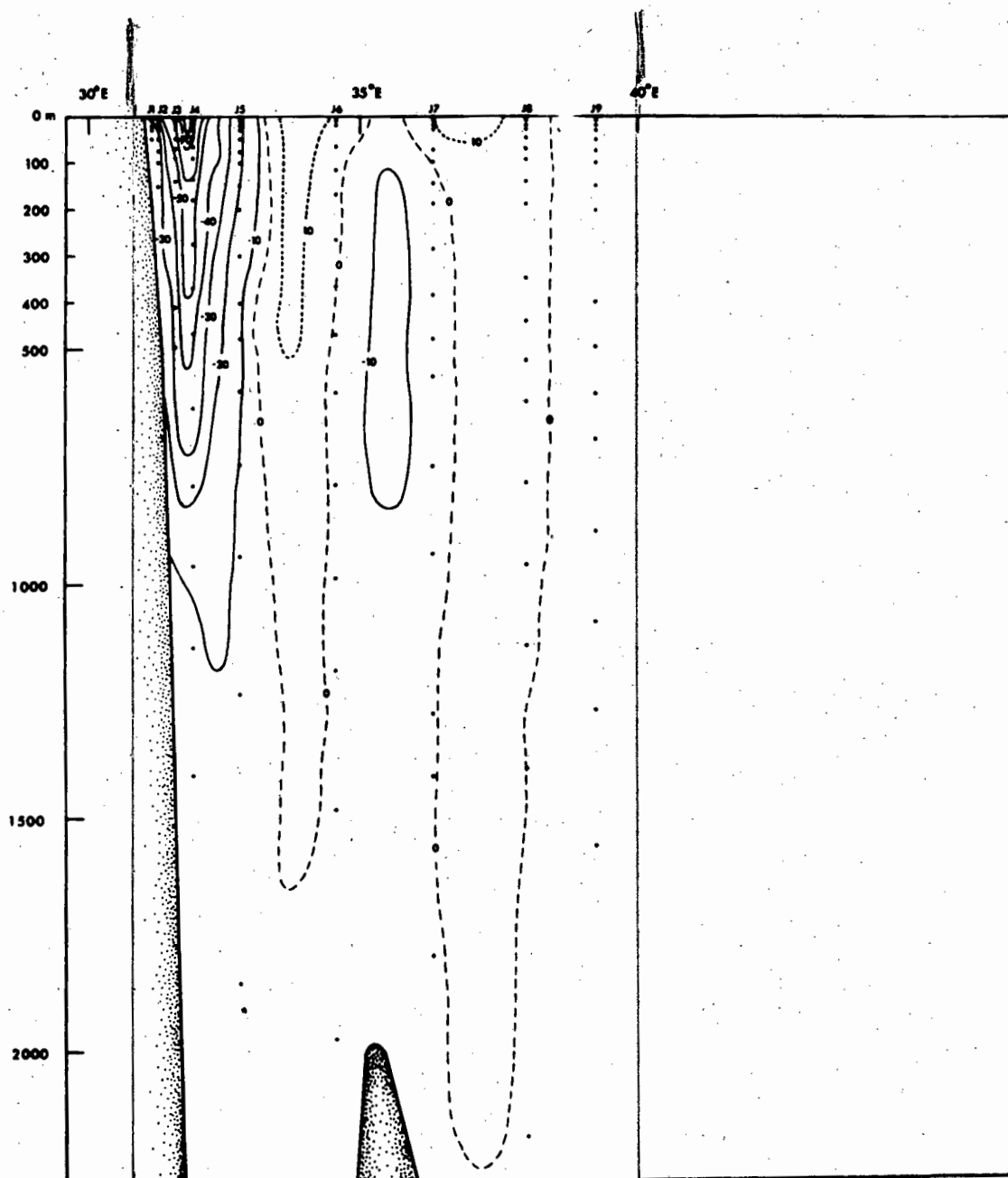
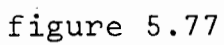


figure 5.76

Velocity profile for vertical section J.



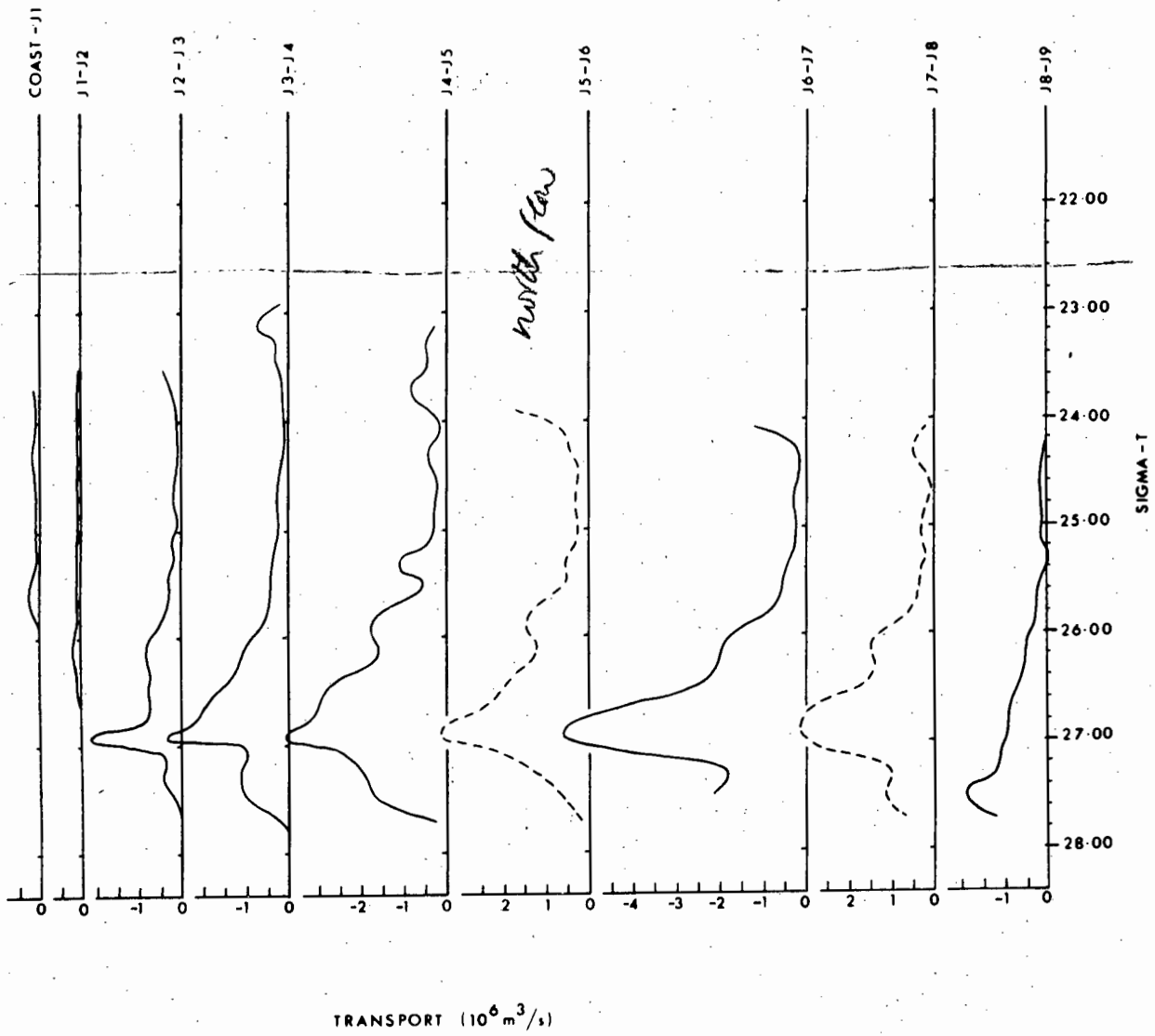


figure 5.78

Graphs of volume transport according to σ_t between stations for vertical section J.

5.19 THE VERTICAL SECTION J (figure 5.75 - 5.78)

The last section to be considered runs from Durban across the Agulhas Current in a southeasterly direction. It was occupied by the Natal in April 1962 and the stations were spaced in such a way that the narrow nearshore core of the Agulhas Current would be well covered.

The slopes of the σ_t -surfaces above 300 m show a steep slope downwards from the coast outwards. Below this the surfaces slope steeply up and down again between stations J 6 and J 7. Below 900 m there is a second positive slope between stations J 7 and J 8. This wavy nature of the σ_t -surfaces is reflected in the alternating south and northward flowing currents on proceeding from the coast along this section (figure 5.76). The Agulhas Current is clearly profiled in depth with a velocity of still 10 cm/s at 1200 m. Its maximum velocity at the sea surface is 81 cm/s between stations J 3 and J 4. Seaward of this is a deep counter current, a flow parallel to the Agulhas Current and between stations J 7 and J 8 another, even deeper flow going north. The Mozambique Ridge is depicted at 2000 m and coincides with the division between the first counter current and the flow parallel to the Agulhas Current. The curves relating transport to σ_t (figure 5.78) show very distinctly the concentration of the volume transport at 27.00 σ_t . To consolidate the diagram the axes of the curves for northward flowing water have been switched, shown by broken lines for these curves. The main transport at all depths is between stations J 4 and

J 5. The two curves for J 5 - J 6 and J 6 - J 7 are nearly identical except that in figure 5.78 the curve for J 5 - J 6 is transposed. The sharpness of the peak showing maximum transport at 27.00 ot evens off as distance offshore becomes greater so that by the last station pair (J 8 - J 9) the last sign of this peak has disappeared. The distribution of oxygen (figure 5.77) portrays the low oxygen of the upper part of the Agulhas Current. On the whole this distribution is very complicated and shows no clear maxima and minima. An oxygen maximum of greater than 5.00 ml/l at 600 m does not stretch right across the section. A small oxygen minimum at 1000 m coincides with the northward flow at station J 8. At 1700 m there exists a high oxygen water mass inshore (> 4.50 ml/l) but a definite oxygen minimum of less than 2.50 ml/l at station J 9.

CHAPTER VI

DISCUSSION OF RESULTS

6.1 INTRODUCTION

In chapter III it was seen that certain questions about water circulation in the South West Indian Ocean have not been answered by the previous research. It was further pointed out in chapter III that the remaining problems fell, rather loosely, into three categories: the problem of the large scale ocean circulation, various problems of specifically regional nature and the problem of the possible variability of the system. Having applied the isentropic method with certain additions to this part of the Indian Ocean in depth, an attempt is made in this chapter to place the results obtained in perspective by relating them to existing knowledge and by commenting on their validity and accuracy. The measure in which these results contribute to an understanding of the problems mentioned will also be discussed. In comparing the main findings of this work with previous work, the emphasis was on the more modern research. In the review of the literature it was necessary to show how contemporary research was built up on the foundation of previous studies; in discussing the results found there is no need to contrast them to findings that may now be out of date.

6.2 THE SOUTH EQUATORIAL CURRENT

This current is generally accepted as the original source of the Tropical Surface Water of the surface flow of the Agulhas Current (Duncan 1970), and as lying between 8°S and 20°S during the Northeast Monsoon Season (Pickard 1964). Throughout the depth topographies of the σ_t -surfaces this current was a sustained feature although its flow broadened considerably the deeper the σ_t -surfaces went. Since the South Equatorial Current flows zonally it does not carry water into areas where the contrast with the properties of surrounding water will make it stand out. As a result the isolines of identifying properties on the whole run parallel to the main stream of the current. Vertical section A encompasses the whole of the current and section B the northern part (figure 4.18).

Section A (figure 5.41) has its stations spaced very close to one another and possesses very regularly and closely spaced measurements with depth. The velocity profile thus shows up smaller features and details that would otherwise be missed. The concept of the South Equatorial Current as a unidirectional, wide and slow current (Duncan 1970) is contradicted by the complicated velocity structure shown in figure 5.41. A multitude of current segments flowing east and west are shown, some showing a velocity of 10 cm/s at 800 m. A remarkable feature, especially south of 15°S is the reversal in current at depth. The σ_t -surfaces (figure 5.40) show a slight overall downward slope from north to south which accounts for the total volume transport of $50 \text{ Mm}^3/\text{s}$ (Mega cubic meters per

second) to the west (table III). The undulations of σ_t -surfaces and the lack of coherence in slope of shallow and deeper σ_t -surfaces was also shown by Tchernia (1958) although his stations were further apart. Just for the area 8° to 20°S alone the volume transport is $34 \text{ Mm}^3/\text{s}$ to the west and for the surface flow at these latitudes only 62% is in fact flowing west. A line of GEK surface current measurements were done on a line nearly identical to A during November 1955 (Crepon 1965) which on the contrary showed all the currents setting west. These measurements, however, were not continuous along this line. The distribution of oxygen (figure 5.42) on section A delineates the subsurface flow of the Antarctic Intermediate Water and the North Indian Deep showing their respective oxygen maximum and minimum. This gradual rise of the Antarctic Intermediate Water is portrayed in a very similar way by the salinity distribution described by Whithers (1970). The oxygen distribution is of no help, however, in judging the validity of the current profiles and serves only to illustrate the non-zonal flow below 300 m. Rochford (1966) shows something of the combination of the zonal flow of Banda Intermediate Water at 1000 to 1400 m and the meridional flow of Antarctic Intermediate Water and Red Sea Water. The Discovery data (excepting at times the oxygen values) is generally accepted as trustworthy, so that there is no reason to doubt the results on these grounds. The argument against applying the geostrophic calculation near the equator was dealt with in chapter IV. The graphs relating transport (figures 5.43 - 5.44) to σ_t reflect the velocity profiles. They show the major volume transport

taking place at about 27.00 σ_t , the changes in direction of the currents proceeding from north to south, as well as the change in direction of flow at depth. The fact that they show no general increase in transport with decrease in latitude supports the view concerning the practical implication of the Witte-Margules equation this near to the equator.

The vertical section B presents a totally different velocity profile (figure 5.46) although it also lies perpendicular to the axis of the northern part of the South Equatorial Current, and was also occupied towards the end of the Northeast Monsoon Season. Here the current is indeed weak and shallow declining to 10 cm/s at 200 m and is unidirectional at the surface for 95% of the width of the section. At some stations the current also changes its direction with depth. The oxygen distribution (figure 5.47) lends itself to the same interpretation as that of section A, while the transport curves relate nothing new. Due to the smaller velocities the total volume transport across this section is only 15 Mm^3/s (table III).

The depth topography on the σ_t -surfaces makes an interesting contribution. In the range from σ_t 24.00 to σ_t 26.80 (figures 5.5, 5.10, 5.15, 5.20), the corresponding depths being from about 50 m to 500 m, the northern limit of the current remains at 10°S , but the southern limit moves south from about 15°S on considering deeper layers until deeper than 500-600 m no eastward flowing water is encountered in this area. This serves as corroboration of the change in current direction at these depths depicted in sections A and B. For the reasons mentioned before the identifying properties are of little help in this regard.

The following conclusions are thus reached: that the South Equatorial Current is not a homogeneously shallow slow moving current at all times; that it may vary greatly in structure and transport from year to year and that its southern extension is covered under eastward moving surface water.

Variation of a seasonal nature is partially supported by Duing (1970) who shows, using dynamic topographies for the surface relative to 1000 db, seasonal variation in the South Equatorial Flow. For October-November he shows no continuous flow across the ocean and the edge of the gyre that supports the flow just east of Madagascar may well cause a complicated circulation as depicted for section A.

Rochford showed tongues of Banda Intermediate Water at depths of 1000 to 1400 m in this region moving westward with side-tongues branching south and north (Rochford 1966, also presented by Highley 1968). The σ_t 27.50 level falls at this depth and there are various indentations in the east-west isohalines that seem similar, but these may be due to wanderings or eddies in the current or even to the unevenness in the measurements due to the unsynopticity or otherwise, so that no definite conclusions in this regard can be drawn.

The sections across the Indian Ocean published in 1951 and 1958 by Tchernia confirm the distribution of salinity shown by Whithers (1970). It is very noticeable that these salinities do not show the influence of the North Indian Deep Water as far south as do the oxygen distributions on figures 5.42 and 5.47. This same effect is also shown by Clowes & Deacon (1935) who used the oxygen and salinity distributions of one cruise. It may thus be assumed that the oxygen and salinity distributions

do not contradict each other, but supplement one another so that when one indentifying property has lost its distinguishing value, the other one may still be of use.

This is an area very rarely traversed by commercial shipping so that surface current atlases have very little to add to the interpretation. The Kon. Ned. Met. Instituut publication of surface currents (— 1952) shows strong currents in this area and some variation from month to month, but during the month in which most readings are available, April, the currents over the whole area set west. The Routing Chart (— 1970) of the British Admiralty shows a considerable variation in width of the South Equatorial Current from March to April, water recurving in April to join the Equatorial Counter Current.

Duncan (1970) showed that although the flow was predominantly a surface one, the current existed to depths of 2000 m. He found that the South Equatorial Current varied in width and depth with season. The variation in the transport as well as the current profiles for the two sections A and B cannot only be due to seasonal variations of this nature but must be due to variations from year to year as well. This will be further discussed in paragraph 6.12.

6.3 THE FLOW EAST OF MADAGASCAR

When the South Equatorial Current has passed the meridian of Mauritius and is confronted by the landmass of Madagascar some of the water moves north and some south to pass the island at its extremities. That this current system is a seasonally varying one was shown by Michaelis as early as 1923. During the Southeast Monsoon he shows that the water off Madagascar's east coast south of 20°S sets south and north of this latitude sets north, while during the Northeast Monsoon all the water, even that of the northern branch, sets south along the east coast of Madagascar. Of the three vertical sections east and north of Madagascar that cross this flow the northern two (C and D) were done in March, while the southern one, E, was occupied in November.

The velocity profiles for section E (figure 5.57) portrays slow and shallow currents in this region. A maximum velocity for surface flow of 24 cm/s is found just west of Reunion. The total flow in depth is predominantly north so that the net volume transport is $12.93 \text{ Mm}^3/\text{s}$ northwards. The southward branch of the East Madagascar Current flows very close to the coast and has a transport of $13.59 \text{ Mm}^3/\text{s}$. Between 50°E and the coast of Madagascar the current setting south as well as the outer current setting north both show an increase in velocity with depth up to about 400 m.

It is noted that the oxygen minimum is at about 500 m (figure 5.58). The slopes of the oxygen lines show some similarity to the slope of the σ_t -lines across the section below about 700 m. This was also noticeable in some other

sections. Whereas the two sections across the South Equatorial Current, notwithstanding their very different nature, both showed the maximum transport per σ_t to take place between 27.00 and 27.40, section E shows the maximum transport per σ_t between 26.60 and 27.00. These peaks are only pronounced in the stations just east of Madagascar and just west of Reunion. The great similarity between the curves for transport between E 1 - E 2 and E 2 - E 3 can possibly imply a meandering in the current so that this is in fact the same water. Below 27.20 this does no longer hold true.

Although section D was occupied in a different month, it shows very similar features in its velocity profile to that of section E (figure 5.53). Just offshore is a shallow (300 m), slow (23 cm/s) current flowing south, imbedded in a general flow north (volume transport $9.23 \text{ Mm}^3/\text{s}$, table III). Just seaward of this is a current of 26 cm/s at the surface setting north. The transport at depth is a combination of that of the South Equatorial Current and the southern branch of the East Madagascar Current showing peaks at 26.80 and again at 27.50. The oxygen distribution (figure 5.54) shows tongues of low oxygen and high oxygen moving parallel to the section. This may most probably be interpreted not as a zonal flow but as a meridional flow that shows these tongues only as a result of the acute angle across the flow by the line of oceanographic stations chosen.

Where the northern branch of the East Madagascar Current turns westward as it passes Cape d'Ambre is portrayed in the Routing Charts (— 1970) as a very constant and strong current. This high velocity is also shown by section C

running north-northeast from the northern tip of Madagascar with an overall volume transport of $46.27 \text{ Mm}^3/\text{s}$ towards the African coast. The flow is not, however, a coherent flow west, but consists of various branches of very high (up to 128 cm/s) velocity flowing east and west. The flow as a whole is westwards but two currents flowing east are imbedded in it. The current between station C 6 and C 5 is supported by σ_t -surface slopes which are consistent to 1200 m . The current between C 3 and C 2 is only supported by the very steep slopes of the 27.40 and 27.60 surfaces below 1000 m . There is no way of telling how reliable these measurements are, but this single steep slope at these depths might have been due to some inaccuracy in the measurements. The extremely large peaks for the transport of station pairs C 3 - C 2 and C 2 - C 1 should thus also be treated with some caution (figure 5.51). It is interesting to note that the other curves again show a tendency for double peaks, with maximum transports at $26.70 \sigma_t$ and at $27.40 \sigma_t$. It is also interesting to compare the transport curves for C 7 - C 6, C 6 - C 5 and C 5 - C 4. Although these portray alternating directions of the current, C 7 - C 6 and C 6 - C 5 may well be part of a meandering of the current due to the sharply variable bottom topography since they show a marked similarity in their transport/ σ_t relation, while C 6 - C 5 and C 5 - C 4 show very little similarity and are therefore most probably distinct and separate flows.

The depth topography of the σ_t -surfaces and the distribution of the identifying properties give some aid in judging the validity of the current profiles since they use data lying outside the one line forming a section. The isobaths on the

various σ_t -surfaces (figures 5.10, 5.15, 5.20, 5.25, 5.30) show the surface current up to 300 m to be part of an anti-cyclonic gyre driven in the north by the South Equatorial Current and in the south by the general Agulhas Return Flow. The western side of this gyre (clearly delineated in figure 5.15) flows along most of the east coast of Madagascar. In figure 5.5 there is a flow south past the line forming section E, but since the velocity at this depth is increasing with depth this is probably misleading. The flow past the north of Madagascar at these depths is due only to the continuation of the northern part of the South Equatorial Current. Deeper than 500 m, the flow is clearly in the direction usually associated with this area (figure 5.20), with water flowing north and south along the coast with the point of divergence at about 16°S . The identifying properties are not so clear on this matter. On figures 5.7 and 5.8 the salinity and oxygen distribution seemingly support such a gyre in the vicinity of Mauritius as do the salinities on σ_t 25.80 (figure 5.17), but in many other cases, although there seems to be some kind of disturbance, this could be interpreted in other ways as well. On the deeper levels the flow north and south is well supported, for instance the oxygen distribution on 26.80 σ_t (figure 5.23), the salinity on σ_t 27.25 (figure 5.27) and the phosphate distribution on σ_t 27.50 (figure 5.34).

The conclusion is thus reached that during this season the flow along most of this coast is southwards. Above about 500 m it is part of a gyre and below this part of a feeding current past Cape St. Marie. This will be further discussed in section 6.7. From the transport curve for the vertical

section E it is indicated that the main transport takes place at about 26.80 °S when the first signs of a flow past the southern part of Madagascar are noticeable. The flow past Cape d'Ambre is fast and deep.

Very little work has been done in this region and as can be seen from figure 4.1 oceanographic stations are extremely sparse. Duing (1970) has indicated, in the same way as Michaelis (1923), that the flow past Cape d'Ambre is intense, and a direct continuation of the South Equatorial Current. The complicated structure of east and west flowing currents in this area is not supported by the continuous GEK measurements by Crepon (1965) who shows a unidirectional and intensifying current from 7°S southwards on a line slightly to the west of the line used for this work. The only extensive work in this region was done by Duncan (1970). It is in agreement with some of the main conclusions stated above. He also shows, on the sea surface, an anti-cyclonic gyre off the east coast of Madagascar unconnected with the flow past the south of the island and the flow north of Madagascar as a direct continuation of the South Equatorial Current. The centre of this gyre is at about 20°S and is found during all seasons. He also states that the velocity of the coastal current is of the order of 30 cm/s and extends to depths of 1400 m, which is contrary to sections D and E. He infers that some water is recycled but that most of the transport escapes from the eddy and passes past the southern tip of Madagascar although his dynamic topographies of the surface do not indicate this directly. During Autumn he assumes a recycled mass transport down to 1000 m of 3 and a feeding flow of 18 megatons/s. On analysis of table

III this figure for the transport south would seem to be in agreement, but the transport northwards was found to be much greater. The flow at the surface past Cape St. Marie as shown by Duncan was not substantiated by this study.

Lacombe (1951), although he had considerably less data at his disposal, used the dynamic topography and also found an anticyclonic eddy to the east of Madagascar. This work shows water passing west past Cape St. Marie, but, instead of linking up with the Agulhas Current, turns back to form part of the Agulhas Return Flow.

6.4 THE AREA NORTH OF THE SOUTH EQUATORIAL CURRENT

This area has long been known to be more variable than any other part of the area under investigation and is therefore to be treated with much caution. According to the Routing Chart for April (figure 3.1) the flow consists of a strong East African Coastal Current, an equally strong counter flow seaward of this, the Equatorial Counter Current and a northward flow of South Equatorial Water to join the Counter Current.

Only one section, F, (see figure 4.18) falls entirely in this region. It was done in April 1965 by the Alantis and shows clearly (figure 5.61) the East African Coastal Current with speeds of up to 181 cm/s, the southward flowing current just seaward of this as well as several shallow surface currents flowing north that may be of South Equatorial Current origin. As discussed in chapter V, this section has very few stations at which there is not an increase of velocity with depth at

some deep level. An investigation of the volume transport curves brings this out. This fact makes interpretation across this line of various bathymetries of σ_t -surfaces below 300 m extremely difficult, since there is no reason to believe that this increase in velocity with depth will also hold for other stations in this area occupied at different times. Here the plotted identifying properties may be of some help. Figure 5.6 (temperature on σ_t 24.00) shows a clear tongue of South Equatorial Water moving north, as does the salinity distribution on σ_t 25.80 (figure 5.17). These are only vague signs though, and as a whole this area has no distinct flow patterns depicted on the σ_t -surfaces for the shallower water. Contemporary papers on this area have some bearing on this.

Truesdale (1971), by working with synoptic cruises only, showed that there exists a large variation in the circulation from year to year. Bruce (1968) showed little of the East African or the "counter" current when using dynamic topographies. The continuous GEK measurements by Crepon (1965) during December show eastwards flow from 2°N to 4°S with the core of the Equatorial Counter Current between 1°S and 2°S . These papers give an indication of the complicated nature of this area and the large variability to be expected in the surface layers, which may explain the inability to interpret the diagrams in a succinct and crisp way.

A few other papers may be mentioned. Ovchinnikov (1961) depicts the circulation at 500 m which shows up the same feature off Tanzania as do the isobaths on σ_t 26.80 and 27.25 (figures 5.20 and 5.25), namely a cyclonic vortex just east of Zanzibar.

This is also during the Northeast Monsoon.

This area is also of importance because of the controversy about the meridional influence of the North Indian Deep and the Antarctic Intermediate Water. Rochford (1964) shows streams of the different constituents of north Indian water flowing towards the mouth of the Mozambique Channel: Arabian Sea Water at 100 m, Persian Gulf Water at 200 to 500 m and Red Sea Water at 800 m. Clowes & Deacon (1935) showed the North Indian Deep Waters salinity maximum and oxygen minimum at about 1000 m and the overriding oxygen maximum and salinity minimum of the Antarctic Intermediate Water at about 500 m in this region. If we scrutinise the σ_t diagrams we find that at 100 m (figure 5.12) there are distinct tongues of high salinity water pressing southwards, especially on the western side of the area, indicating Arabian Sea Water. This is even more distinct at 150 m (figure 5.17) which is where Persian Gulf Water is to be expected and is supported by the oxygen distribution, especially in the west. At about 1000 m the existence of North Indian Deep Water with its attendant salinity maximum and oxygen minimum is predicted by Rochford (1964) and Clowes & Deacon (1935). The tongues of high salinity (figure 5.32) and low oxygen on the 27.50 σ_t -surface (figure 5.33) confirm this, although the bathymetry of the σ_t -surface is not able to present a clearcut picture at this depth. It seems clear that in the case when attention is concentrated on the distribution of identifying properties on σ_t -levels where maxima or minima of such properties are concerned, the method can be of great help in interpretation of water movement. The oxygen distribution across section F (figure 5.62), although quite complicated, only shows the

oxygen minimum at about 1000 m associated with the North Indian Deep Water. Of the Antarctic Intermediate Water there is little positive trace at this latitude.

The large scale analyses by Lacombe (1951) and Duncan (1970) lend some interesting support to the complicated current structure found along section F. Lacombe is only able to give the general cyclonic sweep of South Equatorial - East African Coastal Currents, which is probably due to his lack of stations, but Duncan shows, by a complicated set of eddies, a very similar circulation during the period March to May. This consists of the East African Coastal Current, a Counter Current seaward of this, and a northward branch of the South Equatorial Current at about 53°E . An identical circulation to this is depicted by the current map of the Kon. Nederlandsch Met. Inst. for April (— 1952) and even the Indian Ocean Currents (— 1939) shows very clearly this northward branch of the South Equatorial Current. The current velocity of the East African Coastal Current was shown to decrease rapidly with depth up to about 500 m (figure 5.61), a conclusion which is also supported by Duncan (1970). Below this, as was seen, there is often a slight increase of velocity with depth.

6.5 FLOW IN THE NORTHERN MOUTH OF THE MOZAMBIQUE CHANNEL

This area was denoted in chapter IV as an area in which the circulation was poorly understood and it served as an example of problems of regional nature that need investigation. There is no vertical section in this area since no synoptic closely spaced stations across the mouth exist for this time

of year. The area of cross-section of the channel mouth is not nearly as big as the width at the sea surface would lead one to believe (figure 6.1). Section G forms the southern boundary to this area and lies across the narrowest and shallowest part of the channel. The Routeing Chart (— 1970) for April shows the surface circulation as consisting of the South Equatorial Current crossing the whole mouth as a single coherent current and only near the coast dividing into the East African Coastal and the weaker Mozambique Current (see figure 3.1). Just off Madagascar's west coast there is a fairly strong current setting north.

This circulation, as portrayed on the σ_t -surfaces, is very clear at all depths up to about 400 m. This is shown on figures 5.5, 5.10 and 5.15. From this level downwards the flow west past the mouth of the channel is clear, but the way in which it then flows into the two currents going north and south is not clear. The possibility exists that the northern branch of the South Equatorial Current as it passes Cape d'Ambre is intense and deep but as it reaches the coast of Africa loses its intensity and only shallower currents then are clearly observed. The identifying properties offer no evidence of the flow past the Comore Islands. In many cases the characteristic high (or low) value for some identifying property shown near Cape d'Ambre is also present near Cape Delgado on the African coast, but there is no connection between them. This is illustrated by figures 5.6 and 5.7. At times there is an anti-cyclonic circulation around the Comores Islands similar to that shown by Dongue & Piton (1969) (figure 5.20). The circulation depicted by Duing (1970) for

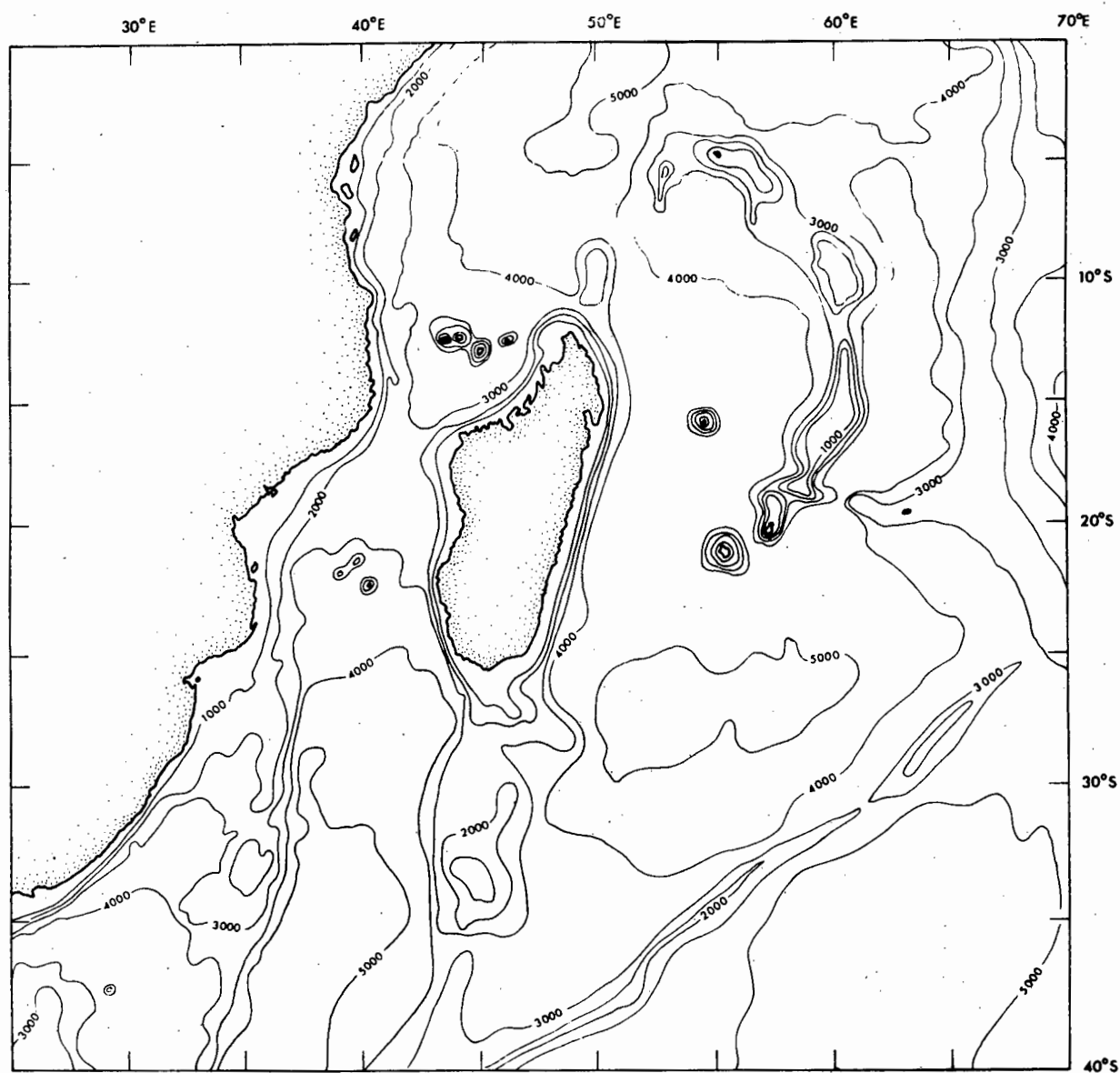


figure 6.1

Bathymetry of South West Indian Ocean according to Simpson & Forder (1969) and the Carte Général Bathymétrique des Océans (— 1938).

March and April, in which part of the water that has passed Cape d'Ambre flows between Madagascar and the Comores to form the Mozambique Current, is not seen on the σ_t -surfaces under discussion, although Lacombe (1951) shows something slightly similar. The latter case was, however, based on only one or two stations.

Unfortunately very little work on deeper water has been done in this area. Duncan (1970) states that the Mozambique Current flows deeper than does the East African Coastal Current and has a greater transport. This is not confirmed by a comparison of sections F and G (figures 5.61 and 5.66) or by the depth topography of say figure 5.20. The different transports can be obtained from table III. On the whole the surface work confirms the conclusions reached above. Duncan (1970), Truesdale (1971) and Bruce (1968) all show the current as flowing due west past the Comores and approaching very close to Cape Delgado before dividing.

No evidence for the flow towards the north just west of Madagascar was found.

6.6 THE FLOW IN THE MOZAMBIQUE CHANNEL

The Mozambique Channel is an area of considerable oceanographic interest. Not only does it show a varying bottom topography (figure 6.2) that restricts any through flow to the top 2500 m, but it has also been considered to be the main area of supply of water to the Agulhas Current. It is one of the areas in the South West Indian Ocean that has been investigated most thoroughly and a good coverage of oceanographic

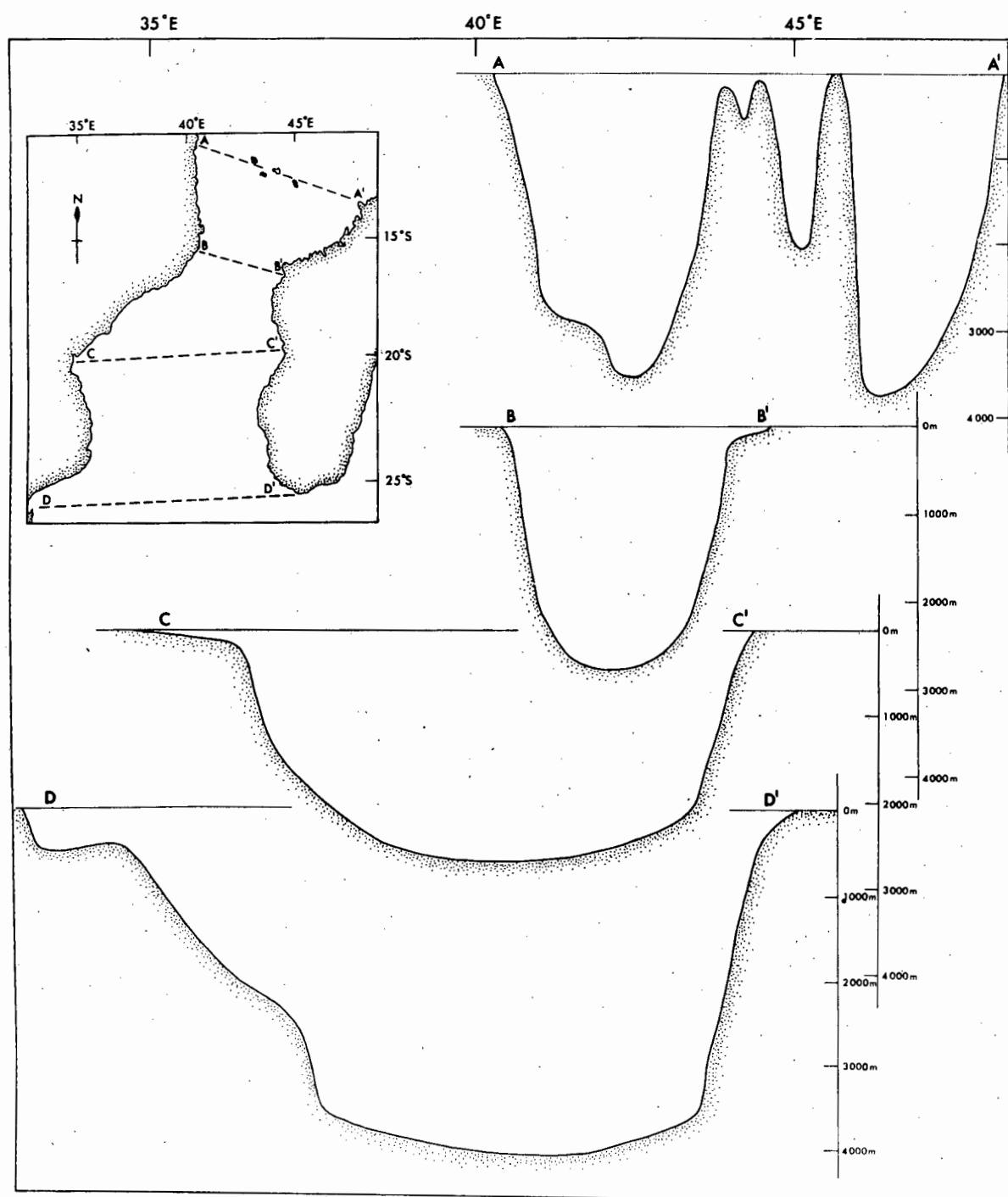


figure 6.2

Bathymetry for four vertical sections across the Mozambique Channel according to ships measurements and Simpson & Forder (1969)

stations is available (figure 4.1). The T/S and temperature/oxygen scatter diagrams for all stations available in the channel is presented in figure 4.12. These show very distinctly the types of water masses present and gives a clear portrayal of the predominance of the Red Sea Water over the Antarctic Intermediate Water in this area. Three sections were done in this area: G, H, I (figure 4.18) all three of which were occupied in November, so that, if there are no year-to-year variations these should give a coherent description of the flow.

The σ_t surfaces 24.00 and 25.00 have been selected to show the surface flow. Comparing the depth topography on each (figure 5.5 and figure 5.10) almost identical flow patterns emerge. On the west side of the Mozambique Channel is the Mozambique Current, limited in lateral extent. Some of its water passes out of the channel hugging the coast near Lourenço Marques, the rest curving back on itself to flow north again in the channel. Some of this latter water then, before it reaches the narrowest part of the channel, recurves back to flow down the west coast of Madagascar. A small anti-cyclonic vortex exists on the eastern side of the channel and is shown in both these figures. The temperature distribution on σ_t 24.00 (figure 5.6) shows the Mozambique Current as a clear tongue of 23.25°C water. The salinity distribution (figure 5.7) shows very distinct tongues for the Mozambique Current, the northward reflection, as well as the final southwards reflection. Even the oxygen tongues (figure 5.8), so near the surface (100 m) show up the features described, in particular the eddy in the southern mouth. On the σ_t 25.00 level the identifying properties also combine to depict coherently

the detail of water movement as described (see figures 5.11, 5.12 especially).

The three sections across the channel (G,H,I) reinforce the concepts of surface circulation as described. In the narrowest part of the channel (figure 5.66) the shallow (500 m) Mozambique Current is shown imbedded in a general northerly flow which makes itself felt as a strong surface current off the west coast of Madagascar. At section H, further down the channel (figure 5.69) these two currents still exist, but the Mozambique Current now extends down to the bottom although the surface velocities have declined. The return current is also slower and between this current and Madagascar is the final flow southward. This same current picture is found in the mouth of the channel (figure 5.72) except that the currents are deeper and a small clockwise eddy on the continental shelf off Lourenço Marques has developed. The currents as portrayed by these sections thus closely corroborate the conception of the surface currents.

The surface flow in the channel has always been of considerable interest to oceanographers. Michaelis (1923) showed the circulation in the channel differing only in one respect between the Southeast and the Northwest Monsoon Season. At both times the Mozambique Current and the northward flow next to the Madagascar coast (the West Madagascar Current) were continuous; the water for the latter coming past the southern tip of Madagascar. During the Southwest Monsoon water flowed from the Mozambique to the West Madagascar flow to recirculate in a similar way to that described above as seen in figures 5.5 and 5.10. During the Northeast Monsoon water of the West

Madagascar Current flowed west across the channel to join the Mozambique flow. These concepts are therefore by no means new, although in this case the season is different. Menache (1961) showed by his dynamic topographic analysis of a November cruise of the Giraud that the recycling was complete for this month and that no water passes south into the Agulhas Current. Since he used 1000 db as reference level and could therefore not approach closer to the coast with his analysis, his conclusions do not preclude the possibility of some water continuing south. It should be noted that some of this same data was used for the present analysis and that two sections are based on this data. Nevertheless, the corroborating evidence of many other stations confirm much of this description. Harris (1970) for instance, using completely different winter data (June, July) described a very similar surface circulation with both the counter current and reflected counter current being present. He concludes that some water does pass south to form part of the Agulhas Current surface flow. The reflection of at least part of this water is also shown by direct current measurements (Crepon 1965, plate 80). For March, April and May Duncan (1970) shows no continuous Mozambique Current, but two anticyclonic eddies. He shows a complicated system of transports with some feeding from the south of Madagascar.

It can be concluded that the surface circulation of the Mozambique Channel as presented by the σ_t -surfaces is basically correct for this time of year and is supported by previous work as well as all the other diagrams discussed.

The 25.80 σ_t and 26.80 σ_t surfaces should both lie in or

near the Indian Ocean Central Water, but from figure 4.12 it can be seen that the water types in the Mozambique Channel group themselves to form two distinct lines on the T/S curve which portray the subsurface water masses of the Equatorial Water and the Central Water. Thus 25.80, which coincides with a salinity maximum and oxygen minimum, falls in both. This water lies at depths of between 200 and 500 m. At 25.80 σ_t (figure 5.15) the circulation is still basically the same as before although the depth topography does not show it as clearly. The temperature, salinity and oxygen, however, portray the recurvature well (figure 5.16, 5.17, 5.18). The way in which the current arrows and oxygen isolines in the middle of the Mozambique Channel supplement each other (figure 5.18) is especially noteworthy. At 26.80 σ_t (~ 500 m) there is no longer any flow of the Mozambique Current past section G (figure 5.66). At this depth for the first time water flows past Cape St. Marie from the east. It then flows north in the channel and feeds the Mozambique Current on the lower depths as depicted in figure 5.20. This σ_t -surface coincides with an oxygen maximum in the channel and of all the identifying properties the oxygen distribution shows this circulation most clearly.

There are few publications that deal with the circulation at depth. Duncan (1970) plotted the isohalines of the σ_t 25.8 surface for the four seasons, but the sparse covering of stations for three month periods precludes any details from emerging. It does show, however, the probability of the Mozambique Current as a continuous flow at depth. Lutjeharms (1968) in analysing the synoptic April-May cruise of the

Almirante Lacerda in 1964 showed by the dynamic topography as well as the slope of the σ_t -surface the same circulation at this depth as found in the present work. Harris (1970) showed that, using synoptic stations September-October, the large anti-cyclonic circulation does exist, but that this is strengthened at 24.9 σ_t by a continuous Mozambique Current. There is therefore some support in the literature for the circulation as described, always dependent upon variations of various time period which have, as yet, not been discussed.

The next two σ_t -layers (27.25, 27.50) were chosen to trace Antarctic Intermediate and Red Sea Water and lie at about 900 and 1200 m respectively. At these two depths the circulation changes notably (figures 5.25 and 5.30). Although the flow past Cape St. Marie still feeds the Agulhas Current, there is only a faint indication that it turns north to drive an anticyclonic circulation in the channel itself (figure 5.25). At σ_t 27.50 (figure 5.30) the flow in the channel is in fact cyclonic and the water coming past Cape St. Marie does not pass into the channel at all. The strong hydrological barrier shown by the distributing properties at this level support this. The flow of the Antarctic Intermediate and Red Sea Waters will be dealt with in more detail later, as will the circulation at greater depths.

The circulation in the Mozambique Channel thus consists of three parts. On the surface the Mozambique Current is continuous through the channel, but part recurves to flow eastwards in the mouth and northwards in the middle of the channel. Some of this counter flow then recurves again to flow south along the west coast of Madagascar. Below 500 m

the Mozambique Current is no longer fed from the northern part of the channel, but by water that flows south of Cape St. Marie, northwards along the west coast of Madagascar and feeds the Mozambique Current at about 18°S in the channel. At about 1000 m this has changed and the remaining short section of the Mozambique Current is fed directly past Cape St. Marie with no recurving into the channel.

6.7 THE FLOW IN THE AREA SOUTH AND SOUTHEAST OF CAPE ST. MARIE

This area is of crucial importance to the understanding of the whole water supply of the Agulhas Current, the Mozambique Current and the West Madagascar Current. Although it is traversed regularly by commercial shipping and the surface currents from ships drift are thus well known (see The General Current Circulation, — 1952) it is an area in which little oceanographic work has been done and for the Northeast Monsoon Season devoid of stations (see figure 4.14). The water movement here can thus only be inferred. Partially this has already been done for the other areas bordering on this one, but because of its importance it is treated as an area on its own here.

The two vertical sections that border this area (I,E) are part of one line of stations carried out by the Atlantis in November 1963 and are thus synoptic. Comparing the velocity profiles for these sections (figures 5.57 and 5.72) it is clear that at this time of year the classical idea (Michaelis 1923) that the East Madagascar and West Madagascar Current are one continuous stream with feeding from east to

west past Cape St. Marie does not hold. Although the East Madagascar Current is evident, the flow on the west coast of Madagascar is southward. On investigation of the isobaths on the σ_t -surfaces (figures 5.5, 5.10, 5.15, 5.20, 5.30) it is clear that near the surface the areas east and west of Madagascar form two independent circulations. The flow on the surface past Cape St. Marie is eastwards and forms part of the Agulhas Return Flow (e.g. figure 5.15). A shallow, anti-cyclonic eddy southeast of Cape St. Marie is a well established feature at these depths (see figure 5.5 and attendant identifying properties). Menache's (1963) vertical sections across this area show a similar feature although he only considers it as a deflection in the east-west current. Since the flow past Cape St. Marie on these σ_t -surfaces is parallel to the isolines they cannot confirm or contradict the eastward flow. At 700 m (figure 5.20) the Agulhas Return Flow has moved considerably south and the flow from the east of Madagascar passes Cape St. Marie to flow northwards into the channel which is confirmed by the oxygen (figure 5.23). Some kind of disturbance is still noticeable southwest of the Cape, which may possibly be the last remnant of the eddy discussed above. By 1000 m even this has vanished and the flow (figures 5.25 and 5.30) is straight past Cape St. Marie on towards the Agulhas Current. It should be stressed again that this interpretation rests on very few stations in this area and in many cases the broken lines point to the degree of subjectivity employed.

This interpretation stands in some contrast to some of the published work. All surface current atlases show the surface current off Cape St. Marie as setting west. Menache

(1961,1963) makes the same inference for November as does Harris (1970) for June-July. Orren (1963), in his analysis of data from a line of stations occupied during June from Lourenzo Marques across this area makes no mention of an eastward flow either.

Lacombe (1951), using 1000 db as a reference level, does show water passing past Cape St. Marie but being caught up in the Agulhas Return Flow before it can reach the African coast. Using 2000 db as a reference level there is no flow westward past Cape St. Marie. Further partial support for the present analysis is to be found in the Indian Ocean Currents (— 1939) which for the period February-March-April shows water flowing east-west past the southern tip of Madagascar, but shows the Return Flow as far north as 30°S. Crepon's (1965) direct current measurements at the surface support this.

It is to be noted that the weekly analyses by Crawford (1970) of surface temperature very seldom show a tongue of warm water joining the Mozambique-Agulhas flow from the east. Duncan (1970) also shows, for summer and winter, the circulations east and west of Madagascar as being separate with the Agulhas Return Flow far to the north. For his transport calculations he assumes, however, that the flow at the surface does take place past Cape St. Marie in a westward direction and that it forms the major part of the East Madagascar Current.

The oceanographic stations in this area are so sparse that no definite conclusion can satisfactorily be reached. Duncan (1970) also commented on the severe lack of data in this area. It may be surmised that the flow past Cape St. Marie westward is narrow and close to the coast and, at the

surface, carries only a small part of the transport from east to west. The general flow at the surface is sluggish and eastwards. At depth all the flow is westwards past Cape St. Marie. This interpretation would also be supported by the transport/ σ_t curves (figures 5.59 and 5.74).

6.8 THE AGULHAS CURRENT

The Agulhas Current is the main current of the whole South Indian Ocean. It has attracted much oceanographic study and is generally accepted as being fast moving, narrow in lateral extent and deep. One section across it was considered sufficient (J), since its coherence from the σ_t -surfaces made closer examination unnecessary. Since only a small part of the geographical area occupied by the Agulhas retroflexion falls in the area being considered, it will be included in the present section, while the Agulhas Return Flow, which covers a much greater area, will be considered separately.

On all the σ_t -surface diagrams the Agulhas Current stands out clearly. Because of its high velocity the isolines of identifying properties show few tongues and usually run parallel to the flow, but because the Agulhas Current is carrying higher temperature water into areas of lower temperature the contrast delineates the current well. On the surface this is particularly noticeable in figure 5.2. This same diagram shows a few tongues of warm water breaking off to flow away from the coast. These tongues seem to support some of the work by Crawford (1970). They are not shown by the isobaths of the σ_t -surfaces, but the oxygen distributions (e.g. figures 5.13,

5.18) and the salinity distributions (figure 5.17) near the sea surface possibly confirm their existence. The main area of retroflexion of the Agulhas Current has not been incorporated in this study, but the beginning of the Return Flow is quite noticeable at all levels as the perturbations in isolines just south of Port Elizabeth (figures 5.5, 5.10, 5.15). The surface flow of this area has been described thoroughly for March by Bang (1970). The data on this area used by the present work was the same as that used by Bang.

The vertical velocity structure of the current is portrayed in detail in figure 5.76. The current is narrow, strong and deep, still possessing velocities of 10 cm/s at 1000 m. The same current structure is shown by Dietrich (1935) and Anderson (1965) and also in the frontispiece of Duncan (1970) although in the last two analyses there also exists an inshore counter-current setting north. Snyman's (1968) analysis shows that this is not present at all times. The total transport to 2280 m of the Agulhas Current itself is $55.66 \text{ Mm}^3/\text{s}$ (table III). This agrees well with Duncan's (1970) estimate of 64 megatons/s. Just offshore of this is a countercurrent which may be part of an offshore eddy. The slope of the σ_t -surfaces (figure 5.75) show features very similar to those above the Altair cone as described by Defant (1961) and this hypothetical eddy may thus possibly be related to the Mozambique Ridge (see figure 6.1) which stands out as a peak in section J. The slopes of the two transport/ σ_t curves for station pairs J 5 - J 6 and J 6 - J 7 are so closely identical that this would support the concept of an eddy. Although the concept of such an eddy is supported by a few isobath diagrams (figure

5.10, 5.20) there is no confirmation of this by the identifying properties, and on most levels these currents just form part of the general circulation to be discussed later. Bang (1970) found a similar eddy further along the current which was part of the whole circulation and countercurrent pattern. A further contribution to the question of eddy or countercurrent was made by Orren (1966) who found an eastward moving counter current with a salinity equal to that of the main body of the Agulhas but with a temperature of 3°C lower. Shannon (1967) supports this strongly and gives an example of another cruise on which this current and line of divergence was found. Darbyshire (1964) considered this to be an eddy, but his area of research was limited so that he was not able to relate this to flow further afield.

As was described before, the Mozambique-Agulhas current is fed through the Mozambique Channel down to depths of 500 m (σ_t 26.80, figure 5.20). The water from the deeper levels comes from the eastern side of Madagascar. At a depth of 1200 m (figure 5.30) the Mozambique Current is no longer continuous with the Agulhas Current. The transport/ σ_t curves for section J across the Agulhas Current and the counter-current just seaward of it show (figure 5.78) very sharp maxima peaks of σ_t 27.00 which may indicate that the greater volume of water carried by the Agulhas Current is of east Madagascar origin, and has not come through the channel. It may be noted that the transport peaks of the section E (east of Madagascar; figure 5.59) are sharper, in the way of the Agulhas water, than those of section I (across the southern mouth of the Mozambique Channel; figure 5.74).

6.9 THE AGULHAS RETURN FLOW

Under this heading will be discussed the Agulhas Counter Current, the possibility of recirculation (the Agulhas Eddy - Duncan 1970) as well as the general eastward or northeastward Agulhas Return Current. Because of the slow and, in many cases variable, current in the whole region south of Madagascar and because of the shortage of stations in this area for this season (figure 4.14), the flow here is very poorly understood.

On the sea surface it is already noticeable that isolines (figure 5.1) do not run west-east but have a definite northerly component. The σ_t -level closest to the surface (24.00) shows a return flow or counter current just seaward of the Agulhas Current (figure 5.5). It may be argued that this is due to the shallowness of the σ_t -surface which makes interpretation here misleading, but when the deeper σ_t -surfaces 25.00 and 25.80 are considered this counter flow, in a varied form, still exists just seaward of the Agulhas Current (figures 5.10, 5.15). Section J (figure 5.76) shows the vertical structure and limited depth of such a counter current. As remarked on before, the existence of this counter current was also mentioned by Orren (1966) and further discussed by Shannon (1967). The fact that this water is now 3°C colder can well be understood from the fact that it has travelled several hundred miles through much colder surroundings.

At this depth it would seem that the return flow had two components: one flowing away to the east to complete the South Indian Gyre and one that is recirculated into the

Agulhas Current to complete an "Agulhas Gyre". The temperature distribution of σ_t 25.00 (figure 5.11) gives a very clear indication of this although the isobaths are not clear in this regard. At greater depths the salinity (figure 5.17) and the temperature (figure 5.16) also show this. At 700 m (figure 5.20) this recirculation is well developed and one can with confidence speak of an Agulhas Gyre. This gyre is then to be found on all deeper σ_t -surfaces and shows up strongly on figures 5.25 and 5.30. Even on figure 5.35 (2400 m) the central axis of this gyre is still retained and water flows around it in an anti-cyclonic fashion. Depth analyses of σ_t -surfaces at this depth may however, be deceptive, so one must treat this latter evidence with some caution.

At the same depths that this gyre of recirculation develops, the northeast component of the Agulhas Return Flow disappears. On σ_t 25.80 where the first signs of a gyre are noticeable (figure 5.15), the Return Flow past the southern tip of Madagascar is still strongly shown and the two circulations east and west of Madagascar independent. At σ_t 25.80 the gyre has developed (figure 5.20), the Agulhas Return Flow has moved south and water flows from east Madagascar around Cape St. Marie into the Mozambique Channel. This process continues until at σ_t 27.50 (figure 5.30) no Agulhas Return Flow is seen north of 35°S or east of 50°E . This disappearance of a counter current and later the northerly part of the Return Flow is reflected also in figure 5.76 which shows the counter current as going little deeper than 1500 m and the general deep flow being southwards along this line. This is corroborated by the transport/ σ_t curves (figure 5.78). This

fact, namely that the general return flow lies close to the surface is supported by Orren (1963,1966) and Shannon (1967).

Visser & van Niekerk (1965) found recirculation in the deeper layers (1000, 1500 m) that bears a very close resemblance to the present results, but the axis of the gyre was further to the east, an area in which there were no available stations during the Northeast Monsoon. Dietrich's (1935) presentation of isolines can be interpreted in different ways. The way in which he interpreted them, the Agulhas Current comes to a rather abrupt end, being rapidly dissipated and drawn into the West Wind Drift. Bang (1970) points out that other interpretations give more logical and accurate results. If Bang's composite reconstruction method of flow, which shows up countercurrents (p.72), is applied to Dietrich's work, the existence of these counter currents may also in this case be inferred. Harris (1970) showed that from the west-east Return Flow, various current branches flow north. He discusses all the evidence for this and shows the possibility of a Southwest Indian Gyre. The present analysis puts these possibilities on better foundations and at depth. Duncan (1970) considers the Agulhas Gyre ("Agulhas Eddy") to exist at all depths and to, at times, recirculate up to a third of the total flow of the Agulhas Current. For this he gives a figure of 10 megatons/s for the period March-May. If the counter current alone is considered part of this eddy (figure 5.76), the transport according to the present work is 21.34 Mm^3/s (table III).

In 1970 Harris proposed a theory of planetary type waves in the South West Indian Ocean, in which deflections in the Agulhas Return Flow were related to the changing bottom topo-

graphy over which it flows namely the Agulhas Plateau and the Madagascar Ridge. Some evidence for a perturbation at the latitude of 30°E exists (figure 5.20, 5.25), but on the whole the station spacing prevents any conclusive evidence from emerging.

It may be concluded from all the results of the present and previous research that the Agulhas Gyre at depth is a reality and that at the surface a counter current exists which may have a crucial influence on the water transport south past Madagascar.

6.10 WATER MASSES AND THEIR SPREADING THROUGH THE OCEAN

In some of the previous sections reference has been made in passing to various water masses and how they made their presence felt in the area under discussion. In this section each particular water mass will be defined as it is found in the South West Indian Ocean and spreading of it as shown by the σ_t -diagrams and other illustrations will be discussed and contrasted with other work of this nature. Shannon (1967) has summarised the results of many cruises and his nomenclature and definitions for the various water masses will be used as a guide.

He states that north of about 25°S the Tropical Surface Water is to be found with a temperature of 25°C and above and a salinity of below $35.3^{\circ}/\text{oo}$. On comparing figures 4.9 and 4.10 this delimitation seems sound. The upper parts of these two curves show a notable difference, the water north of the Tropical Front never exceeding $35.3^{\circ}/\text{oo}$. The upper part of

the T/S scatter curve for figure 4.11 shows this even more clearly. Figure 4.12 (see table IV.5) shows that in the Mozambique Channel both types of water masses are present. The reason for this can be seen from figure 5.2 and figure 5.3 which show the 25°C isotherm to lie just north of the southern mouth of the Mozambique Channel. This is nearly identical to the presentation by Menache (1963). This isotherm lies slightly further north in the area to the east of Madagascar, thus agreeing with Shannon (1967). The flow of the Mozambique Current thus brings Tropical Surface Water further south in the channel, while the closed circulation east of Madagascar contains Tropical Water to the north of about 24°S .

The water to the south of this is called Subtropical Surface Water (Shannon 1967) and lies between the Tropical Front (or Convergence) and the Subtropical Convergence at about 42°S . Its salinity range is from $35.3^{\circ}/\text{oo}$ to $35.7^{\circ}/\text{oo}$ and its temperature lies between 15° and 23°C . It can be seen (figure 5.2) that the surface flow of the Agulhas Current is an admixture of these two water masses.

The subsurface waters extending to moderate depths are divided into two groups that have the same horizontal limits as the surface waters, namely 25°S . Sverdrup (1942) called these the Indian Ocean Central Water and the Indian Ocean Equatorial Water. On the T/S diagram these are defined as follows: Central Water lies between $34.60^{\circ}/\text{oo}/8^{\circ}\text{C}$ and $35.50^{\circ}/\text{oo}/15^{\circ}\text{C}$; Equatorial Water between $34.90^{\circ}/\text{oo}/4^{\circ}$ and $35.25^{\circ}/\text{oo}/17^{\circ}\text{C}$. On the T/S curve the Central Water is thus shown by a steeper slope. The completely natural grouping of stations to form

the two diagrams figure 4.10 and figure 4.11 demonstrates that this is not an arbitrary defining of water masses which show a gradual gradation, but that a definite boundary between two noticeable different water masses exists; what was previously called the Tropical Front. The figures as given by Sverdrup (1942) fit the two curves mentioned perfectly, showing the accuracy of his judgement. These two water masses can also be seen very clearly on figures 4.12 and 4.6. Above 26.80 σ_t the dots show a grouping into two different lines which is best seen on figure 4.12. It is the contention of the present work that these represent the shallower parts of these two distinct water masses. Because of the similar range of values over which they fall it is difficult to use the σ_t -diagrams to define the limits of these subsurface water masses and the clear indication of the T/S diagrams will suffice. The way in which stations grouped themselves for the two water masses of figure 4.10 and 4.11 is given in table IV.6 in the appendices.

According to Shannon (1967) the Antarctic Intermediate Water lies between 900 and 1300 m, has a salinity of between 34.4 and 34.5 $^{\circ}$ /oo and a temperature of between 4 $^{\circ}$ C and 5 $^{\circ}$ C. It shows on the T/S curve a salinity minimum and has a high oxygen content. From the T/S diagrams on figures 4.9, 4.10, 4.11 it is quite clear that on moving north this characteristic of this water mass gradually disappears. South of the Tropical Front is a strong minimum (figure 4.9), between 25 $^{\circ}$ S and 10 $^{\circ}$ S it is still noticeable (figure 4.10), but north of 10 $^{\circ}$ S it has disappeared for all practical purposes (figure 4.11). The combination of these three diagrams gives figure 4.6 which

at σ_t 27.25 shows the broad scatter expected. Since Red Sea Water is also of a similar density (Sverdrup 1942) this manifests the influence of the two water masses. This water is of north Indian Ocean origin, but what constituent; Red Sea, Arabian Sea or Persian Gulf, is predominant is difficult to tell and not of much importance for this work. When referring to the general water mass it will therefore be called North Indian Deep Water. If we compare figure 4.6 with figure 4.12 we see that Antarctic Intermediate Water is also present in the Mozambique Channel although the North Indian Deep Water has a predominant effect. It can be seen that σ_t 27.25 was chosen to trace the Antarctic Intermediate Water while 27.50 σ_t was used for the Red Sea Water.

From an investigation of the σ_t 27.25 surface oxygen and salinity values (figure 5.27 and 5.28) it is seen that Antarctic Intermediate Water is especially dominant in the southeastern part of the area under consideration, that its influence east of Madagascar is greater than in the Mozambique Channel, that it proceeds furthest north just off the east coast of Madagascar and that tongues of it go up a little way on the western side of the Mozambique Channel (figure 5.27). This last figure also would indicate that North Indian Deep Water spills out of the eastern side of the channel confirming Harris's (1970) contention. North of 10°S various indentations in the isolines could be due to flow of water. This was discussed previously in the section dealing with this area, and will not be repeated here. Attention is only drawn to the sharp tongues of south flowing water of low oxygen and high salinity just off the African coast which show North Indian Deep Water penetrating south.

North Indian Deep Water lies between 800 and 1500 m according to its salinity distribution and between 800 and 2000 m as inferred from its oxygen distribution (Clowes & Deacon 1935). It shows a salinity maximum and oxygen minimum. On σ_t 27.50 (figures 5.31, 5.32, 5.33) the description of the flow of water of this water mass is upheld. The isohalines and isotherms show in a more pronounced way the flow out from the eastern side of the Mozambique Channel, the flow of Antarctic Intermediate Water up the east coast of Madagascar and the North Indian Deep close to the African coast flowing south. This last is shown also by the oxygen (figure 5.33). The flow of these water masses past the vertical sections was discussed previously.

6.11 DEEP CIRCULATION

Of all the water movement this is perhaps the most difficult to reach any conclusions on. Figures 5.35 to 5.39 show the circulation between 2400 and 3200 m, but the analysis is severely handicapped by the few stations available. The reliability of the isentropic method at these depths decreases, the available deep channels through which water can still flow become complicated (figure 6.1) and the effect of flowing over the very variable topography at this depth may affect the directions of the currents greatly. A continuation of the Agulhas Gyre coinciding with the southern part of the Mozambique Ridge was surmised before and the distribution of salinity (figure 5.37) and temperature (figure 5.36) may support this. On the other hand the salinities may also support

the flow depicted by Le Pichon (1960) in which water of Atlantic Ocean origin flows north towards the channel and eastwards along 40°E . Le Pichon's diagrams are difficult to interpret because he did not draw in the bottom topography. The oxygen distribution (figure 5.38) does not support this flow. Zaklinskii (1963) has drawn detailed flow patterns for various depths. The anti-cyclonic circulation to the north of the Mozambique Channel is upheld by his work and is well supported by the temperature and salinity (figures 5.36 and 5.37). The other circulation is well supported. The circulations by Visser & van Niekerk (1965) also show little similarity to the present work. It thus seems that little value can be attached to the circulations shown at this depth.

6.12 VARIABILITY

The seasonal variability in the North Indian Ocean is well known. That this is bound to have an influence on the South West Indian Ocean seems logical and has been the object of some research which was discussed before. Duing (1970), for example, did extensive work in this regard. The latest work of this nature that includes the variation with season of the transports was done by Duncan (1970). In chapter III it was also pointed out that various authors have commented on variations from year to year. In this regard Truesdale (1971) may be again mentioned, who showed, using two cruises of different years, big differences in current structure from one year to another.

It was found impossible to balance the volume transports.

TABLE 6.1

VOLUME TRANSPORT FOR TWO CONSECUTIVE VERTICAL SECTIONS ACROSS THE MOZAMBIQUE CHANNEL FOR THE SAME MONTH IN DIFFERENT YEARS

σ_t	section I volume transport (in $10^6 \text{ m}^3/\text{s}$)	section H volume transport (in $10^6 \text{ m}^3/\text{s}$)	section I totals of volume transport and depth	section H totals of volume transport and depth
22.80		-1.88		
23.20		-2.77		
23.60	0.10	-4.76		
24.20	-0.31	-1.86	-0.21 (~ 50 m)	-11.27 (~ 100 m)
26.40	0.47	-1.40		
25.00	-0.95	-0.98		
25.40	-0.59	-1.70		
25.80	-0.95	-0.45		
26.20	-0.80	-1.83	-2.82 (~ 250 m)	-6.36 (~ 230 m)
26.60	-1.41	-2.81		
27.00	-0.42	-3.30	-1.83 (~ 700 m)	-6.11 (~ 650 m)
27.20	-0.25	-1.74		
27.40	2.38	-0.40		
27.60	1.77	-2.40	3.90 (~ 1500 m)	-4.54 (~ 1700 m)
-	1.19 (27.70 σ_t)	-0.69 (27.77 σ_t)		
net total transports	0.23	-28.97		

across the vertical sections. Although the vertical sections on the whole enclosed certain areas, the net inflow or outflow out of these areas was of a magnitude that could not be balanced by up or down-welling. The possibility of balancing transports by considering also the flow below 2280 m (the level-of-no-motion used) and using the sea bottom as reference level was not successful. This attempt included the accurate calculation of the cross sectional areas of the vertical sections to the sea bottom, taking into consideration the variable bottom topography. Another attempt was made by neglecting water above certain σ_t surfaces so that any variations of the surface flow, which is subject to variable winds, were neglected. This also was fruitless. It might be argued that, although each vertical section in itself is synoptic, different ones do not fall in the same month and might thus be subject to seasonal variations. The volume transport across two sections that fell in the same month and that are nearly parallel to one another in the Mozambique Channel (sections H and I, see figure 4.18) are given in table 6.1. Transports have been collected for σ_t bands, but it is clear from the table that any attempt to balance the flow is profitless. Not only is the total volume transport above 2280 m of a completely different order, but even considering the stratums of σ_t layers, no correlation is shown. Below about 700 m the total water transport across the sections is in fact in a different direction. This is probably due to the strong, deep West Madagascar Current portrayed in figure 5.69 and 5.70 the penetration into the channel of which might quite conceivably vary from month to month and from year to year. Within the

assumptions of the Witte-Margules equation, the volume transport was calculated very accurately and the only conclusion one can come to is that there is a big variation in even the deeper flow from year to year. An analogous case, which was not tabulated but which may warrant some attention, is the case of the two parallel vertical sections A and B. A comparison of their velocity structures (figures 5.41 and 5.46) and their transports (table III) show distinctly the type of variation under discussion.

It is conceivable that the surface and subsurface flow, which are subject to the Monsoon Winds, may vary from year to year as the duration and the intensity of these winds vary. For the intermediate waters a year-to-year variation is more difficult to comprehend. Sverdrup (1942) has commented on the year-to-year variation in outflow from the Red Sea and the complicating influence this will have at great distances and at depth. Dietrich (1935, p.65) dealing with the Agulhas Current stated that not only are unperiodic pulsations in the current to be found, but also in depth, in the Antarctic Water masses, are there large variations with no regular period.

Variations of this kind would throw serious doubt on any smaller scale analysis using non-synoptic data. Although the main features might remain, any detailed analysis, such as accurate transport calculations only denote what is happening in a specific locality at a specific time with the possibility that a similar relationship between current branches across such a section would hold in the future. Any quantitative deductions extrapolating in time would be of little

use. The transport calculations in the present analysis and the volume transport/ σ_t curves thus act as guides and indicators only and no attempt has been made to make quantitative deductions on the flow. Wherever on a σ_t -surface a combination of stations from various cruises and years gives a coherent, clear-cut result, it may be accepted that this feature is one of some permanence and only for this reason may features on σ_t -surfaces, as discussed, be treated with anything but extreme caution.

CHAPTER VIII

CONCLUSIONS

As was seen, the main problems confronting research workers in the South West Indian Ocean are threefold. There is, in the first place, the problem of variability in the water flow, seasonally and also from year to year. The poorly understood large scale circulation in depth, as well as several problems of regional nature also make themselves felt.

By a careful and detailed analysis of current velocities on various σ_t -surfaces, using the Witte-Margules equation, the volume transport was calculated across certain selected vertical sections. This method is not generally used and produced some new and useful results, one of which was the deduction that volume transports across sections show important variations from year to year. The implication of this variation is that the flow of water, even at depth, undergoes variations of such a magnitude that any large scale analysis of water movement, depending on a combination of non-synoptic data, can only demonstrate features of some permanence. Although variations of this nature have been surmised in previous papers it is thought that this is the first quantitative result to be brought forward in its support. These variations may severely restrict the application of any large scale analysis.

In this work the interpretation of the isentropic method used for a large scale analysis was greatly enhanced by using it in conjunction with the calculated velocities on the different σ_t -surfaces. Although this addition to the isentropic method was a departure from the usual application, the results indicate

its usefulness under certain conditions. The results as depicted for the Northeast Monsoon showed that at and near the sea surface the South Equatorial Current, with its main axis at about 10°S carries water into the area and passes uninterrupted past Cape d'Ambre towards the African coast. Close to the coast it divides, to form the Mozambique and the East African Coastal Currents. Seaward of the East African Coastal Current a counter current flowing south and various offshoots from the South Equatorial Current are shown. Only part of the surface flow of the Mozambique Current flows through the channel, a large volume recurving at the southern mouth to flow northward in the middle of the channel. On the eastern side of the channel there is a current flowing south. The Agulhas Current is bordered on the seaward side by a counter current which eventually passes past Cape St. Marie flowing eastwards. On proceeding to deeper waters this portrayal of water movement is changed in four aspects: the axis of the South Equatorial Current moves southwards, a semi-closed anti-cyclonic eddy of large dimensions forms off east Madagascar, the Agulhas Return Flow loses some of its northerly component in its flow towards Cape St. Marie and an Agulhas Gyre starts to develop off Port Elizabeth. At σ_t 26.80 there is no more continuous flow through the Mozambique Channel, the Mozambique Current deriving all its water from the now fully developed East Madagascar Current that flows past Cape St. Marie recurving back into the channel and feeding the Mozambique Current at about 18°S . At this depth the general Agulhas Return Flow has moved far to the south, a large part of it recirculating in a strongly evolved Agulhas Gyre. At deeper

levels this tendency increases, the gyre growing more pronounced, the flow past Cape St. Marie moving straight on towards the Agulhas Current and the Return Flow lying far to the south. At these depths the East African Coastal Current has disappeared and the circulation north of the South Equatorial Current, as also in the Mozambique Current, is indistinct, existing of numbers of disjointed eddies. The analysis showed that the identifying properties on the σ_t -surfaces are helpful as indicators but as a rule do not of themselves give clear portrayals of water movement. This limitation was felt most acutely in the analysis of the meridional movements of the deeper water masses such as the Antarctic Intermediate and the North Indian Deep Waters. In these cases only vague indications could be derived from the distribution of identifying properties on σ_t -surfaces.

Any attempts to answer questions relating to smaller scale problems of a regional nature are even more severely handicapped by the year-to-year variations, the inability of identifying properties to demonstrate water movements and also by the lack of data. One area in which stations were relatively plentiful and in which consequently some clear deductions could be made about the regional circulation, was the Mozambique Channel of which the circulation was described above in the paragraph dealing with the analysis of the large scale circulation. The finding that at different depths the Mozambique Current is supplied from different sides of Madagascar was new and was partially supported by the transport/ σ_t curves.

The use of these curves relating volume transport to σ_t

was a novel attempt at depicting characteristic transport curves for various water masses. In this some success was shown especially in the problems of regional nature. The high transport peaks at σ_t 26.80 for the Agulhas Current for instance were an important results showing at what density the main transport of the Agulhas Current took place.

In many areas the lack of data prevented any definite answers on some of the regional problems from emerging. This was especially true in the crucial areas in the northern mouth of the Mozambique Channel and the area south of Cape St. Marie. It would seem that the only way in which this problem could satisfactorily be solved would be by a synoptic multi-ship cruise in this area with stations spaced in such a way that smaller scale features will become clear. The rewarding results shown by Bang (1970) for a similar cruise in the Agulhas retroflexion area support this view. Another cruise, occupying the same stations in the same month a year or two later will make data available to get the first quantitative conception of the year-to-year variations to be expected. The need for such cruises, in this area in particular, needs no supporting argument.

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APPENDICES

(i)

APPENDIX I

The following computer program was developed by Mr. T. Radford of the University of Cape Town Computer Centre under the guidance of Mr. J.R.E. Lutjeharms.

Using the oceanographic data as supplied on standard computer cards by the National Oceanographic Data Centre of the U.S.A., the program draws curves for temperature v. depth, sigma-t v. depth, salinity v. temperature, oxygen v. temperature and phosphate v. temperature. The curve is a weighted second degree polynomial fit passing through observed values only, interpolated data being ignored. Where the data is of such a nature that a second degree polynomial fit would cause the curve to digress outside acceptable boundaries, only the parameter values are plotted and least curvature fitting is done by hand afterwards.

The computer used was an IBM 1130 combined with a CALCOMP 1627 plotter. About 600 oceanographic stations were treated in this way, the average running time being of the order of seven minutes per station. The curves were drawn on mm graph paper 75 cm wide.

Fig. 4.15 is a reproduction of a typical output of this program.

(v)

C THIS PROGRAM UTILISES NATIONAL OCEANOGRAPHIC DATA CENTRE
C DATA TO DRAW SMOOTHED GRAPHS FOR TEMPERATURE V DEPTH,
C SIGMA-T V DEPTH, TEMPERATURE V SALINITY, TEMPERATURE V
C OXYGEN AS WELL AS TEMPERATURE V PHOSPHATE

// * SUBROUTINE OCRED READ IN AND EXTRACT DATA
// FORTRAN PROGRAM BY TIM RADFORD

SUBROUTINE OCRED(REFR,SQRE,LATD,LATM,LNGD,LNGM,YEAR,
1MONTH,DAY,DEPTH,TEMP,SALL,SIGMT,O2,PO4,TYPE)
INTEGER CARD(80),TYPE,YEAR,DAY

C THIS SPECIAL READING SUBROUTINE IS NEEDED DUE TO CERTAIN
C ANOMALIES IN THE DATA. IN CERTAIN COLUMNS, ROWS 10, 11,
C AND 12 ARE SOMETIMES OVERPUNCHED. THE PROGRAM READS EACH
C COLUMN LITERALLY AND MASKS THEM SO THAT THESE OVERPUNCHES
C ARE IGNORED. THEN, ACCORDING TO THE CARD TYPE (COLUMN 80)
C EITHER THE DATA IS EXTRACTED, OR THE HEADING INFORMATION,
C OR THE CARD IS IGNORED

1 READ (2,100) CARD
100 FORMAT(80A1)
CALL MASK (CARD)
TYPE=CARD(80)

C TYPE ZERO CARD (BLANK) RETURNS DIRECTLY

IF(TYPE) 5,22,5

C TYPE ONE CARD IS HEADER SO HEADER VALUES ARE COMPUTED

5 IF(TYPE-1) 15,10,15
10 YEAR=10*CARD(19)+CARD(20)
MONTH=10*CARD(21)+CARD(22)
DAY=10*CARD(23)+CARD(24)
LATD=10*CARD(5)+CARD(6)
LATM=10*CARD(7)+CARD(8)
LNGD=100*CARD(10)+10*CARD(11)+CARD(12)
LNGM=10*CARD(13)+CARD(14)
REFR=10000.*CARD(1)+1000.*CARD(2)+100.*CARD(73)+10.*
1CARD(74)+CARD(75)
SQRE=100.*CARD(16)+10.*CARD(17)+CARD(18)
RETURN

(vi)

C TYPE THREE CARD IS DATA, SO DATA IS EVALUATED
C TYPES FOUR AND FIVE BECOME TYPE THREE

```
15 IF (TYPE-3) 25,20,16
16 IF (TYPE-4) 25,18,17
17 IF (TYPE-5) 25,18,25
18 TYPE=3
20 DEPTH=1000*CARD(28)+100*CARD(29)+10*CARD(30)+CARD(31)+
  1.1*CARD(32)
20 TEMP=10*CARD(33)+CARD(34)+.1*CARD(35)+.01*CARD(36)+
  1.001*CARD(37)
  SAL1=10*CARD(38)+CARD(39)+.1*CARD(40)+.01*CARD(41)+
  1.001*CARD(42)
  SIGMT=10*CARD(43)+CARD(44)+.1*CARD(45)+.01*CARD(46)
  O2=CARD(51)+.1*CARD(52)+.01*CARD(53)
  PO4=CARD(54)+.1*CARD(55)+.01*CARD(56)
22 RETURN
```

C CARD TYPES SIX, SEVEN, AND EIGHT ARE SKIPPED

```
25 IF (TYPE-6) 26,1,26
26 IF (TYPE-7) 27,1,27
27 IF (TYPE-8) 30,1,30
```

C TYPE NINE CARD INDICATES END OF PLOTTING. TYPE TWO RESULTS
C IN PAUSE 5555 AND NEXT CARD IS READ ON RESTART, THE CARD
C OTHERWISE BEING IGNORED.

```
30 IF (TYPE-9) 35,22,35
35 PAUSE 5555
  GO TO 1
  END
```

```
// DUP
*STORE      WS  UA  OCRED
// EJECT
```

(vii)

```
// *      SUBROUTINE OCPNT      POINT IDENTIFICATION
// FORTRAN PROGRAM BY TIM RADFORD
```

```
      SUBROUTINE OCPNT(K)
      DIMENSION K(5)
```

```
      C  THIS SUBROUTINE IS COMPLETELY TRIVIAL AND CONSISTS SIMPLY
      C  OF MOVING THE PEN APPROPRIATELY TO DRAW A CROSS
```

```
      K(1)=K(1)+3
      CALL DRAW(K)
      K(1)=K(1)-6
      CALL DRAW(K)
      K(1)=K(1)+3
      CALL DRAW(K)
      K(3)=K(3)+3
      CALL DRAW(K)
      K(3)=K(3)-6
      CALL DRAW(K)
      K(3)=K(3)+3
      CALL DRAW(K)
      RETURN
      END
```

```
// DUP
*STORE      WS  UA  OCPNT
// EJECT
```

/** SUBROUTINE OCPLT, DRAWS SMOOTH CURVE THROUGH POINTS
 // FORTRAN PROGRAM BY TIM RADFORD

SUBROUTINE OCPLT(XP,YP,N,K,LET)
 DIMENSION C(3),D(3)
 DIMENSION K(5),X(50),Y(50),XP(50),YP(50)

C INTERPOLATION INCREMENT SIZE

DELT=5.
 CMM=39.37043

C SET UP DUMMY PLOTTING ARRAY. FOR OXYGEN AND PHOSPHATE
 C PLOTS ZERO VALUES ARE NOT ACCEPTED
 C 'LET' INDICATES WHICH PLOT THIS IS, AND 'KL' BECOMES AN
 C INDICATOR FOR CERTAIN CONDITIONAL BRANCHES LATER

KL=1
 IF (LET-196) 1,7,1
 1 IF (LET-227) 2,7,2
 2 IF (LET-226) 4,3,4
 3 KL=2
 GO TO 7
 4 IF (LET-214) 5,6,5
 5 IF (LET-215) 7,6,7
 6 KL=3
 7 J=0
 DO 20 I=1,N

C PHOSPHATE AND OXYGEN MAY NOT ASSUME ZERO SCALE VALUES AS
 C THEY ARE SOMETIMES OMITTED FROM DATA CARDS AND READ AS
 C ZERO IN THESE CASES

GO TO (15,15,10), KL
 10 IF (YP(I)-787.4086) 15,20,15

C TEST THAT THE POINTS LIE WITHIN THE BORDERS OF THE GRAPH

15 IF(XP(I)-2.5*CMM) 20,16,16
 16 IF(42.5*CMM -XP(I)) 20,17,17
 17 IF(YP(I)-4.*CMM) 20,18,18
 18 IF(54.*CMM-YP(I)) 20,19,19
 19 J=J+1
 X(J)=XP(I)
 Y(J)=YP(I)
 20 CONTINUE

```

C ARRANGE IN ASCENDING ORDER OF X-VALUES (BUBBLE-SORT)
C METHOD) THE POINTS ARE ORDERED AND THE CURRENT POINT IS
C THE POINT WITH THE LARGEST X-VALUE AND THE POINT WITH THE
C LARGEST X-VALUE IS EXCHANGED WITH THE POINT WITH THE
C LARGEST X-VALUE.
21 M=1
DO 25 I=2, J, C(10)
S=X(I-1)*X(I)+(1-I)*X(I-1)+I*X(I)
Y=Y(I-1)*Y(I)+(1-I)*Y(I-1)+I*Y(I)
IF (S-X(I-1)*25,25,23) GOTO 23
23 M=2
X(I-1)=X(I)+S*(1-I)+X(I-1)*I
Y(I-1)=Y(I)+S*(1-I)+Y(I-1)*I
X(I)=S
Y(I)=T
25 CONTINUE
GO TO (26,27,M), C(10)
C QUADRATIC ARE HEIGHTS ACCORDING TO X-POSITION OF
C MOVE PEN TO FIRST POINT, LOWER, AND DRAW POINT.
26 K(1)=X(1)
K(3)=Y(1)
CALL DRAW(K)
CALL DOWN(K(5))
CALL OCPNT(K)
C DRAW ARC OF PARABOLA BETWEEN FIRST TWO POINTS
C SUBROUTINE SKOEF CALCULATES THE COEFFICIENTS OF A
C QUADRATIC THROUGH THREE SUCCESSIVE POINTS. POINTS ARE
C INTERPOLATED HENCE CALL SKOEF(X,Y,C)
CALL SKOEF(X,Y,C)
XI=X(1)
29 XI=XI+DELT
IF (XI-X(2)) 30,35,35
30 YI=C(1)+C(2)*XI+C(3)*XI*XI
C CHECK THAT THE INTERPOLATED POINTS LIE WITHIN THE BORDERS
IF (YI-4.*CMM) 29,31,31
31 IF (54.*CMM-YI) 29,32,32
32 K(1)=XI
K(3)=YI
CALL DRAW(K)
GO TO 29
35 K(1)=X(2)
K(3)=Y(2)
CALL DRAW(K)
CALL OCPNT(K)
C DRAW 'WEIGHTED' PARABOLAS BETWEEN MIDDLE SET OF POINTS
L=J-2
DO 50 I=2, LMM
XI=X(I)
Q=X(I+1)-X(I)
CALL SKOEF(X(I-1),Y(I-1),C)
CALL SKOEF(X(I),Y(I),D)

```

C READ IN DATA

```
KT=0
15 KT=KT+1
   IF (KT-100) 20,20,50
20 CALL OCRED (REFR, SQRE, LATD, LATM, LNGD, LNGM, YEAR,
  1MONTH, DAY, DEPTH(KT), TEMP(KT), SAL(KT), SIGMT(KT),
  102(KT), PO4(KT), TYPE)
```

C A BLANK CARD INITIATES PLOTTING OF DATA JUST READ, UNLESS
C THIS IS THE FIRST TIME AROUND, IN WHICH CASE PLOTTING IS
C BYPASSED AND NOMGR IS INCREMENTED

```
   IF (TYPE) 30, 25, 30
25 IF (NOMGR) 55,27,55
27 NOMGR = NOMGR+1
   GO TO 20
```

C A MASTER CARD INITIATES FURTHER DATA READING

```
30 IF (TYPE - 1) 35, 4, 35
```

C A DATA CARD CAUSES NEXT DATA CARD TO BE READ BUT IS
C ITSELF IGNORED

```
35 IF (TYPE-3) 45,39,45
39 IF(TEMP(KT)) 40,20,40
40 IF (DEPTH(KT)-4000.*IJ+3000.) 15, 15, 20
```

C CARD TYPE NINE INITIATES PLOTTING AND CAUSES CALL EXIT
C THEREAFTER

```
45 IF (TYPE - 9) 50, 55, 50
50 PAUSE 5555
   GO TO 20
55 KT=KT-1
```

C DRAW BORDER

```
CALL INTLZ(K,5,IFIX(45.*CMM+.1),0,0,0,9)
CALL DOWN(K(5))
CALL DRAW(K)
K(3)=56.*CMM+.1
CALL DRAW(K)
K(1)=0
CALL DRAW(K)
K(3)=0
CALL DRAW(K)
```

C DRAW AXES

```

CALL UP(K(5))
K(1)=X1
K(3)=Y1
CALL DRAW(K)
K(3)=Y3
CALL DOWN(K(5))
CALL DRAW(K)
K(1)=X2
CALL DRAW(K)
K(3)=Y1
CALL DRAW(K)
K(1)=X1
CALL DRAW(K)
CALL UP(K(5))

```

C THE FOLLOWING SECTION USES, IN PARTICULAR -
 C PVALP - WRITING LITERAL INFORMATION
 C PSNO - WRITING NUMERIC INFORMATION
 C ANOTS - PRODUCING SCALE ANNOTATIONS
 C DATA SWITCH 11, WHEN UP, SUPPRESSES ANNOTATION

```

CALL DATSW(11,J)
GO TO (65, 60),J

```

C ANNOTATE TEMPERATURE AXIS

```

60 CALL PVALP(800,2150,K,2.,3.,0.,T)
K(1)=X1
K(3)=Y3+4
CALL DRAW (K)
CALL PSNO(0.,-5.,0,K)
CALL INTLZ(B,9,X1+5.*CMM,Y3,0.,L2-6.*CMM,5.*CMM,4.,
1SCAT,-360.,0.)
CALL ANOTS(B,K)

```

C ANNOTATE SALINITY-PHOSPHATE AXIS

```

CALL INTLZ(B,9,X2,Y3,3.*PI/2.,L1,5.*CMM,B(6),SCAS,-360
1.,33.)
CALL ANOTS(B,K)
CALL PVALP(1740,1180,K,3.,2.,3.*PI/2.,S)
CALL INTLZ(B(2),8,Y2,B(3),L3,4.*CMM,4.,SCAP,0.,0.)
CALL ANOTS(B,K)
CALL PVALP(1630,560,K,3.,2.,3.*PI/2.,P)

```

C ANNOTATE DEPTH-OXYGEN AXIS

```

CALL INTLZ(B,9,X1,Y3,B(3),L1,5.*CMM,4.,SCAD,0.,0.)
CALL ANOTS(B,K)
CALL PVALP(30,1010,K,3.,2.,PI/2.,D)
CALL INTLZ(B,9,X1,Y2,B(3),L3,4.*CMM,4.,SCAD,-360,0.)
CALL ANOTS(B,K)
CALL PVALP(150,410,K,3.,2.,PI/2.,O)

```

(xiv)

C ANNOTATE SIGMA-T AXIS

```
CALL INTL2(B,9,X1,Y1,0.,L2,4.*CMM,B(6),SCAST,0.,20.)
CALL ANOTS(B,K)
```

C WRITE HEADING INFORMATION

```
CALL PVALP(1250,80,K,2.,2.,0.,DATE)
K(1)=K(1)+10
CALL DRAW (K)
CALL PSNO(0.,FLOAT(DAY),0,K)
K(1)=K(1)+10
CALL DRAW (K)
CALL PSNO(0.,FLOAT(MONTH),0,K)
K(1)=K(1)+10
CALL DRAW (K)
CALL PSNO(0.,FLOAT(YEAR),0,K)
CALL PVALP(1250,50,K,2.,2.,0.,REF)
K(1)=K(1)+10
CALL DRAW (K)
CALL PSNO(0.,REFR,0,K)
CALL PVALP(1250,20,K,2.,2.,0.,SHIP)
CALL PVALP(840,105,K,2.,3.,0.,ST)
CALL PVALP(750,15,K,3.,4.,0.,HEAD)
CALL PVALP(230,80,K,2.,2.,0.,LAT)
K(1)=K(1)+10
CALL DRAW (K)
CALL PSNO(0.,FLOAT(LATD),0,K)
CALL PVALP(396,80,K,2.,2.,0.,DEG)
K(1)=K(1)+10
CALL DRAW (K)
CALL PSNO(0.,FLOAT(LATM),0,K)
CALL PVALP(477,80,K,2.,2.,0.,MIN)
CALL PVALP(230,50,K,2.,2.,0.,LONG)
K(1)=K(1)+10
CALL DRAW (K)
CALL PSNO(0.,FLOAT(LNGD),0,K)
CALL PVALP(396,50,K,2.,2.,0.,DEG)
K(1)=K(1)+10
CALL DRAW (K)
CALL PSNO(0.,FLOAT(LNGM),0,K)
CALL PVALP(477,50,K,2.,2.,0.,MIN)
CALL PVALP(230,20,K,2.,2.,0.,SQR)
K(1)=K(1)+10
CALL DRAW(K)
CALL PSNO(0.,SQRE,0,K)
```

C CONVERT DATA VALUES TO COORDINATE VALUES IN HUNDREDTHS OF
C AN INCH

```

65 DO 70 J=1,KT
    DEPTH(J)=54.*CMM-100.*DEPTH(J)/SCAD
    TEMP(J)=2.5*CMM+100.*(TEMP(J)+5.)/SCAT
    SAL(J)=54.*CMM-100.*(SAL(J)-33.)/SCAS
    O2(J)=20.*CMM-100.*O2(J)/SCAO
    PO4(J)=20.*CMM-100.*PO4(J)/SCAP
    SIGMT(J)=2.5*CMM+100.*(SIGMT(J)-20.)/SCAST
70 CONTINUE

```

C PLOT THE CURVES USING THE SUBROUTINE 'OCPLT'

```

CALL OCPLT(TEMP,DEPTH,KT,K,196)
CALL OCPLT(SIGMT,DEPTH,KT,K,227)
CALL OCPLT(TEMP,SAL,KT,K,226)
CALL OCPLT(TEMP,O2,KT,K,214)
CALL OCPLT(TEMP,PO4,KT,K,215)

```

C RAISE PEN AND POSITION FOR NEXT PLOT

```

K(1)=45.*CMM+.1
K(3)=0
CALL UP(K(5))
CALL DRAW(K)
IF (TYPE - 9) 20, 80, 20
80 CALL EXIT
END

```

// EJECT

// DUP

*STORECI WS UA OCEAN

THE FOLLOWING TWO PROGRAMS HAVE TO BE IN ASSEMBLER

```
*****
*      SUBROUTINE MASK      *
* THE DATA HAS BEEN READ IN IN AI-FORMAT, BUT *
* ONLY THE 0-9 PUNCH IS REQUIRED. FORTUNATELY THE *
* VALUE IN THE RIGHT FOUR BITS OF THE EBCDIC CODE *
* CORRESPONDS TO THE HOLE PUNCHED, SO BY SHIFTING *
* THE CODE OVER TO THE RIGHTMOST EIGHT BITS AND *
* MASKING OUT THE EXTRANEIOUS PART OF THE CODE, *
* THE DESIRED RESULT IS OBTAINED. *
*****
```

	ENT	MASK	*		MASK	1
DIM	DC	160	*	DIMENSION OF ARRAY	MASK	2
RMASK	DC	/000F	*	MASK	MASK	3
MASK	DC	*--*	*	ENTRY POINT	MASK	4
	LD	I MASK	*	LOAD ADDRESS OF ARRAY	MASK	5
	S	DIM	*	SUBTRACT 160	MASK	6
	STO	CARD+1	*	MODIFY AT CARD	MASK	7
	STO	BACK+1	*	MODIFY AT BACK	MASK	8
	STX	1 INDEX+1	*	STORE INDEX 1	MASK	9
	LDX	L1 160	*	160 IN INDEX 1	MASK	10
CARD	LD	L1 *--*	*	LOAD CURRENT WORD	MASK	11
	SRT	8	*	EBCDIC CODE IN RIGHT 8	MASK	12
	AND	RMASK	*	MASK EXTRANEIOUS BITS	MASK	13
BACK	STO	L1 *--*	*	REPLACE MASKED WORD	MASK	14
	MDX	1 -2	*	DECREMENT INDEX 1	MASK	15
	MDX	CARD	*	LOOP TO CARD	MASK	16
INDEX	LDX	L1 *--*	*	RESTORE INDEX 1	MASK	17
	MDX	L MASK,1	*	BUILD EXIT	MASK	18
	BSC	I MASK	*	RETURN TO MAINLINE	MASK	19
	END		*		MASK	20

```

*****
*      SUBROUTINE INTLZ                      *
* THE PARAMETER LIST CONSISTS OF AN ARRAY ADDRESS,*
* A NUMBER, AND THAT NUMBER OF FURTHER PARAMETERS.*
* THE FURTHER PARAMETERS ARE LOADED, IN ORDER,   *
* INTO THE ARRAY                               *
*****

```

	ENT		INTLZ	*		INTLZ	1
ARRAY	DC	*--*		*	ADDRESS OF ARRAY	INTLZ	2
DIM	DC	*--*		*	ADDRESS OF DIMENSION	INTLZ	3
NEG1	DC	-1		*		INTLZ	4
INTLZ	DC	*--*		*	ENTRY POINT	INTLZ	5
	STX	1	X1+1	*	STORE INDEX 1	INTLZ	6
	LD	I	INTLZ	*	OBTAIN AND STORE	INTLZ	7
	STO		ARRAY	*	ADDRESS OF ARRAY	INTLZ	8
	MDX	L	INTLZ,1	*	NEXT PARAMETER	INTLZ	9
	LD	I	INTLZ	*	OBTAIN AND STORE	INTLZ	10
	STO		DIM	*	ADDRESS OF DIMENSION	INTLZ	11
	LD	I	DIM	*	N	INTLZ	12
	SLA		1	*	2N	INTLZ	13
	STO	L	1	*	2N IN INDEX 1	INTLZ	14
	M		NEG1	*		INTLZ	15
	SLT		16	*	-2N	INTLZ	16
	A		ARRAY	*	ADDRESS OF ARRAY - 2N	INTLZ	17
	STO		M2+1	*	MODIFY AT M2	INTLZ	18
LOAD	MDX	L	INTLZ,1	*	OBTAIN ADDRESS OF	INTLZ	19
	LD	I	INTLZ	*	NEXT PARAMETER AND	INTLZ	20
	STO		M1+1	*	MODIFY AT M1	INTLZ	21
M1	LDD	L	*--*	*	LOAD PARAMETER	INTLZ	22
M2	STO	L1	*--*	*	STORE IN NEXT POSITION	INTLZ	23
	MDX	1	-2	*	DECREMENT INDEX 1	INTLZ	24
	MDX		LOAD	*	LOOP TO LOAD	INTLZ	25
	MDX	L	INTLZ,1	*	BUILD EXIT	INTLZ	26
X1	LDO	L1	*--*	*	RESTORE INDEX 1	INTLZ	27
	BSC	I	INTLZ	*	RETURN TO MAINLINE	INTLZ	28
	END			*		INTLZ	29

APPENDIX II

The following computer program was developed by Johann R.E. Lutjeharms.

The depths of standard σ_t levels at each oceanographic station in a selected line of stations are determined from the curves drawn by the program in Appendix I. Using these in conjunction with the latitude of each station, the velocity on each σ_t level between each pair of stations is calculated. Integrating over the cross sectional area occupied by water between two σ_t levels, the program calculates the volume transport of water of that density across the section. The total volume transport for the whole water column down to 2300 m between adjacent stations is calculated as well as the total volume transport of water falling between two σ_t -levels across the whole line of stations.

The printout gives the velocity and transport for every standard σ_t -level at each station as well as the different transport totals mentioned.

Due to the irregular boundary conditions certain slopes of σ_t -levels and certain cross-sectional areas cannot be calculated. These are fed in as input data.

The computer used was an IBM 1130. The relative smallness of the immediate access store of this type of computer caused severe storage problems. As a result the running of the program was time consuming, needing about four minutes for each station pair. About a hundred stations, constituting ten lines, were treated in this way.

Some of the results are reproduced in the tables in Appendix III. Simplified flow diagrams for the core as well as the output section of the program are given in fig.II.1 and fig.II.2.

(xxii)

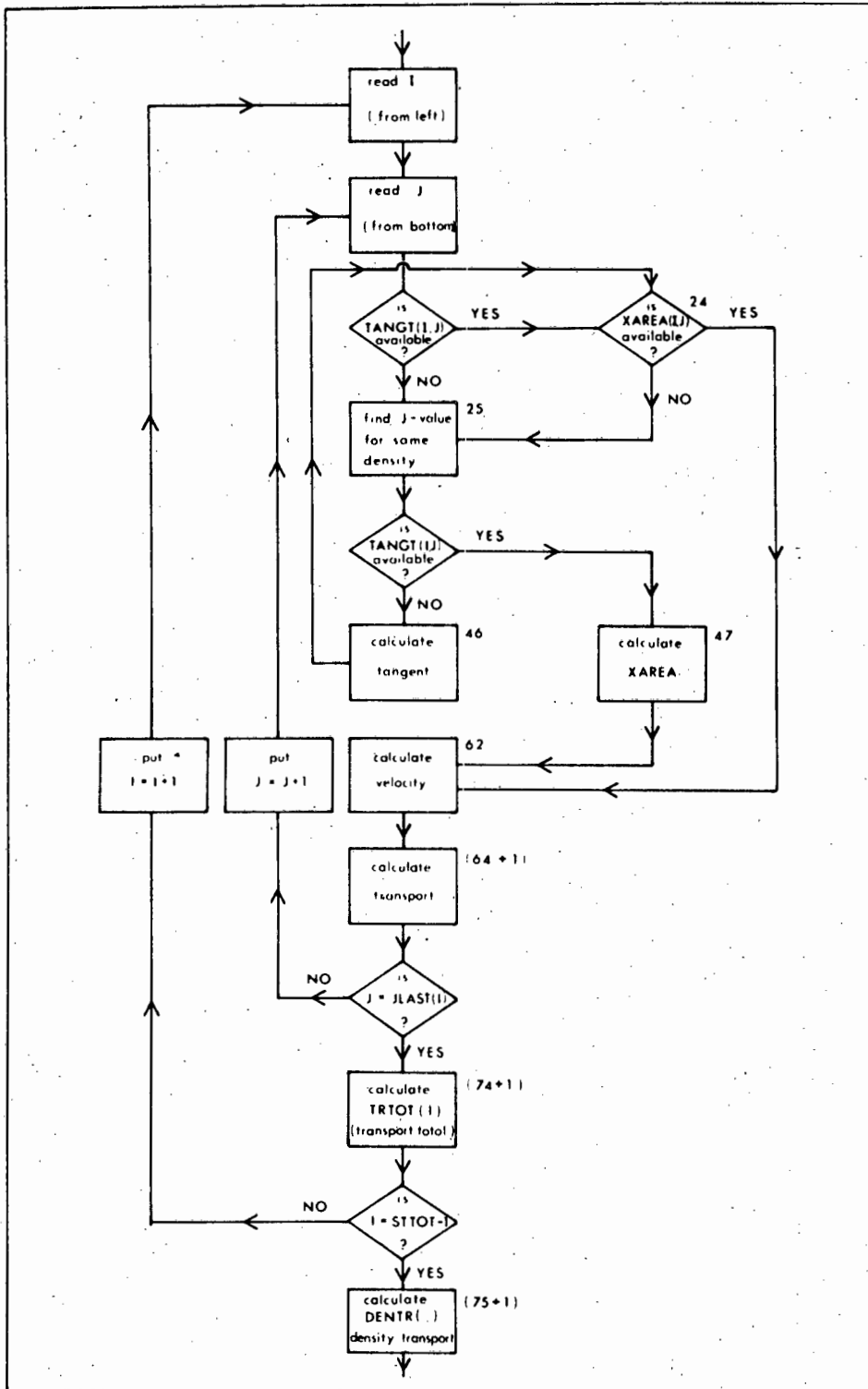


figure II.1

Simplified flow diagram for the core of the computer program for calculating water velocity.

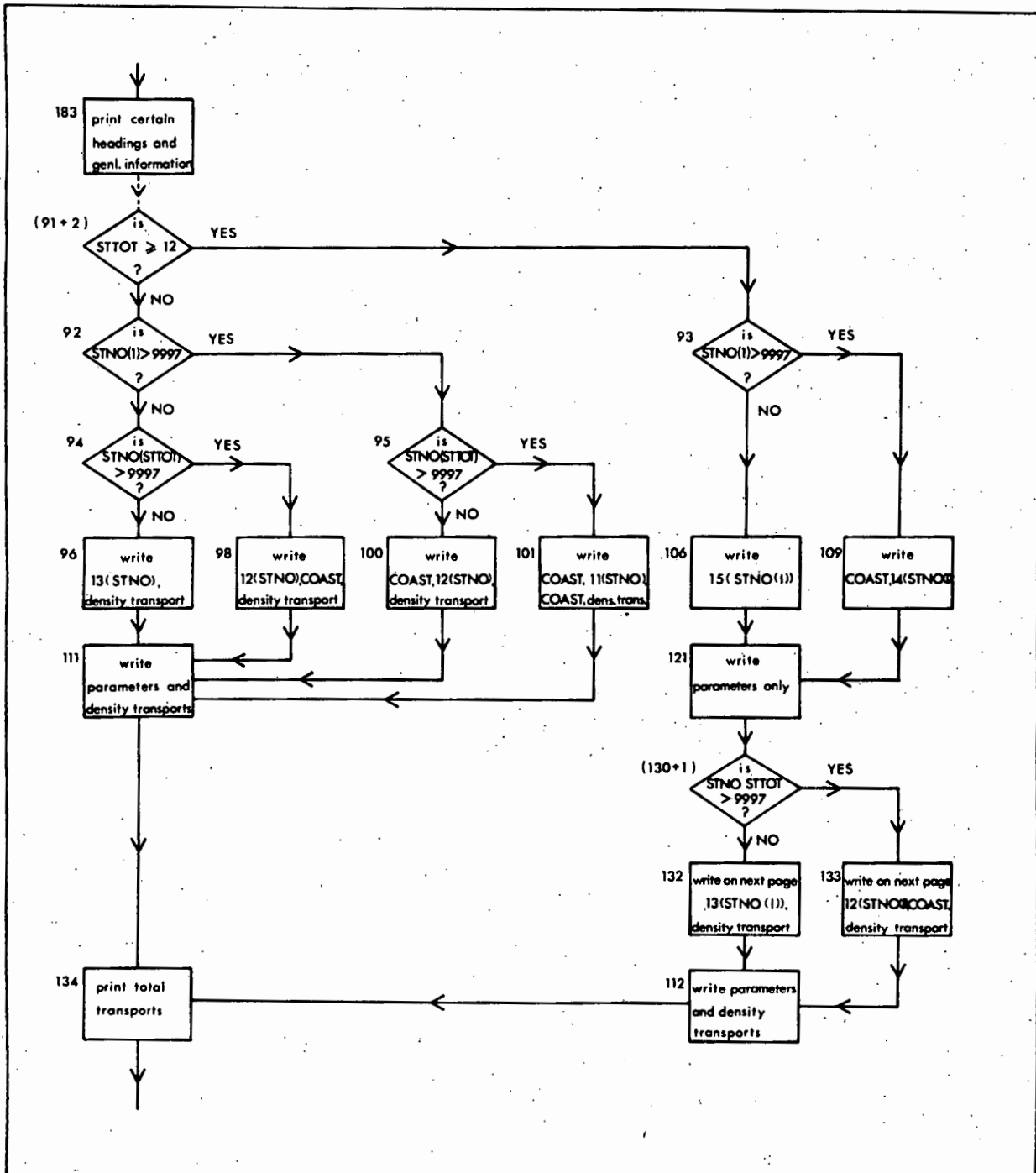


figure II.2

Simplified flow diagram for the printout of the computer program for calculating water velocity.

// JOB 0004 0006

0J01

// FOR

*IOCS(2501 READER, 1403 PRINTER, DISK)

*ONE WORD INTEGERS

C THIS PROGRAM CALCULATES THE VELOCITY AND TRANSPORT OF WATER
 C AT CERTAIN DENSITY LEVELS OF AN OCEANOGRAPHIC SECTION AND
 C FINDS THE SUM OF THE TRANSPORTS BETWEEN TWO ADJACENT
 C STATIONS, BETWEEN TWO ADJACENT DENSITY LEVELS AS WELL AS FOR
 C THE WHOLE SECTION

C TYPE STATEMENTS FOR ALL PARAMETERS

1 INTEGER YEAR, I, STNO(30), STTOT, JLAST(30), J,
 1MILES(30), N, DEPTH(30,40), L, M, Q, S, T, LL, LM, LN,
 1ML,MM, MN, ARRAY(30),ERRAY(30),JJ,II,JI,JK,QQ,IL,IZ

REAL G, DTRHO,PI, K, PHI(30),DENS(30,40), TANGT(30,40),
 1XAREA(30,40), TAN(40), VELOC(30,40), X, Y, Z, A, B, TRAN,
 1TRANS(30,40), TRTOT(30), RHO(40), DENTR(40), ARRY(15),
 1ERRY(30), AVDEN, AREA, SHIP(3), MONTH(3),
 1SECTN, COAST(2), C, IDENO(3), LDENT

DEFINE FILE 1(1200,2,U,II), 3(1200,2,U,II),
 1 4(1200,2,U,II), 5(1200,2,U,II)

EQUIVALENCE (VELOC(1),TANGT(1)),(TRANS(1),XAREA(1))

C PUT ALL ELEMENTS OF ALL ARRAYS EQUAL TO ZERO

DATA STNO,JLAST,MILES,DEPTH,ARRAY,ERRAY /1350*0/
 DATA PHI,DENS,TANGT,TAN,TRTOT,RHO,DENTR,TRANS,ARRY,ERRY,
 1SHIP,MONTH,COAST /3833*0.0/

C INITIALIZE CERTAIN ARRAYS AND INITIALIZE AND CALCULATE
 C CONSTANTS THAT HOLD THROUGHOUT THE PROGRAM

DATA G,DTRHO,PI,COAST /9.80665,0.20,3.141592,'COAS','T'/
 WRITE (1'1) TANGT
 WRITE (5'1) TRANS
 WRITE (4'1) VELOC
 WRITE (3'1) XAREA
 FIND(1'1)
 $K = G * DTRHO * 24 * 60 * 60 / (2 * 2 * PI)$

C READ INFORMATION THAT HOLDS THROUGHOUT A SECTION

READ (8,3) SECTN, SHIP, MONTH, YEAR, IDENO
 3 FORMAT (A4,3A4, 3A4, I5, 3A4)

C READ IN STATION NUMBERS AND PUT TOTAL NUMBER IN STTOT

```

DO 5 LL = 1,4
LM = 1+ (LL - 1)*10
LN = LL*10
READ (8,4)(STNO(I), I=LM,LN)
4 FORMAT (10(I8))
DO 5 I= LM,LN
IF (STNO(I)) 6,6,5
5 CONTINUE
6 STTOT=I-1

```

C READ LATITUDE (PHI) OF EACH STATION

```

S=STTOT-1
READ (8,7) (PHI(I), I=1,S)
7 FORMAT (16 F 5.4)

```

C READ SIGMA-T VALUES INTO DENS(I,J) AND PUT TOTAL NUMBER OF
C SIGMA-T LEVELS IN JLAST(I) FOR EACH RESPECTIVE STATION

```

DO 11 I= 1,STTOT
DO 9 ML = 1,4
MM = 2+ (ML-1)*13
MN = (ML*13) + 1
READ (8,8) (DENS(I,J), J= MM,MN)
8 FORMAT (13 F6.2)
DO 9 J = MM, MN
IF (DENS(I,J)) 10,10,9
9 CONTINUE
10 JLAST(I) = J-1
11 CONTINUE
READ (8,12) AVDEN
12 FORMAT(F6.2)
DO 13 I=1,STTOT
13 DENS(I,1) = AVDEN

```

C READ THE DISTANCES OF STATIONS FROM THE FIRST STATION IN
C NAUTICAL MILES

```

READ (8,14) (MILES(I), I=1,STTOT)
14 FORMAT (16 I 5)

```

C READ IN THE DEPTHS OF EACH SIGMA-T LEVEL AT EACH STATION

```

DO 15 I=1,STTOT
DEPTH (I,1) = 2280
N=JLAST(I)
15 READ (8,16)(DEPTH(I,J), J=2,N)
16 FORMAT(16I5)

```


C READ IN THE TANGENTS OF THE SLOPES OF THOSE SIGMA-T LEVELS
 C THAT CANNOT BE CALCULATED

```

17 READ (8,18) (ARRAY(3*JI-2), ARRAY(3*JI-1), ARRY(3*JI),
   1 JI=1,5)
18 FORMAT (5(2I3,F10.6))
DO 19 JI= 1,5
  I= ARRAY(3*JI - 2)
  J = ARRAY (3*JI -1)
  TANGT(I,J)= ARRY(3*JI)*1000
  IF (TANGT(I,J)) 19,20,19
19 CONTINUE
  GO TO 17
20 WRITE (1*1) TANGT
  FIND (3*1)
  
```

C READ IN THE CROSS-SECTIONAL AREA OF THOSE POSITIONS THAT
 C CANNOT BE CALCULATED

```

913 READ (8,21) (ERRAY(3*JK-2), ERRAY(3*JK-1), ERRY(3*JK),
   1 JK=1,6)
21 FORMAT (6(2I3,F6.3))
DO 22 JK=1,6
  I = ERRAY(3*JK-2)
  J = ERRAY(3*JK - 1)
  XAREA(I,J)= ERRY (3*JK)
  IF (XAREA(I,J)) 22,23,22
22 CONTINUE
  GO TO 913
23 WRITE (3*1) XAREA
  
```

C START CALCULATION TOWARDS VELOCITY AND TRANSPORT

C CHOOSE STATIONS FROM THE LEFT

```
DO 75 I=1,S
```

C CHOOSE DENSITY LEVELS FROM BOTTOM

```

N=JLAST(I)
DO 74 J=1,N
  READ (1*1) TANGT
  TGT = TANGT(I,J)
  READ (3*1) XAREA
  
```

C DECIDE WHETHER TANGT (I,J) IS AVAILABLE

```
IF (TANGT(I,J)) 24,25,24
```

C DECIDE WHETHER XAREA(I,J) IS AVAILABLE

```
24 IF (XAREA(I,J)) 62,25,62
```

C FIND J-VALUE FOR SAME DENSITY

```

25 IF (DENS(I,J) - DENS(I+1,J)) 27,26,36
26 L=J
   GO TO 45

27 IF (DENS(I,J) - DENS(I+1,J+1)) 28,32,31
28 IF (DENS(I,J) - DENS(I+1,J+2)) 29,33,31
29 IF (DENS(I,J) - DENS(I+1,J+3)) 30,34,31
30 IF (DENS(I,J) - DENS(I+1,J+4)) 31,35,31
31 STOP 31
32 L=J+1
   GO TO 45
33 L=J+2
   GO TO 45
34 L=J+3
   GO TO 45
35 L=J+4
   GO TO 45

36 IF (DENS(I,J) - DENS(I+1,J-1)) 40,41,37
37 IF (DENS(I,J) - DENS(I+1,J-2)) 40,42,38
38 IF (DENS(I,J) - DENS(I+1,J-3)) 40,43,39
39 IF (DENS(I,J) - DENS(I+1,J-4)) 40,44,40
40 STOP 40
41 L=J-1
   GO TO 45
42 L=J-2
   GO TO 45
43 L=J-3
   GO TO 45
44 L=J-4
   GO TO 45

```

C DECIDE WHETHER TANGT(I,J) IS AVAILABLE

```

45 IF (TGT) 47,46,47
46 TAN(L)= (DEPTH(I,J)-DEPTH(I+1,L))/((MILES(I+1)-MILES(I))
  1*1.852)
   TGT = TAN(L)
   GO TO 24

```

C CALCULATE CROSS-SECTIONAL AREAS XAREA(I,J) IN SQUARE
C KILOMETERS STARTING WITH J=1

```

47 FIND (3*1)
   IF (J-1) 49,50,48
48 IF (J-JLAST(I)) 53,57,49
49 STOP 49

```

(xxix)

```
50 A= (DEPTH(I,1)-DEPTH(I,2))*0.001
    B= (DEPTH(I+1,1)-DEPTH(I+1,2))*0.001
    Z= (MILES(I+1)-MILES(I))*1.852
    IF (A-B) 51,51,52
51 XAREA(I,1)= Z*(A+.5*ABS(B-A))
    GO TO 61
52 XAREA(I,1)= Z*(B+.5*ABS(B-A))
    GO TO 61

53 X= (DEPTH(I,J)-DEPTH(I,J+1))*0.001
    Y= (DEPTH(I+1,L)-DEPTH(I+1,L+1))*0.001
    Z= (MILES(I+1)-MILES(I))*1.852
    IF (X-Y) 54,55,54
54 XAREA(I,J) = Z*(Y + ABS(X-Y)*0.5)
    GO TO 61
55 XAREA(I,J)= Y*Z
    GO TO 61
56 XAREA(I,J) = Z*(Y - ABS(X-Y)*0.5)
    GO TO 61

57 C = (DEPTH(I,N)-DEPTH(I+1,L))*0.001
    IF (C) 58,59,60
58 XAREA(I,J) = (0.5*ABS(C)+(DEPTH(I,N)*0.001))*Z
    GO TO 61
59 XAREA(I,J) = DEPTH(I,N)*0.001*Z
    GO TO 61
60 XAREA(I,J) = (0.5*ABS(C)+(DEPTH(I,L)*0.001))*Z
61 WRITE (3,1) XAREA
```

C CALCULATE VELOCITY VELCC(I,J)

```
62 TDEN1 = DENS(I,J)/1000.0 + 1.0
    TDEN2 = DENS(I,1)/1000.0 + 1.0
    READ (4,1) VELOC
    VELOC(I,J) = K*TGT/ (SIN(PHI(I))*(TDEN1+TDEN2)*500000.0)
    IF (J-1) 64,64,63
63 VELOC(I,J) = VELOC(I,J) + VELCC(I,J-1)
64 WRITE (4,1) VELOC
```

C CALCULATE TRANSPORT TRANS(I,J)

```
    IF (J-1) 65,66,67
65 STOP 65
66 GO TO 74
67 IZ=J-1
    AREA = XAREA(I,J-1)
    IL=0
    GO TO 69
68 IZ=J
```

(xxx)

```
      READ (3*1) XAREA
      AREA = XAREA(I,J)
      IL=1
69  TRAN=(VELOC(I,IZ)+VELOC(I,J))*0.5*AREA
      READ (5*1) TRANS
      TRANS(I,IZ)=TRAN
      WRITE(5,70) TRANS(I,IZ), I, IZ
70  FORMAT(1H , F6.2, ' SV ', 2I3)
      WRITE (5*1) TRANS
      N=JLAST(I)
      IF(IL-1) 72,74,71
71  STOP 71
72  IF (N-J) 73,68,74
73  STOP 73
74  CONTINUE
```

C CALCULATE TOTAL TRANSPORT BETWEEN STATIONS WHERE TRTOT(I)
C WILL DENOTE TRANSPORT TO THE RIGHT OF STATION I

```
      TRTOT(I)=0.0
      N=JLAST(I)
      DO 75 J=1,N
75  TRTOT(I)= TRTOT(I) + TRANS(I,J)
```

C CALCULATE TRANSPORT FOR DIFFERENT DENSITY LAYERS DENTR(M)

C MAKE A LIST OF POSSIBLE SIGMA-T VALUES RHO(M)

```
      READ (8,76) (RHO(M), M=1,35)
76  FORMAT (13 F6.2)
```

C READ IN TRANSPORTS INTO CORRECT DENSITY GROUP

```
      LDENT = 0.0
      DO 80 I=1, S
      N=JLAST(I)
      LDENT = LDENT + TRANS(I,1)
      DO 80 J=2,N
      DO 77 M=1,35
      IF (RHO(M)-DENS(I,J)) 77,78,79
77  CONTINUE
78  DENTR(M) = DENTR(M) + TRANS(I,J)
      GO TO 80
79  STOP 79
80  CONTINUE
      DO 182 M=1,35
      IF (DENS(I,1)-RHO(M)-0.20) 181,180,182
180  DENTR(M)=LDENT
      GO TO 183
181  DENTR(M+1)=LDENT
      RHO(M+1) = DENS(I,1)
      GO TO 183
182  CONTINUE
```

(xxxi)

C PRINT CERTAIN HEADINGS AND GENERAL INFORMATION

```
183 WRITE (5,81) SECTN
81 FORMAT (1H1, 'SECTION ', A4)
   WRITE (5,82)
82 FORMAT (1H , 13(' '))
   WRITE (5,83) SHIP, IDENO, MONTH, YEAR
83 FORMAT (1H0, 3A4, 3A4, 3A4, 15)
   WRITE (5,84)
84 FORMAT (1H0)
```

C ARRANGE RESULTS IN NATURAL ORDER

C TO GIVE M A VALUE SUCH THAT RHO(M) IS THE SMALLEST DENSITY
C ENCOUNTERED IN A SECTION

```
      DO 85 M=1,35
      DO 85 I=1,STTOT
      N=JLAST(I)
      IF (RHO(M) - DENS(I,N)) 85,86,87
85 CONTINUE
86 GO TO 88
87 STOP 87
```

C SELECT LARGEST JLAST(I)

```
88 QQ=JLAST(1)
   DO 91 I=1,S
   IF (QQ-JLAST(I+1)) 89,90,90
89 QQ=JLAST(I+1)
   GO TO 91
90 QQ=QQ
91 CONTINUE
```

C TO CHANGE AROUND ORDER OF J IN EACH STATION

```
      JJ = QQ-Q+1
```

C PRINT ADDITIONAL HEADINGS AND GENERAL INFORMATION ACCORDING
C TO THE NUMBER OF STATIONS IN THE SECTION

C DECIDE WHETHER MORE THAN ONE PRINTING PAGE IS NEEDED

```
      IF (STTOT-12) 92,93,93
```

C DECIDE IF THE SECTION INCLUDES ANY COASTS

```
92 IF (STNO(1) - 9997) 94,94,95
93 IF (STNO(1) - 9997) 106,94,109
94 IF (STNO(STTOT) - 9997) 96,96,98
95 IF (STNO(STTOT)-9997) 100,100,101
```

C PRINT HEADINGS ACCORDING TO TYPE OF SECTION

```

96 WRITE (5,97) (STNO(I), I=1,STTOT)
97 FORMAT (1H0, 13(I8))
  WRITE (5,105)
  GO TO 111

```

```

98 WRITE (5,99) (STNO(I), I=1,S)
99 FORMAT (1H0, 12(I8))
  WRITE (5,104) (COAST(I), I=1,2)
  WRITE (5,105)
  GO TO 111

```

```

100 WRITE(5,102)(COAST(I),I=1,2)
  WRITE(5,110)(STNO(I),I=2,S)
  WRITE (5,105)
  GO TO 111

```

```

101 WRITE (5,102) (COAST(I), I=1,2)
102 FORMAT (1H0, 3X, 2A4)
  WRITE (5,103) (STNO(I), I=2,S)
103 FORMAT (1H+, 8X, 11(I8))
  WRITE (5,104) (COAST(I), I=1,2)
104 FORMAT (1H+, 50X, 2A4)
  WRITE (5,105)
105 FORMAT (1H+, 104X, 'TOTAL TRANSPORT'//
1      1H , 90('-'), 14X, 'PER DENSITY' //
1      1H, 104X, 'LEVEL')
  GO TO 111

```

```

106 WRITE (5,107) (STNO(I), I=1,15)
107 FORMAT (1H0, 15(I8))
  WRITE (5,108)
108 FORMAT (1H ,120('-'))
  GO TO 121

```

```

109 WRITE(5,102) (COAST(I), I=1,2)
  WRITE(5,110)(STNO(I),I=2,S)
110 FORMAT (1H+, 8X, 14(I8))
  WRITE (5,108)
  GO TO 121

```

C PRINT REQUIRED PARAMETERS IN NATURAL ORDER ACCORDING TO THE C TYPE OF SECTION

C WRITE PARAMETERS AND TOTAL TRANSPORT PER DENSITY LEVEL

```

111 T=1
  GO TO 113
112 T=16
113 M=M-1
  DO 120 Q=1,CQ
    M=M+1
    JJ=CQ-Q+1

```

(xxxiii)

```
      WRITE (5,114)
114  FORMAT (1H0)
      WRITE (5,115) (VELOC(I,JJ), I=T,S)
115  FORMAT (1H0, 13(F5.2, 'M/S'))

      WRITE (5,116) (TRANS(I,JJ), I=T,S)
116  FORMAT(1H0, 13(F6.2, 'SV'))
      WRITE (5,117) DENTR(M)
117  FORMAT (1H+, 104X, F6.2, 'SV')

      WRITE (5,118) (DENS(I,JJ), I=T,S)
118  FORMAT (1H0, 13(F7.2, 1X))
      WRITE (5,119) RHO(M)
119  FORMAT (1H+, 104X, F6.2)
120  CONTINUE
      GO TO 134
```

C WRITE PARAMETERS ONLY

```
121  DO 126 Q=1,QQ
      JJ = QQ-Q+1

      WRITE (5,122)
122  FORMAT (1H0)
      WRITE (5,123) (VELOC(I,JJ), I=1,15)
123  FORMAT (1H0, 15(F5.2, 'M/S'))

      WRITE (5,124) (TRANS(I,JJ), I=1,15)
124  FORMAT (1H0, 15(F6.2, 'SV'))

      WRITE (5,125) (DENS(I,JJ), I=1,15)
125  FORMAT (1H0, 15(F7.2, 1X))
126  CONTINUE
      WRITE (5,127)
127  FORMAT (1H , 120(' - '))
      WRITE (5,128)
128  FORMAT (1H0)
      WRITE (5,129) (TRTOT(I), I=1,15)
129  FORMAT (1H , 15(F6.2, 'SV'))
      WRITE (5,130)
130  FORMAT (1H0, 10X, 'TOTAL TRANSPORT PER STATION')
```

C DECIDE WHETHER A COAST IS INCLUDED ON THE SECOND PAGE

```
      IF (STNO(STTOT)-9997) 132,131,133
131  STOP 131
```

(xxxiv)

C PRINT HEADINGS ACCORDING TO TYPE OF SECTION

```
132 WRITE (5,142)
    WRITE (5,97) (STNO(I), I=16,STTOT)
    WRITE (5,105)
    GO TO 112
```

```
133 WRITE (5,142)
    WRITE (5,99) (STNO(I), I=16,S)
    WRITE (5,104) (COAST(I),I=1,2)
    WRITE (5,105)
    GO TO 112
```

C PRINT TOTAL TRANSPORT ACCORDING TO TYPE OF SECTION

```
134 TOTTR=00.00
    DO 135 I=1,STTOT
135 TOTTR= TOTTR + TRTOT(I)
    WRITE (5,136)
136 FORMAT (1H0)
    WRITE (5,137)
137 FORMAT (1H0, 120(' '))
    WRITE (5,138) (TRTOT(I), I=T,S)
138 FORMAT (1H0, 11(F6.2, 'SV'))
    WRITE (5,139) TOTTR
139 FORMAT (1H+, 104X, F8.2, ' SV ')
    WRITE (5,140)
140 FORMAT (1H0, 10X, 'TOTAL TRANSPORT PER STATION', 67X,
    1 'TOTAL TRANSPORT')
```

C END OF PROGRAM

```
    WRITE (5,142)
142 FORMAT (1H1)
    CALL EXIT
    END
```

```
// DUP
*STORE      WS UA OJ01
// XEQ OJ01  2
*FILES(1,,0004),(5,,0004)
*FILES(3,,0006),(14,,0006)
```

0006

APPENDIX III

TABLE III

TABLE OF TOTAL VOLUME TRANSPORT BETWEEN STATIONS IN THE
SECTIONS A TO J, AS WELL AS TOTAL VOLUME TRANSPORT ACROSS
SECTIONS. TRANSPORT IS IN $10^6 \text{ m}^3/\text{s}$

stations	A1 - A2	A2 - A3	A3 - A4	A4 - A5	A5 - A6	A6 - A7
transport	24.64	13.20	-1.81	1.80	<u>-51.98</u>	7.88
stations	A7 - A8	A8 - A9	A9 - A10	A10 - A11	A11 - A12	A12 - A13
transport	-5.66	-21.76	6.91	-6.22	3.45	6.82
stations	A13 - A14	A14 - A15	A15 - A16	A16 - A17	A17 - A18	A18 - A19
transport	5.21	6.30	-18.01	4.17	3.82	-12.38
stations	A19 - A20	A20 - A21	A21 - A22	A22 - A23	A23 - A24	A24 - A25
transport	-6.71	8.36	-5.77	-7.70	-4.18	-0.66

(section A : total transport -50.28)

stations	B1 - B2	B2 - B3	B3 - B4	B4 - B5	B5 - B6	B6 - B7
transport	2.30	3.16	<u>-13.00</u>	<u>13.13</u>	-11.00	-9.75

(section B : total transport -15.14)

stations	C1 - C2	C2 - C3	C3 - C4	C4 - C5	C5 - C6	C6 - C7
transport	<u>54.50</u>	<u>-74.24</u>	13.76	<u>38.09</u>	<u>-40.48</u>	<u>46.65</u>

stations C7 - coast

transport 9.98

(section C : total transport 46.27)

stations	coast - D1	D1 - D2	D2 - D3	D3 - D4	D4 - D5
transport	-0.56	3.24	15.85	4.69	-13.99

(section D : total transport 9.23)

2

TABLE III (continued)

stations	coast-E1	E1 - E2	E2 - E3	E3 - E4	E4 - E5	E5 - E6
transport	-1.49	-12.10	15.36	-1.61	-4.21	18.21

stations	E6 - E7	E7 - E8	E8 - E9

transport	-1.15	1.58	-1.64

(section E : total transport 12.93)

stations	coast-F1	F1 - F2	F2 - F3	F3 - F4	F4 - F5	F5 - F6
transport	18.88	20.65	20.19	40.86	-4.18	0.19

stations	F6 - F7	F7 - F8	F8 - F9	F9 - F10	F10 - F11	F11 - F12

transport	-41.47	15.00	-3.50	-22.65	-14.40	-2.92

(section F : total transport 26.76)

stations	coast-G1	G1 - G2	G2 - G3	G3 - G4	G4-coast

transport	-9.04	-10.57	46.13	11.94	4.36

(section G : total transport 42.82)

stations	coast-H1	H1 - H2	H2 - H3	H3 - H4	H4 - H5	H5 - H6

transport	-5.47	-14.92	-16.44	22.34	3.42	-8.64

stations	H6-coast

transport	-9.40

(section H : total transport 29.10)

stations	coast-I1	I1 - I2	I2 - I3	I3 - I4	I4 - I5	I5 - I6

transport	0.11	1.67	-17.16	-1.58	-9.97	-6.19

stations	I6 - I7	I7 - I8	I8 - I9	I9 - coast

transport	8.55	38.94	-3.54	-10.60

(section I : total transport 0.21)

TABLE III (continued)

```
stations. coast-J1 J1 - J2 J2 - J3 J3 - J4 J4 - J5 J5 - J6
transport -1.17 -0.68 -8.08 -17.01 -28.72 21.34
stations J6 - J7 J7 - J8 J8 - J9
transport -30.98 19.34 -9.88
```

(section J : total transport -55,85)

(xli)

APPENDIX IV

This appendix consists of tables of oceanographic stations as used for various purposes. These are:

TABLE IV.1

A list of all stations used in the construction of the σ_t surface diagrams. (fig. 5.1 - 5.39)

TABLE IV.2

A list of stations used in constructing the vertical sections (fig. 5.40 - 5.78), giving the original station number and the number for use in the vertical sections. See also fig. 4.18.

TABLE IV.3

A list of station pairs used in relating water velocity to depth by the geostrophic method (see fig. 4.17), as well as station pairs used in determining the reference level by Defant's method (see fig. 4.16).

TABLE IV.4

A list of oceanographic stations used in constructing the T/S scatter diagram for the South West Indian Ocean (fig. 4.6).

TABLE IV.5

A list of oceanographic stations used in constructing a T/S and T/O₂ scatter diagram for the Mozambique Channel (fig. 4.12).

TABLE IV.6

This table indicates how stations in table IV.4 were divided into groups according to their characteristic curves to represent the water characteristics of certain geographical areas (fig. 4.7 - 4.11).

Only the main part of ships' names has been used throughout. Wherever the three last digits of the N.O.D.C. reference identity number are missing it indicates that no such number exists and/or that data was obtained from the cruise reports. Station numbers are those of the original cruise reports, 2381-93 meaning that stations 2381 through 2393 were used.

TABLE IV.1

LIST OF ALL OCEANOGRAPHIC STATIONS USED IN CONSTRUCTING SIGMA-T-SURFACE DIAGRAMS

ship	NODC ref.id.no. of cruise	time (month/ year)	station numbers
Meteor	06004	3/1926	133-4
Meteor	06007	1/1965	148-57, 160-6, 168-75
Möwe	06043	2/1913	80, 86, 90-1
Planet	06049	4/1906	56, 60
Planet	06049	5/1906	82, 98
Canepa	08692	11/1957	242, 248
Dana	26003	12/1929	3928, 3938, 3944
Dana	26009	1/1930	3946, 3948, 3953, 3956, 3959-60, 3962, 3964-7
Galathea	26014	1/1951	178, 180-1, 184-6
Galathea	26014	2/1951	191, 197-8, 200, 216-8
Galathea	26014	3/1951	228-30, 232, 236, 240, 262-4
Argo	31181	12/1960	IV 2, IV 5, IV 9
Argo	31184	11/1962	109-11
Argo	31184	3/1963	31-8, 42
Argo	31184	4/1963	48-50
Atlantis	31197	10/1963	164
Atlantis	31197	11/1963	211-30

TABLE IV.1 (continued)

ship	NODC ref.id.no. of cruise	time (month/ year)	stations used
Atlantis	31247	3/1965	656-72
Atlantis	31247	5/1965	673-4, 677, 688-99, 702-18
Anton Bruun	31577	2/1964	293-4, 296-300
Anton Bruun	31577	3/1964	301-7
Anton Bruun	31577	4/1964	416, 418-21
Anton Bruun	31577	5/1964	337-40
Vema	31834	4/1958	48-9
Vema	31834	5/1958	50, 54-6
Vema	31834	12/1959	41-2
Vema	31834	1/1960	43-4, 46-62
Anton Bruun	31918	11/1964	416, 418-21
Giraud	35006	10/1957	14
Giraud	35006	11/1957	29-65
Laperouse	35579	5/1955	1-2
Laperouse	35579	1/1956	1-8
Charcot	35712	4/1950	37-8
various	35771	1/1958	-
various	35771	2/1958	-

TABLE IV.1 (continued)

ship	NODC ref.id.no. of cruise	time (month/ year)	stations used
Norsel	35842	11/1955	5-11
Laperouse	35871	2/1959	10-22
Laperouse	35902	3/1957	3-9
Laperouse	35	11/1959	26-27
Alidade	35	11/1952	1-15
Alidade	35	12/1952	16-33
Kristna	41002	1/1963	113-4
Umitaka Maru	49	12/1956	I 8-16, I 18-21
Umitaka Maru	49	3/1957	I 22
Vauban	55002	11/1966	60-6, 68-70
Vauban	55002	12/1966	71
Vauban	55002	1/1967	72-4
Vauban	55002	2/1967	76-84, 86-7
Vauban	55002	3/1967	89-91
Vauban	55002	4/1967	92-4
Vauban	55002	12/1967	147
Vauban	55004	1/1968	151
Vauban	55004	3/1968	152-69
Lacerda	68001	4/1964	1-35, 20A

TABLE IV.1 (continued)

ship	NODC ref.id.no. of cruise	time (month/ year)	station numbers
Lacerda	68001	5/1964	37-44
Mabahiss	74005	12/1933	102
Mabahiss	74005	1/1934	116-8, 120
Mabahiss	74005	2/1934	127, A 131, B 131, C 131
Discovery	74030	3/1964	5274, 5278, 5280, 5282-6, 5288-9, 5291-2, 5294-6, 5297-303, 5305-10
Discovery	74030	4/1964	5310-1, 5313-4, 5316-22, 5324-9, 5331, 5333-4, 5336-52, 5354-9
Discovery	74035	11/1926	D 107
Discovery	74038	4/1932	846-9
Discovery	74039	5/1934	1370, 1373
Discovery	74039	3/1935	1553, 1556, 1557
Discovery	74039	4/1935	1558, 1565-70, 1572, 1574-5, 1557-9 1581, 1583
Discovery	74040	11/1935	1610-8
Discovery	74040	4/1936	1754, 1756
Discovery	74040	5/1936	1758, 1760, 1763
Discovery	74040	11/1937	2086-8
Discovery	74040	11/1938	2482-3
Discovery	74040	12/1938	2522-3
Discovery	74040	2/1939	2573-6
Discovery	74040	3/1939	2623-5

TABLE IV.1 (continued)

ship	NODC ref.id.no. of cruise	time (month/ year)	station numbers
Discovery	74040	4/1939	2348
Discovery	74040	11/1939	2484
Discovery	74040	12/1939	2521
Scoresby	74041	3/1936	2921-2
Albatross	77418	4/1948	232
Ob	90004	3/1957	250, 254-7, 267-71
Vityaz	90010	2/1960	4633, 4635, 4638A-D, 4639, 4645-6, 4648-51, 4654-5
Vityaz	90010	3/1960	4656-73, 4675-7, 4686, 4688, 4690, 4694-702
Vityaz	90010	4/1960	4731
Ob	90029	3/1959	495-9
Ob	90029	12/1959	504-6
Vityaz	90032	12/1960	4887-94
Ob	90057	12/1960	523, 529
Vorobyev	90410	5/1965	1630, 1632
Ob	90830	5/1956	126-32, 135-8
Vityaz	90864	12/1964	5321, 5323-4
Natal	91040	4/1962	1-15, 25-7
Africana	91041	6/1962	1881-2
Natal	91044	1/1963	144-54, 167-9
Africana	91049	4/1963	A 2390-1, A 2393-2400

TABLE IV.1 (continued)

ship	NODC ref.id.no. of cruise	time (month/ year)	station numbers
Teresa	91051	11/1961	-
Natal	91901	2/1958	1-4, 7
Natal	91901	5/1958	21
Natal	91901	8/1958	63
Africana	91936	3/1964	SA 7-13, SA 18
Davie	91	3/1969	1158-213

TABLE IV.2

LIST OF STATIONS USED IN THE CONSTRUCTION OF VERTICAL SECTIONS

section name	ship	NODC ref.id.no. of cruise	time (month/ year)	station numbers	section station numbers
A	Discovery	74030	3,4/1964	5288-9,5291-2, 5294-5303, 5305-11, 5313-4,5316-7	A1 -A25
B	Vityaz	90010	3/1960	4660-4666	B7 -B1
C	Laperouse	35902	3/1957	3-9	C1 -C7
D	Vityaz	90010	2,3/1960	4656-4660	D1 -D5
E	Atlantis	31197	11/1963	213-221	E9 -E1
F	Atlantis	31247	4/1965	661-672	F12-F1
G	Alidade	35	11/1952	5-6	G1 -G2
	Giraud	35006	11/1957	52-53	G3 -G4
H	Giraud	35006	11/1957	37-42	H1 -H6
I	Atlantis	31197	11/1963	222-230	I9 -I1
J	Natal	91040	4/1962	1-9	J1 -J9

TABLE IV.3

LIST OF STATION PAIRS USED FOR RELATING WATER VELOCITY TO DEPTH

pair number	ship	NODC ref.id.no. of cruise	time (month/ year)	station pairs used in geo- strophic method	in fig. 4.17	station pairs used in Defant method	in fig. 4.16
1	Atlantis	31197	11/1963	223-224	*	224-223	*
2	Natal	91040	4/1962	25-26	*	25-26	*
3	Natal	91044	1/1963	149-150	*	150-149	*
4	Natal	91044	1/1963	167-168	*	167-168	*
5	Atlantis	31197	11/1963	225-226	*	225-226	*
6	Laperouse	35	11/1959	31-30	*		
7	Natal	91044	1/1963	168-169		168-169	
8	Laperouse	35	11/1959	29-30			
9	Atlantis	31197	11/1963	222-223		222-223	*
10	Laperouse	35	11/1959	35-34			
11	Discovery	74030	4/1964	5344-5346		5344-5346	
12	Laperouse	35871	10/1959	15-16			

TABLE IV.4

LIST OF OCEANOGRAPHIC STATIONS USED IN GENERAL T/S SCATTER
DIAGRAM (FIG. 4.6)

ship	NODC ref.id.no. of cruise	time (month/ year)	stations used
Meteor	06004	3/1926	132,133,153
Gauss	06220	12/1903	42
Argo	31184	5,8,11/1963	102,22,109
Atlantis	31197	11/1963	220,230
Atlantis	31247	3/1965	659
Vema	31834	4,5/1958	40,42,45,48,51,52,53,57,58
Giraud	35006	11/1957	48, 64
Laperouse	35579	3/1956	13
Norsel	35842	11/1955	10
Laperouse	35871	2/1959	11
Laperouse	35902	3/1957	4, 6, 9
Alidade	35	11,12/1952	8, 21
Umitaka Maru	49	12/1956,3/1957	I.15, I.20, I.22
Lacerda	68001	4/1964	16
Discovery	74030	3,4/1964	5285,5295,5313,5324,5327, 5334,5344,5355
Discovery	74038	4/1932	850
Discovery	74039	4/1935	1558,1560,1566,1570,1572, 1577,1581,1582

TABLE IV.4 (continued)

ship	NODC ref.id.no. of cruise	time (month/ year)	stations used
Discovery	74040	11/1935	1609,1610,1613,1614,1615, 1617,1620,1752,1754,1756, 1758,2626,1616
Scoresby	74379	3/1950	1000
Challenger	74	1/1874	147, 148
Ob	90004	2/1957	272, 273, 275
Vityaz	90010	2,3/1960	4649, 4658, 4662
Vityaz	90864	12/1964	5319, 5323, 5324
Natal	91040	4/1962	10
Gilchrist	91042	1/1962	460
Africana	91049	4/1963	2391, 2395, 2397, 2399,2400
Africana	91856	4/1957	A, B
Natal	91901	2,3/1958	7, 10
Africana	91936	3/1964	2958

TABLE IV.5

LIST OF OCEANOGRAPHIC STATIONS USED IN T/S AND T/O₂ SCATTER
DIAGRAMS FOR MOZAMBIQUE CHANNEL (FIG.4.12)

ship	NODC ref.id.no. of cruise	time (month/ year)	stations used
Möwe	06	2/1913	80, 86, 90, 91
Dana	26009	1/1930	3953, 3956, 3959, 3960, 3962 3964
Atlantis	31197	11/1963	222-30
Giraud	35006	11/1957	29-65
Alidade	35	11,12/1962	1-33
Ambariaka	55	1-12/1963, 4	3-8
Lacerda	68001	4/1964	1-35
Discovery	74039	4/1933	1572, 1574, 1575, 1577, 1578
Vityaz	90010	3/1960	4671-3

TABLE IV.6

SUBDIVISION OF STATIONS FOR CHARACTERISTIC CURVES OF CERTAIN AREAS						
ship	time (month/ year)	station numbers for each T/S scatter diagram				
		fig.4.7	fig.4.8	fig.4.9	fig.4.10	fig.4.11
Meteor	3/1926	132	133			153
Gauss	12/1903		42			
Atlantis	11/1963			220,230		
Atlantis	3/1965					659
Vema	4,5/1958	45	48-9	40,42,- 51-3, 57-8		
Giraud	11/1957				48,64	
Laperouse	3/1956					13
Norsel	11/1955				10	
Laperouse	3/1957			6		4
Alidade	11,12/1952				8,21	
Umitaka Maru	12/1956, 3/1957			I.15, I.20	I.22	
Lacerda	4/1964				16	
Discovery	3,4/1964				5313, 5327, 5334	5285, 5295, 5344, 5355
Discovery	4/1932	850				