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Hydrography of the Andaman Sea During Late Winter*

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Distributions of temperature, salinity, density and dissolved oxygen during late winter in the Andaman Sea are presented by series of vertical sections and spatial distribution charts; study of the field of motion based on dynamic computations is also included. Surface temperature exceeds 28°C over most of the northern Andaman Sea. Surface salinity increases from 31·0‰ in the northern regions to 32·8‰ in the southern regions. Density distribution in the upper 50 m is primarily controlled by the salinity distribution. Below the sill depth (1300 m), the water mass is characterized by uniform values of temperature, salinity and dissolved oxygen. Geostrophic circulation in the upper layer indicates the formation of cells (100-200 km), and the upper layer dynamics seem to be governed by the fresh water discharge into the region.

THE Andaman Sea is one of the least explored regions in the Indian Ocean. Even during the International Indian Ocean Expedition (IIOE), this area has received very little attention compared to the regions like Somali basin, Arabian Sea, Equatorial Indian Ocean, etc. This is especially so during the south-west monsoon and the postmonsoon seasons.

There is practically no information on the oceanographic features in the Andaman Sea after the studies of Seymour Sewell[1]. Utilizing the data collected during IIOE, some aspects of the Oceanography of Andaman Sea have been published[2,3]. However, it may be mentioned that these investigations do not give comprehensive information on the distribution of parameters in the Andaman Sea.

There is considerable river run off into the Bay of Bengal and Andaman Sea and the surface layers are very much diluted by fresh waters. No attempt has so far been made to study the consequence of dilution and the influence of fresh water discharges on the surface circulation. Meteorologically, the Andaman Sea region has its importance since it is believed that most of the severe cyclones originate in this region. As Reihl[4] points out that the surface temperature is one of the determining factors for cyclogenesis, it would be of interest to study the distribution of surface temperature.

In this paper, study of the distribution of temperature, salinity, dissolved oxygen and density along with the flow patterns during late winter is presented.

Analysis of Data

The Andaman Sea is bordered by Burma, Thailand and North-west Coast of Sumatra, and the Andaman-Nicobar ridge on its west separates it from the Bay of Bengal. In this region, RV *Serrano* of USA has covered about 45 stations during February-March 1963 (Fig. 1). It may be noted that stations in section I (Fig. 1) have been covered during February while the rest of the stations are covered during March. The station location map shows a fairly good coverage northward of 10°N and hence the spatial distribution charts are limited to the northern Andaman Sea alone.

For each of the stations, curves are drawn showing temperature against depth, salinity and dissolved oxygen on the sheets showing σ_t as a function of temperature and salinity. Later these curves are smoothened and various informations necessary for constructing vertical and horizontal distribution charts of temperature, salinity, σ_t and dissolved oxygen are inferred. As there is practically no information in the circulation except those given in Atlases[5,6], a study of geostrophic circulation is also included. Also presented is a study of bottom water characteristics in this region.

Results

Figs. 2 to 4 show the vertical distributions of temperature, salinity and dissolved oxygen along the 3 zonal sections located approximately at 6°N, 11°N and 15°N respectively, and Figs. 5 and 6 show the same distributions along two meridional sections at 95°E and 97°30'E respectively. The easternmost section is located over the continental shelf and is almost parallel to the Burma coast. Fig. 7 shows the spatial distribution of the parameters at surface, 50 and 100 m.

Temperature distribution — At the surface, the temperature over most of the northern Andaman Sea is greater than 28°C and in some isolated pockets, it exceeds 29°C (Fig. 7A-i). In the north-western region, as well as in the southern region of the Andaman Sea (Fig. 2A), the temperatures are less than 28°C. Surface temperature during north-east monsoon season varies from 25·5°C at the head of the Bay of Bengal to more than 28·5°C in the Andaman Sea[7]. In the northern regions, at

*All data reported are available in the data files of the Data Centre of the Institute.

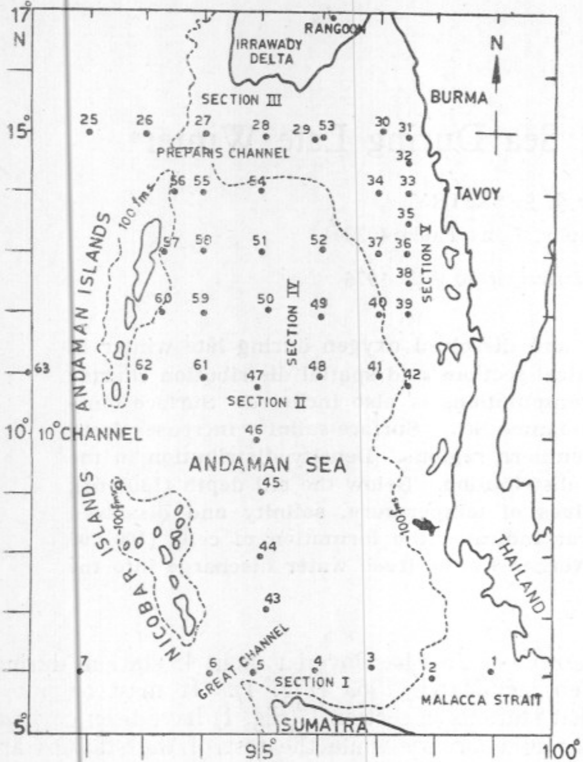

Fig. 1 — Station location map

station 26 (Fig. 4A) a temperature inversion has been observed. During winter, the temperature inversions seem to be a common feature in the northern Bay of Bengal[7].

The thickness of the surface layer over this region extends from 30 to 60 m. Below this layer a strong thermocline develops. Examination of Figs. 2A to 5A suggests that 13°C isothermal surface may be regarded as the bottom of the thermocline and it is located at depths between 120 and 200 m. Below the thermocline the temperature decreases monotonically with depth. In abyssal regions of Andaman Sea, below 1600 m (Figs. 3A and 5A), the temperature remains uniform (5°C). In the northernmost section, the bottom temperatures are generally less than 2°C.

The 50 m temperature distribution shows the temperature variation from less than 24°C to greater than 27°C (Fig. 7A-ii) while at 100 m, it varies from less than 16°C to greater than 24°C. At 100 m, strong horizontal gradients in temperature exist (Fig. 7A-iii).

Salinity distribution — Salinity distribution at the surface is shown in Fig. 7B-i. Salinity increases from less than 31·0‰ in the northern regions to more than 32·8‰ in the southern regions of the northern Andaman Sea. Very low salinities are obviously due to moderate river discharges during this part of the year. It may be noted that maximum river discharges coincide nearly with the times of maximum rainfall distribution in the Gangetic Plain and the Arakan hills and one need not be surprised to find fresher water in this region during the south-west monsoon and postmonsoon seasons. Low salinities in the region of Malacca Straits (Fig. 2B) are due to river runoff and precipitation during winter monsoon in those regions.

Below the surface, salinity increases rapidly and a strong halocline developes in the depth range 10 to 60 m all along this region (Figs. 2B to 6B). Below the halocline, salinity shows a gradual increase and a zone of salinity maximum is seen all along this region. The thickness of salinity maximum zone seem to vary from about 200 m to more than 600 m, maximum thickness occurring in the southern regions. Below this zone of salinity maximum, the salinity decreases gradually. Coinciding with the uniform temperature of 5°C below 1600 m, the salinity is more or less uniform (<34·9‰) in the abyssal regions whereas the bottom salinities in the northern regions (Fig. 4B) are less than 34·8‰.

Distribution of salinity at 50 m shows a variation from 33 to 34‰ (Fig. 7B-ii). Tongues of low and high salinity waters in the north-west and south-west regions respectively are observed and a pocket of low salinity water (<33·2‰) is seen in the east-central Andaman Sea. However, at 100 m, the salinity varies very little with its variations from 34·4 to 34·8‰ (Fig. 7B-iii).

Distribution of σ_t — At the surface, the σ_t varies from 19·2 to 20·8 (Fig. 7C-i). A comparison of distribution of temperature and salinity with those of σ_t shows that, in this region the distribution of σ_t is governed more by the distribution of salinity rather than temperature distribution.

Below the surface a strong mass discontinuity layer develops which envelops both the thermocline and halocline (Figs. 2C to 5C). The mass discontinuity layer thus extends over a greater depth range. The stability distribution is governed by temperature and salinity gradients, and as stability is one of the governing parameters to determine the extent of vertical mixing, the mass distribution suggests that the vertical mixing between the surface and sub-surface water masses is minimal. Zone of salinity maximum is located primarily between 26·8 and 27 σ_t surfaces.

Distribution of σ_t at 50 m (Fig. 7C-ii) shows its dependence both on temperature and salinity, whereas at 100 m, it appears to be mainly governed by the distribution of temperature alone (Fig. 7C-iii).

Distribution of oxygen — Figs. 7D-i, ii and iii show distribution of dissolved oxygen at surface, 50 and 100 m, while Figs. 2 to 6D show the same distribution along 5 vertical sections.

Dissolved oxygen is more or less uniform at the surface (4·6 ml/litre) while at 50 m it varies over a considerable range from 2·2 to 4·4 ml/litre and at 100 m, its range is considerably reduced from 0·4 to 1·6 ml/litre. Larger variations in the range of values at 50 and 100 m seem to be due to the convergences and divergences in the field of motion.

Below the surface layer, a strong oxycline is seen to coincide with the upper regions of thermocline, below which the oxygen minimum zone is observed. In the southern regions within the oxygen minimum zone dissolved oxygen is of the order of 1 ml/litre and the values of oxygen minimum progressively decreases northward to less than 0·25 ml/litre. In the abyssal regions dissolved

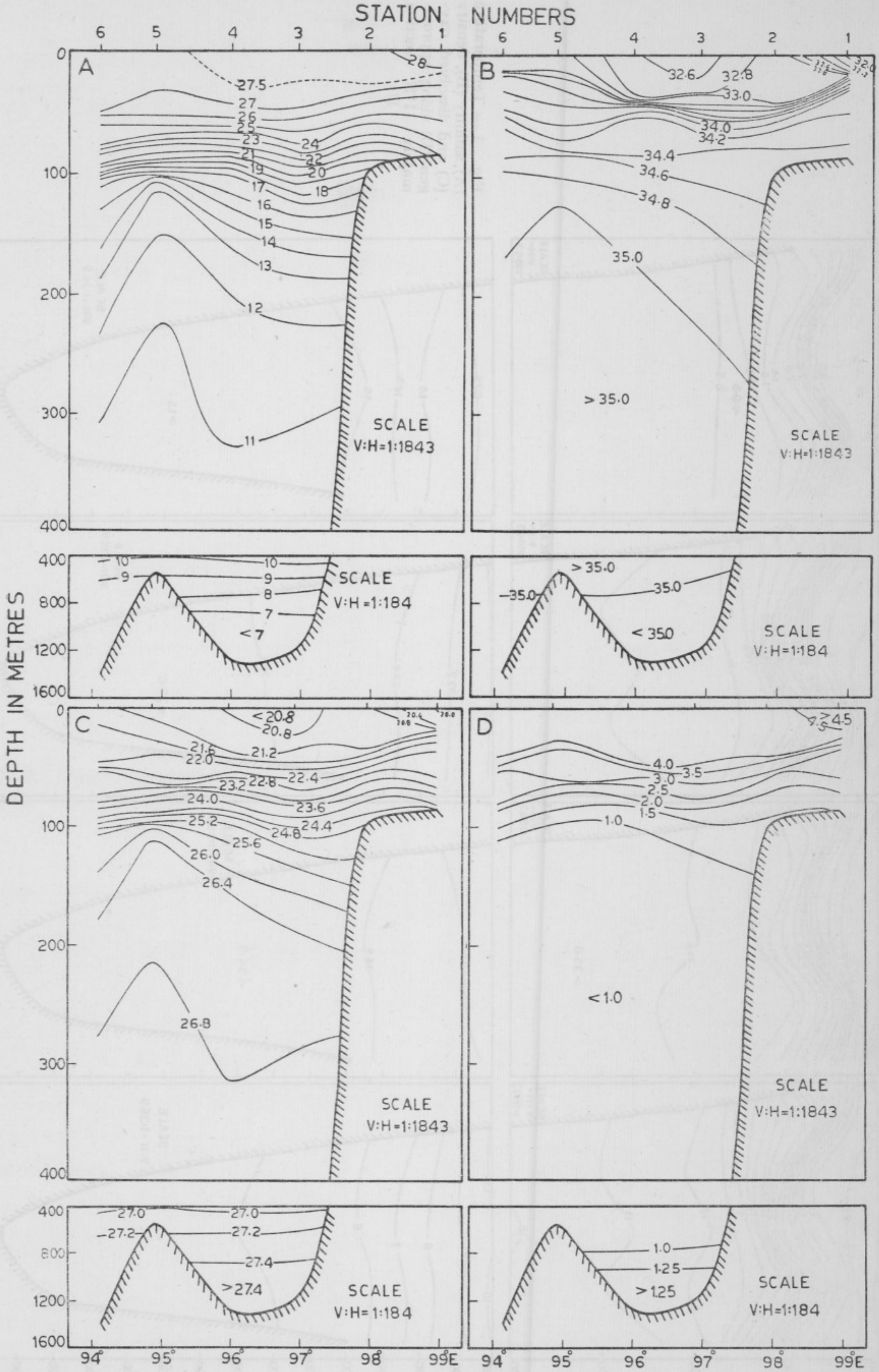

Fig. 2 — Temperature (A), salinity (B), density (C) and dissolved oxygen (D) along approximately 6°N (section I)

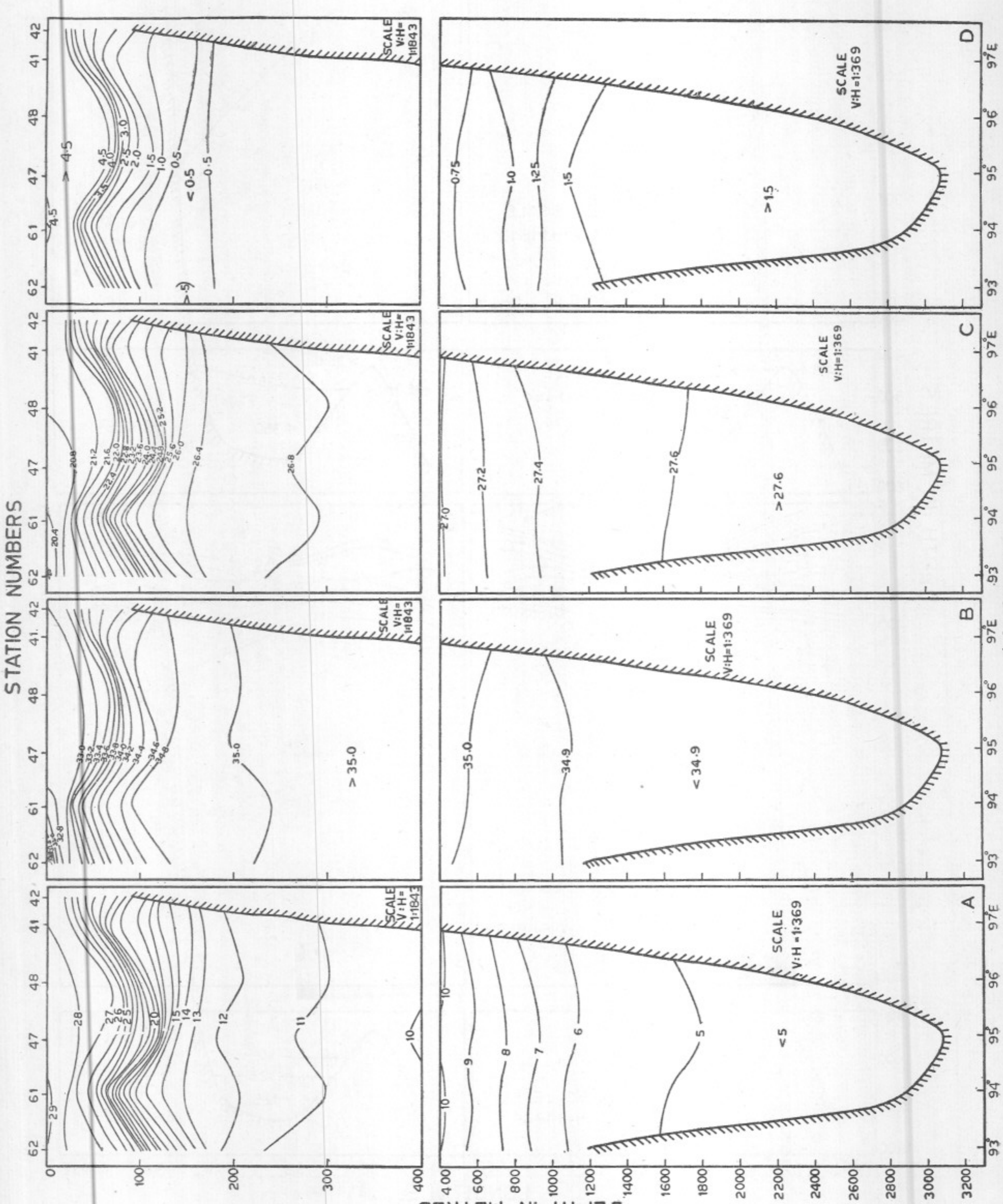

Fig. 3 — Temperature (A), salinity (B), density (C) and dissolved oxygen (D) along approximately 11°N (section II)

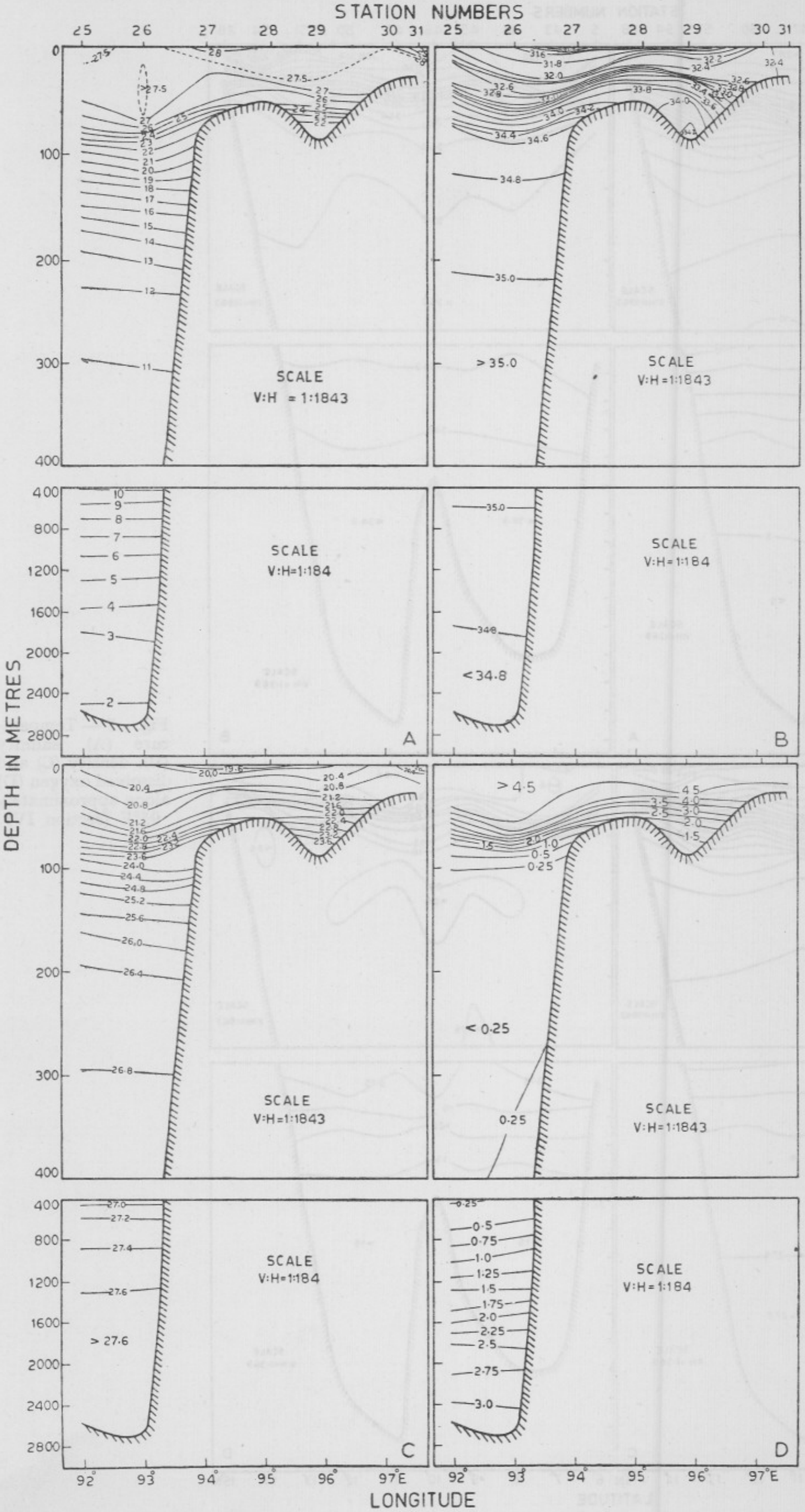

Fig. 4 — Temperature (A), salinity (B), density (C) and dissolved oxygen (D) along approximately 15°N (section III)

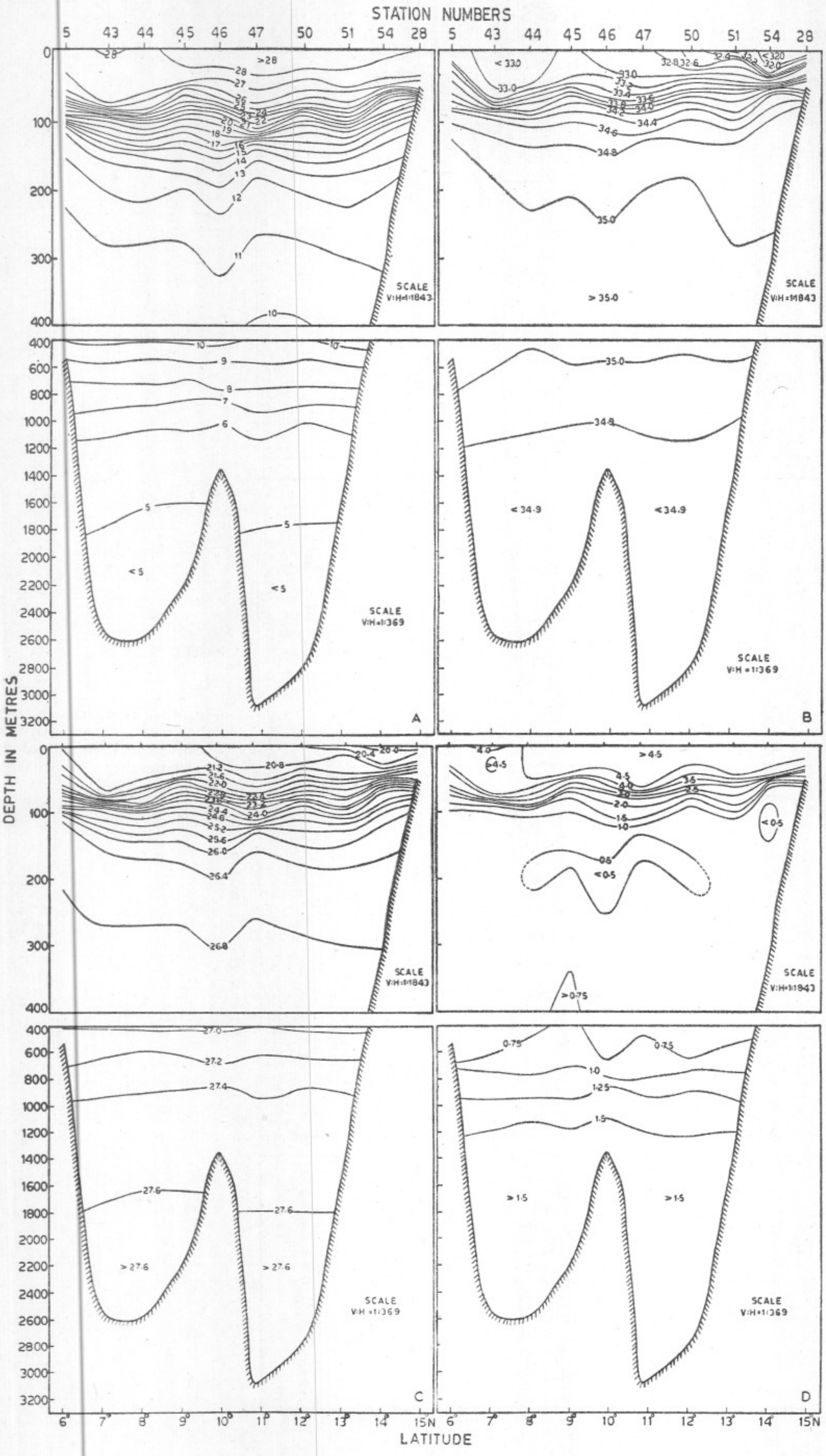

Fig. 5 — Temperature (A), salinity (B), density (C) and dissolved oxygen (D) along approximately 95°E (section IV)

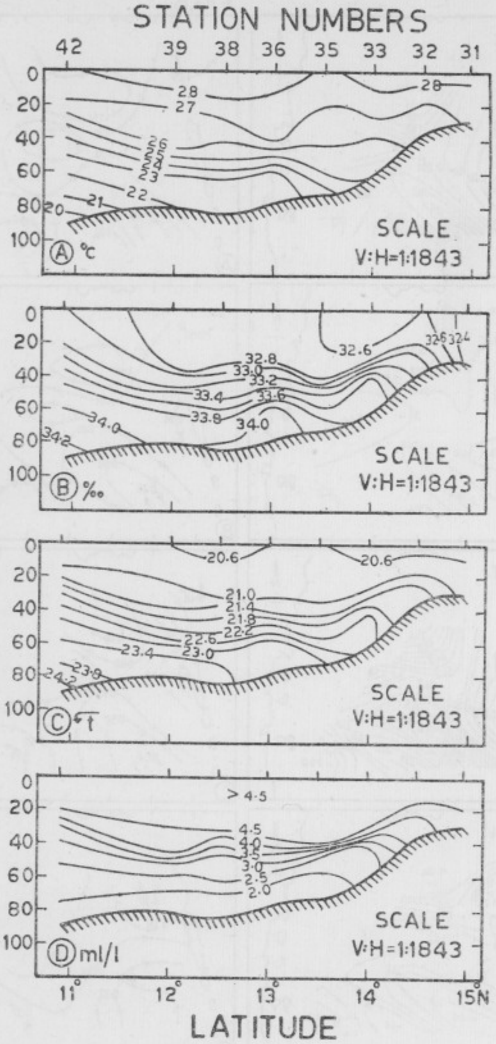

Fig. 6 — Distribution of (A) temperature, (B) salinity, (C) density and (D) dissolved oxygen along 97°30′ (section V)

oxygen is uniform and has values slightly more than 1·5 ml/litre. The bottom oxyty exceeds 3·0 ml/litre along section III.

Geostrophic circulation — Fig. 8 shows the dynamic topography of sea surface, 50, 100 and 200 db surfaces relative to 500 db level. Fig. 9 (A, B and C) shows geostrophic circulation across sections I, II and IV. Varadachari *et al.*[8] have considered 500 db level as the reference level, based on the method after Defant. Zaklinskii[9], while deriving the circulation patterns for the Indian Ocean, in general, considers a sloping surface as a reference level and for the region of our interest it is of the order of 500 m.

While a weak flow into the Andaman Sea at the surface and 50 m from the Bay of Bengal is found, the circulation pattern in the northern Andaman Sea shows an anticlockwise gyre in the south-western regions and a clockwise gyre in the central regions (Fig. 8, A and B). Off the Andaman east coast, the flow is weak at the surface. At 100 and 200 m, the flow is very week as it can be seen by the range of variations in dynamic topography at various levels (Fig. 8, C and D).

Across section I (Fig. 9A) a fairly strong southerly flow greater than 30 cm/sec at the surface into the Malacca Straits is observed. Further westward the flow is directed north and exceeds 40 cm/sec. In the western regions of this section, again a strong southerly flow sets in with speeds exceeding 55 cm/sec. This figure suggests a fairly strong current shear on both sides of northerly flow. Below a depth of 200 m, the flow is generally weak. The flow pattern across section II (Fig. 9B) shows a similar flow as that of across section I but with a slight shifting in the positions of north and south bands.

Fig. 9C gives the geostrophic circulation across section IV located from 9°N to 15°N. The zonal components of geostrophic circulation show strong shears both vertical and horizontal especially in upper 200 m. In the neighbourhood of Great Channel, a strong westerly current with its core speed near the surface exceeding 70 cm/sec is observed. This flow seems to be reinforced by a strong flow northward of Sumatra (Fig. 9A) as well as that coming from northern Andaman Sea. Below, about 200 m, the flow is easterly with a core speed of 3 cm/sec at 300 m. As can be seen from the figure in the upper 200 m the flow alternates in direction along this section. In the central regions, the flows seem to be relatively sluggish compared to either northern or southern portions of the section. The easterly current with core velocities greater than 20 cm/sec at stations 51 and 54 suggest the earlier reasoning of incursion of water from Bay of Bengal in the neighbourhood of Preparis Channel. The dynamic topography chart at surface (Fig. 8A) suggests the reinforcement of the flow by another current which originates near northern regions of Burma coast. The north-south components seen along with the dynamic topography charts suggest the formation of cyclonic cell around station 54.

Characteristics of deep and bottom water — In order to study deep and bottom water characteristics, depth-potential temperature and potential temperature-salinity characteristics at 2 stations in the Andaman Sea (Serrano stations 47 and 50) are presented in Fig. 10. The data at 2 stations in the Bay of Bengal [Vityaz stations 5232 (lat. 10°57′N, long. 91°41′E) and 5233 (lat. 13°01′N, long. 91°27′ E)] are also presented for comparative study. These plots suggest that the water column both in the Andaman Sea and the Bay of Bengal above 1300 m has the same characteristics. Below 1300 m, the potential temperature in the Andaman Sea is nearly uniform. Close to the bottom, it varies from 4·63° to 4·85°C. However, in the Bay of Bengal the potential temperature decreases with depth. For a better appreciation of variation in potential temperature in the Andaman Sea and the Bay of Bengal, the potential temperature of deep and bottom waters in these 2 regions are tabulated in Table 1. Similarly the salinity-potential temperature plots indicate a nearly uniform salinity (34·8‰) in the entire water column of Andaman

FIG.7

FIG.8

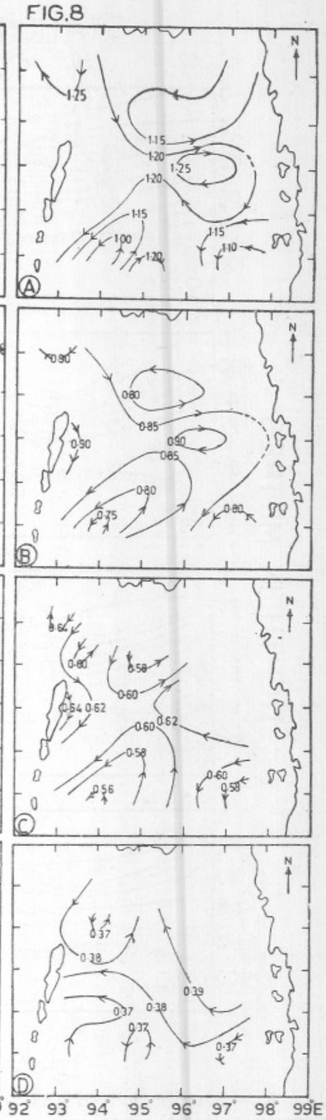

Fig. 7 — Distribution of (A) temperature, (B) salinity, (C) density and (D) dissolved oxygen at (i) surface, (ii) 50 m and (iii) 100 m

Fig. 8 — Dynamic topography of (A) sea surface, (B) 50 db surface, (C) 100 db surface and (D) 200 db surface relative to 500 db surface

Sea below 1300 m where as in the Bay of Bengal the bottom salinity decreases to 34·74‰. These features suggest that the maximum sill depth is at about 1300 m.

Discussion

Surface temperature over this region varies within the narrow limits. Over most of the region, it exceeds 28°C. Hickman[10] has suggested that the sea surface temperature must be more than 27°C as one of the main conditions for tropical cyclone formation.

The basic features of distribution of salinity (Figs. 4B and 7) is the development of fairly strong vertical and horizontal gradients in the near surface layer (0-100 m) in the region under investigation.

Distribution of σ_t at the surface is similar to that of salinity. Its vertical distribution shows a strongly stratified layer just below the surface homogeneous layer. Vertical transfer of any property is very much minimized across this layer. The strong oxycline coincides the highly stratified layer.

Circulation pattern for the month of March, as given in the earlier work[5,11], suggests the incursion of Bay of Bengal water into the Andaman Sea through the Preparis Channel. This water then flows south and leaves the Andaman Sea near 10° Channel. Further southwards, this is reinforced by a strong westerly current which seems to originate in Malacca Straits.

While a weak flow into the Andaman Sea at the surface and sub-surface depths from the Bay of

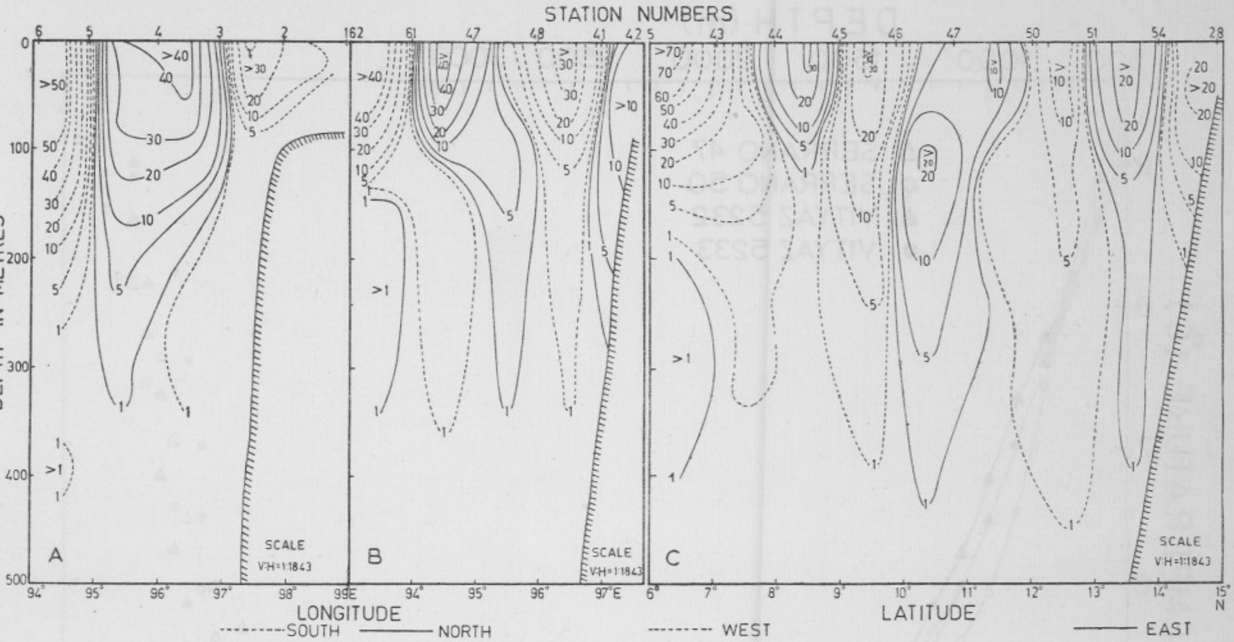

Fig. 9 — Geostrophic currents along section I (A), section II (B) and section IV (C)

Bengal through the Preparis Channel is visualized, it is observed that basically the flow consists of cells (cyclonic and anticyclonic of 100-200 km size) in the region which seem to cause considerable upwelling and sinking extended up to about 100 to 150 m. Similar cells were observed by Maslennikov[12]. But it is not very clear from these studies whether these cells are of seasonal character of duration extending a few days.

Furthermore, the thickness of freshened water on the western side is greater than the eastern side (Fig. 4B). The geostrophic circulation across that section (Fig. 8A) also shows that southward flow along the western side of the section is slightly stronger. All these features show that the dynamics of the upper layer are very much controlled by salinity. Since salinity is very much influenced by river discharges especially those of Irrawady and Salween, an estuarine type of circulation in this region could be easily visualized. In an estuary where the tidal influences are small and where the river discharges are dominant, development of internal waves at the interface (salt wedge) takes place. These internal waves seem to have a tendency to break only upwards[13]. This mechanism transfers both salt and mass into the upper fresh water layer giving rise to the observed distribution of salinity.

Perry and Schemike[2] have observed large amplitude internal waves north of Sumatra and they have mentioned bands of choppy water interspersed by calm zones. Similar features have been reported in the Bay of Bengal and Andaman Sea by various investigators. It is possible, since the Bay of Bengal and Andaman Sea are much influenced by fresh water discharges through the rivers from the Indian subcontinent, that internal waves are likely to develop at the interface. When they break upward close to the surface, the choppy band is one possible result. If this process is occurring, one would expect higher salinities in the choppy bands. However, no salinity data are available to confirm this.

Further studies are required to study the influence of river discharges and the related dynamics especially during the south-west monsoon season.

Deep and bottom waters below 1300 m have nearly uniform values of temperature, salinity and

TABLE 1 — DISTRIBUTION OF POTENTIAL TEMPERATURE OF THE BOTTOM WATER IN ANDAMAN SEA AND THE BAY OF BENGAL

Stn No.	Depth (m)	Max. depth (m) of observations	Potential temp. (°C)
ANDAMAN SEA			
59	1920	1894	4·85
50	2780	2694	4·67
49	2350	2350	4·68
47	3088	3088	4·68
44	2596	2580	4·66
43	2599	2599	4·63
BAY OF BENGAL			
VI 5229 (7°08′N, 91°31′E)	3720	2906	1·55
VI 5231 (9°00′N, 91°32′E)	3070	3070	1·48
VI 5232 (10°57′N, 91°41′E)	2568	2240	2·17
VI 5233 (13°01′N, 91°27′E)	3071	2436	1·94

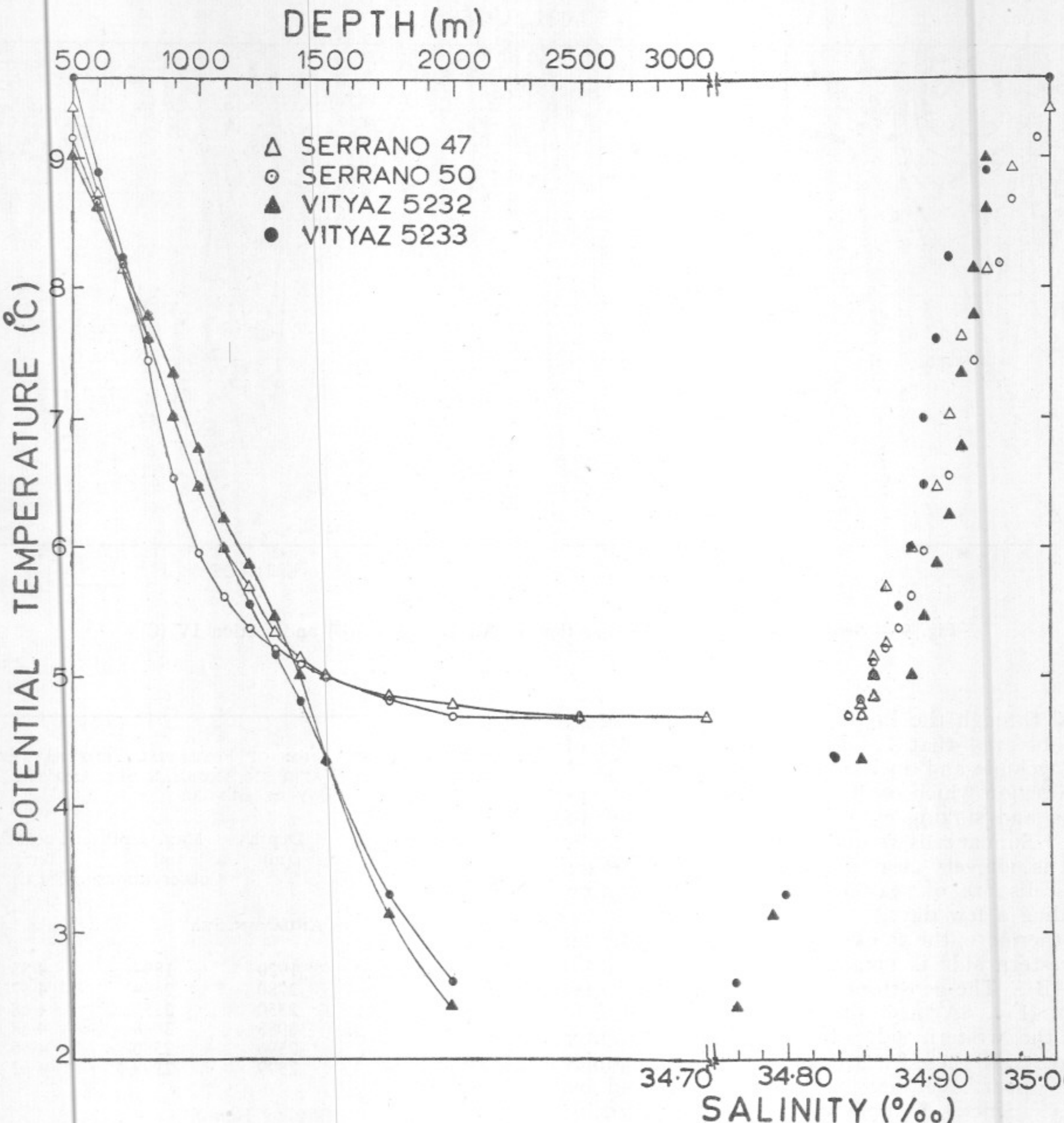

Fig. 10 — Relationship showing potential temperature versus depth and salinity

oxygen indicating the near stagnation of water at these depths. In the Andaman Sea basin, heat flow measurements from the sea bed are known to be very high[14]. The potential temperature data presented in Table 1 suggest a near neutral stratification in the bottom waters. Consequently vertical exchange coefficients could be moderate resulting in uniform distribution of properties.

Acknowledgement

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