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# Watermass structure in the western Indian Ocean– Part III : The spreading and transformation of Red Sea watermass

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**सार** — यहां लालसागर की जलराशि की संरचना प्रस्तुत है। अरब सागर में इस जलराशि का फैलाव 16° उ० अक्षांश तक सीमित है। इस जलराशि के केन्द्र भाग (क्रोड) की उपस्थिति की गहराई जलराशि क क्षेत्रीय रूप से फैलने के साथ ही कम होती चाली जाती है तथा मोजाम्बीक नहर में दक्षिण की ओर गहरी होती चली जाती है। अदन की खाड़ी में ऊर्ध्वाधर मिश्रण के कारण इस जलराशि का रूपांतरण अधिक तेज हो जाता है। इस जलराशि की दक्षिणी सीमा 10° दक्षिण के आसपास पाई गई थी जहां लाल सागर जलराशि का केन्द्र भाग उसी त्रिविम स्तर पर दक्षिण ध्रुवीय मध्यवर्तीय जलराशि के केन्द्र भाग के सम्पर्क में आता है यहां पर समघनत्वी मिश्रण के कारण एक समलवण परत बनती है मिश्रण की इस प्रक्रिया के दौरान इस जलराशि का घनत्व बढ़ने लगता है तथा इसका केंद्र भाग निम्न त्रिविम स्तरों पर ध्यान देने योग्य हो जाता है। सोमाली घाटी मे न्यूनतम लवणता का कारण लाल सागर जलराशि का दक्षिण ध्रुवीय मध्यवर्तीय जलराशि के ऊपर पड़े उप-उष्णकटिबन्धीय उप-स्थलीय जल में प्रवेश है।

ABSTRACT. The structure of the Red Sea Watermass (RSW) is presented. The spread of this watermass is confined to 16° N in the Arabian Sea. The depth of occurrence of its core shallows as the watermass spreads zonally and deepens towards south in the Mozambique channel. The transformation of this watermass is more rapid in the Gulf of Aden due to vertical mixing. The southern boundary of this watermass is fixed at 10° S, where the core of RSW comes in contact with the core of Antarctic Intermediate Water (AIW) which results in the formation of an isohaline layer due to isopycnal mixing. Further south this watermass shows an increase in its density and its core is noticeable at lower steric levels. The occurrence of salinity minimum in the Somali basin has been attributed to the penetration of RSW into the Subtropical Subsurface Water overlying the Antarctic Intermediate Watermass.

## 1. Introduction

Red Sea is located in an arid environment as that of Persian Gulf. Due to the high evaporation rates, 180-230 cm/yr (Previtte 1959; Yegorov 1950 and Morcos 1970) a warm and high saline watermass forms in this region and flows into the Gulf of Aden through the narrow strait of Bab-el-Mandeb where the sill depth is about 100 m. Sverdrup, Johnson and Fleming (1942) have noted the seasonal character of Red Sea Water out-flows into the Gulf of Aden. According to Patzert (1972) the Red Sea Water has a density ($\sigma_t$) of 27.8 at the sill. As this water spills over the sill, it sinks to depths of 400-600 m and subsequently mixes with the waters of Gulf of Aden forming a high salinity watermass called the "Red Sea Watermass" (RSW)†. The spreading of RSW in the Arabian Sea and the Indian Ocean has been studied by several investigators (Moller 1929; Thomson 1935; Tchernia *et al.* 1958; Warren *et al.* 1966; Wyrtki 1971 etc).

## 2. Topography of the core layer of RSW, its salinity and temperature

The core of this watermass appears at depths varying from 600 to 800 m. In the Arabian Sea, north of approximately 16°N the *T-S* curves do not indicate well defined salinity maxima corresponding to RSW. As it spreads along the African coast, the core of RSW progressively deepens to 1100 m south of 10°S with increased density (Wyrtki 1971). To the southeast, this watermass is seen at depths between 500 and 800 m. Between 15° N and 5° N the average depth of the core layer is around 600 m.

In the Gulf of Aden, the salinity in the core layer of RSW decreases rapidly eastward from about 36.2‰ to 35.8‰ (Fig. 1).

The salinity maximum associated with this watermass could be seen off the coast of Oman (upto about 20° N). South of this, the isohalines are nearly zonal with

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†In this paper Red Sea Watermass and Red Sea water have been used as synonyms of each other.

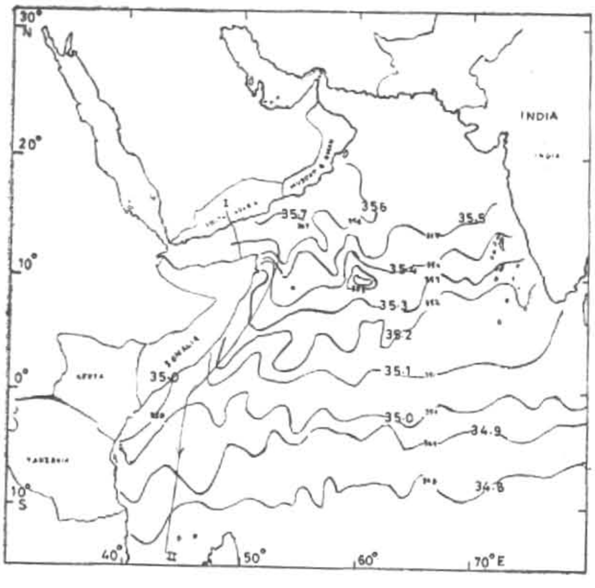
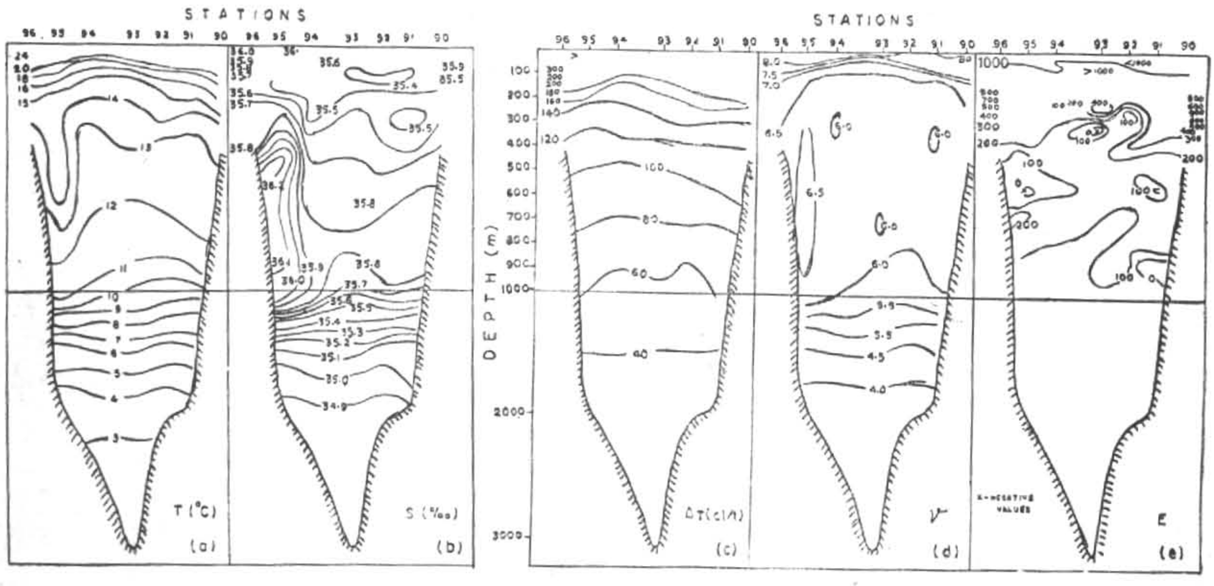



Fig. 1. Salinity (‰) distribution in the core layer of RSW

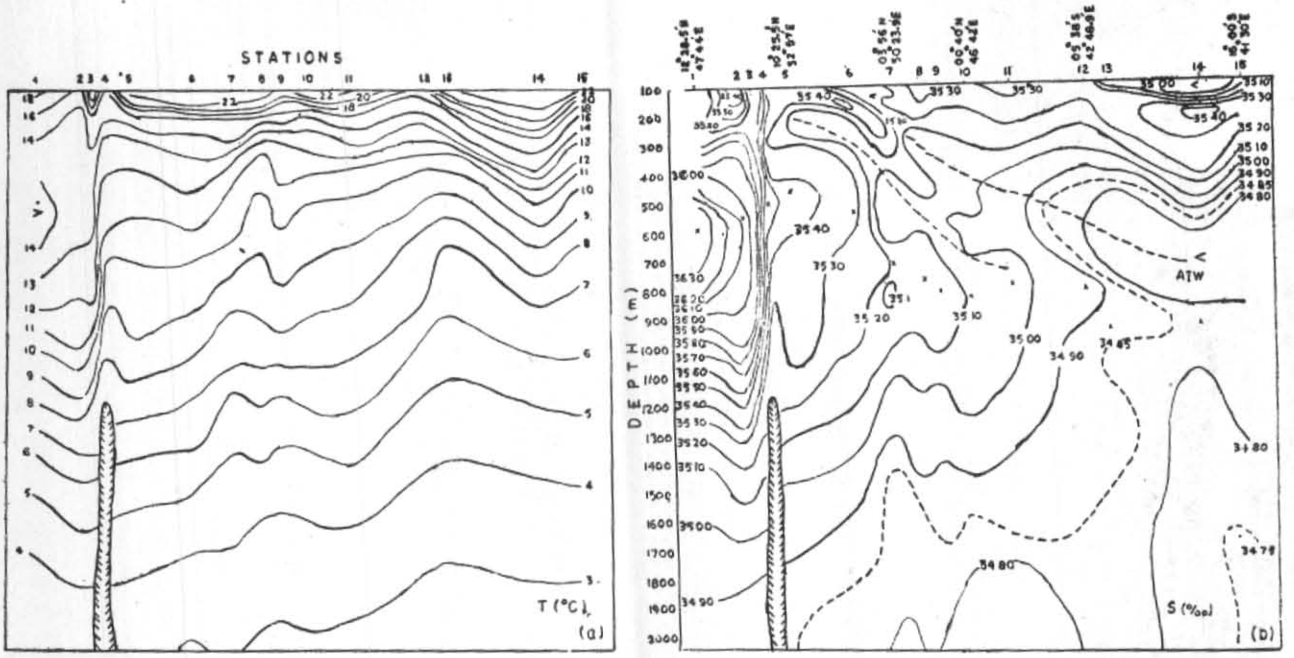



Figs. 2 (a-e). Distribution of (a) Vertical temperature, (b) Salinity, (c) Thermosteric anomaly, (d) Density flux function and (e) Vertical stability along Section I, Fig. 1

salinity decreasing from about 35.5‰ in the north to about 34.8‰ around 10° S. The isohalines along the African coast indicate a strong southerly flow. The distribution of temperature of the core is similar to that of salinity. The isotherms are nearly zonal south of 10° N and the temperature in the core decreases from about 10° C at 10° N to around 6° C at 8° S. In the Gulf of Aden, temperature decreases in a west-east direction from 13° C to 11° C. This watermass is, in general, located within 100-60 cl/t isanosteric surfaces. The isohalines of RSW in the Indian Ocean are oriented zonally in contrast to the spread of Mediterranean Watermass in the Atlantic where tonguelike distribution are observed.

### 3. Property distribution in the Gulf of Aden

Fig. 2 shows the distributions of temperature, salinity, thermosteric anomaly, density, flux function and stability along a section (*see* Fig. 1 for location) across the Gulf of Aden. The stations were occupied by 'Meteor' in December 1964. The thermal structure shows fairly low surface temperatures (24.0° C—a seasonal feature in this area). In the depth range of 250-900 m the isotherms present low temperature gradients. The salinity distribution of the core of RSW (Fig. 2b) shows a high saline (>36.2‰) layer on the southern side of this section around 500 m. The RSW is bounded by the 35.8‰ isohaline. Overlying this, a salinity minimum




Figs. 3 (a & b). Distribution of (a) Vertical temperature, (b) Salinity along Section II, Fig. 1

is seen at depths of 100-200 m and is cleary due to the penetration of the RSW into 'Indian Ocean Common Water' (Premchand 1981, *see* also Mamayev 1975). At the surface, the salinities exceed 36.0‰ in the southern and central regions while they are slightly less on the northern side.

The layer of high salinity is located between 100 & 60 cl/t surfaces while the salinity minimum appears between 160 and 180 cl/t surfaces. The disbtribution of stability along this section shows instablities (marked by x in Fig. 2e) in the intermediate layers and the salinity maximum layers coincides with the zone of minimum stratification and instabilities. Between 300 and 1000 m, the stability values are lower and sometimes negative, indicating favourable conditions for vertical mixing. A comparison of the distribution of the thermosteric anomaly and the density flux function (Figs. 2 c and 2 d) suggests intense vertical mixing in the depth range of the salinity maximum layer. Below and above this layer of salinity maximum, the isanosters and the isolines of density flux functions run parallel to each other. The Persian Gulf Watermass is clearly absent along this section.

#### 4. Property distributions along the African coast

Section II (Fig. 1) is similar to the one examined by Clowes and Deacon (1935); Sverdrup *et al.* (1942) and Wyrtki (1972) along the African coast. Most of the stations were occupied in August and September. Station 3 was occupied in spring 1960 and station 12 in late July 1964. Starting from June, intense upwelling along the Somali coast leads to rapidly changing property distributions in the upper 200 m. Hence, attention is confined in this study to depths below 200 m only.

In the Gulf of Aden, temperature inversions (Fig. 3a) appear at depths of 300-700 m and the isotherms are well spread out with weak vertical gradients. This zone nearly coincides with the core of RSW. Upto a depth of 1000 m, the isotherms appear to diverge (at 10° N) and slowly rise upward to the south with comparatively higher temperature gradients between 5° N & 7° S. For example, the thickness between isotherms 14° and 9° C at station 5 is about 700 m whereas at station 14, it is about 300 m. The isotherms show a similar trend even at greater depths. South of about 7° S, the isotherms slope downwards with a trough like structure especially below 100 m.

The salinity distribution shows the core of RSW at a depth of about 600 m (crosses indicate maxima, Fig. 3b) in the Gulf of Aden at station No. 1. This core appears at shallower depths upto station 5 (about 10° N). Further, south the core deepens progressively to 1000 m. A layer of salinity minimum (<34.8‰) centred around 700 m could be seen at the southern stations and could be traced northwards upto 11° N. The salinity maximum overlying this layer of minimum salinity in the south Indian Ocean is due to the presence of the Subtropical Subsurface Water. South of the equator the isohalines tend to become vertical and form an isohaline layer below a depth of 800 m eventhough the core of RSW could be identified (crosses in Fig. 3b). This isohaline (34.8‰) layer extends upto the bottom. The salinity minimum appears to split into two branches. The upper branch could be traced close to the sea surface (station 6) whereas the lower branch shallows and could be seen at depths of 200-300 m at station 4 (shown by dashes in Fig. 3b).

The distribution of thermosteric anomaly shows that the core of RSW is located between 100 and 80 cl/t

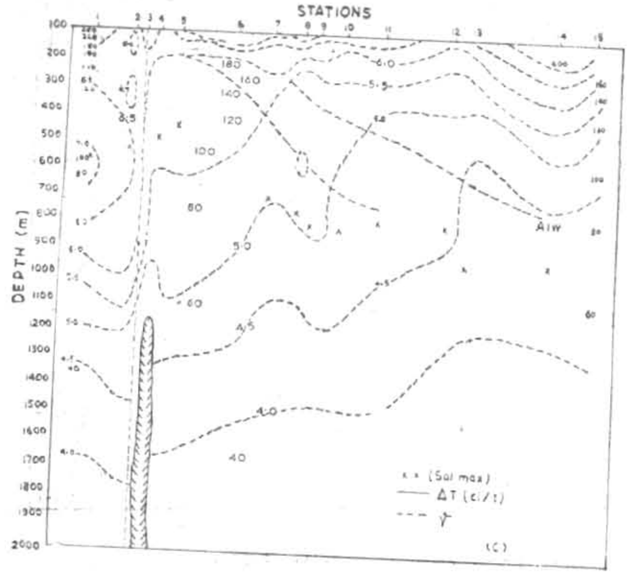



Fig. 3(c). Vertical distribution of thermosteric anomaly (—) and density flux function (— — —) along Secton II, Fig. 2

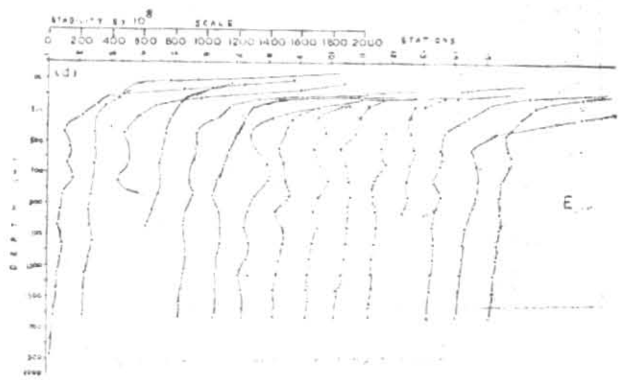



Fig. 3(d). Vertical stability distribution along Section II, Fig. 1

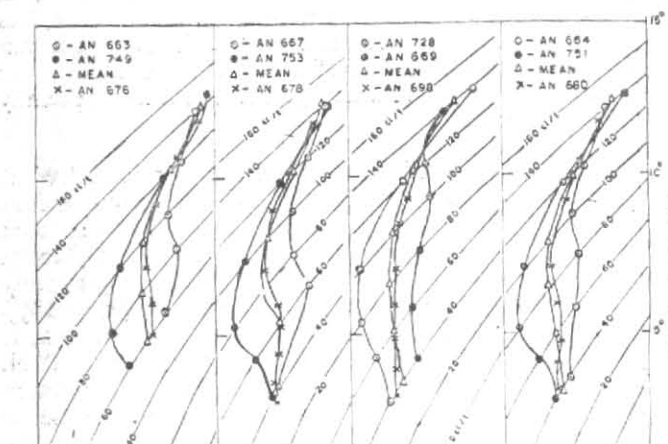



Fig. 4. *T-S* relationships at few stations in the SW Indian Ocean

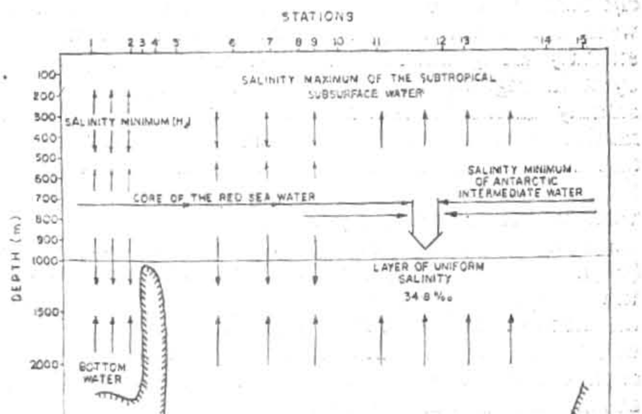



Fig. 5. Schematic diagram showing the mixing processes in the SW Indian Ocean

surfaces (Fig. 3c). The salinity minimum of AIW is also seen at the same surface around 16° S (as shown by the dashed line in Fig. 3 b). and appears to over-ride RSW.

Fig. 3(d) shows the vertical profiles of stratification at the stations along this section. The stability at any station can be assessed by shifting the stability scale to the desired station. In the region of Gulf of Aden, eventhough inversions were seen, stable stratification prevailed in contrast to unstable stratification as has been observed in December (*see* Fig. 2 e). At all the stations, stability decreases rapidly from the surface to about 300 m and thereafter decreases slowly with depth.

The density flux function varies from 8 to 4 (Fig. 3 c). The isohalines are more or less parallel to the density flux contours in the Gulf of Aden and also within the layer of the Subtropical Subsurface Water. A comparison of the density flux function with thermosteric anomaly (Fig. 3 c) suggests fairly intense vertical mixing in the Gulf of Aden. These sets of lines intersect in the depth range of 300-1100 m upto about 10° S. Further south, they are more or less parallel indicating isopycnal mixing.

### 5. Watermass structure in the southwest Indian Ocean

In order to study the processes relating to the development of the isohaline layer in the southern Indian Ocean, the percentage composition of RSW in the vertical and densification upon mixing, the watermass structure in the southwest Indian Ocean has been analysed based on data collected on board R.V. *Atlantis* during 1965 (Premchand 1981) and the salient features are summarised below :

(1) The sea surface temperature distribution shows a general decrease from north to south.

(2) The thickness of the salinity transition layer. Subtropical Subsurface Water (a layer in which salinity decreases with depth), increases southward.

(3) The thickness of the salinity minimum layer (associated with the Antarctic Intermediate Water) increases, with an increase in the absolute value of salinity, northwards.

(4) The salinity minimum layer, in general, occurs between 100 and 80 cl/t.

(5) The salinity minimum layer is conspicuously absent in the northern regions of the Malagasy channel and eastward along 10° S and 3° S. On the other hand, an isohaline layer (34.8 ‰) is seen below 600 m extending to bottom.

(6) A salinity minimum is observed north of Malagasy in the depth range of 800-1100 m (80 and 60 cl/t surfaces) while another salinity minimum is seen along the African coast between 120 and 80 cl/t surfaces.

(7) The oxyty maximum layer is located in the salinity transition zone and is found to be better defined in the northern regions. The oxyty maximum is found to be about 100-150 m above the salinity minimum layer and is observed to be around 125 cl/t.

The cores of RSW and AIW are approximately at the same steric level (between 100 and 80 cl/t) as seen from Figs. 3(b) and 3(c). As they spread from their respective source regions, the absolute value of the salinity minimum of AIW increases while that of RSW decreases due to mixing with the surrounding watermasses. When these two watermasses come into contact with each other on the same steric level, they 'extinguish' each other and their characteristic features (in the present case—the salinities) get obliterated resulting in the formation of an isohaline layer. Fig. 4 shows a few typical *T-S* plots at locations where the salinity minimum of the Antarctic Intermediate Water (Stations AN 749, 751, 753 at 26° S and 728 at 20° S) and the salinity maximum of the Red Sea Water (Stations AN 663, 664, 667, 669 at 4° S) could be clearly seen. The flow is assumed to be isentropic. Within the depth range of contact of these watermasses, the temperatures and salinities were read on the isanosteric surfaces for a few pairs of stations. Assuming a mixture of equal proportions of the two watermasses the mean temperatures and salinities are calculated. These mean values are plotted on the *T-S* diagram and are compared with the station curves at a few stations (AN 676, 678 and 680 at 12° S and AN 698 at about 8° S). The agreement between the observed and computed *T-S* structure is remarkable and thus substantiates the assumption that the mixing is predominantly isopycnal.

The distributions of the density flux function and the thermosteric anomaly along several sections in the south Indian Ocean (south of about 7°S) indicate that mixing is dominantly isopycnal. On the other hand Fig. 3(c), shows that between the equator and 7° S vertical mixing is intense in the depth range of 400-1200 m. Further south, the figure indicates that the mixing is nearly isopycnal. In the Gulf of Aden, the mixing is predominantly across the density surfaces. Fig. 5 shows schematically the various mixing processes mentioned above. The salinity minimum is ~ 34·7‰ just north of Malagasy whereas the salinity minimum close to the African coast is slightly less than 34.9‰. The salinity minimum occurring just north of Madagascar is due to the presence of AIW around 80 cl/t (800-1100 m). On the other hand, the salinity minimum close to the African coast appearing between 80 and 120 cl/t is due to the penetration of RSW into the layer of the Subtropical Subsurface Water overlying AIW. These salinity minima cannot, therefore, be connected with a line of flow.

What is now seen is the formation of a watermass having a uniform salinity with depth at the hydrological barrier between AIW and RSW which shows up as a weak salinity maximum (as suggested by Tchernia *et al.* 1958) below the salinity minimum of AIW. This weak maximum is associated with oxyty minimum and should not be confused with the deep salinity maximum of the Atlantic Deep Waters in the western Indian Ocean.

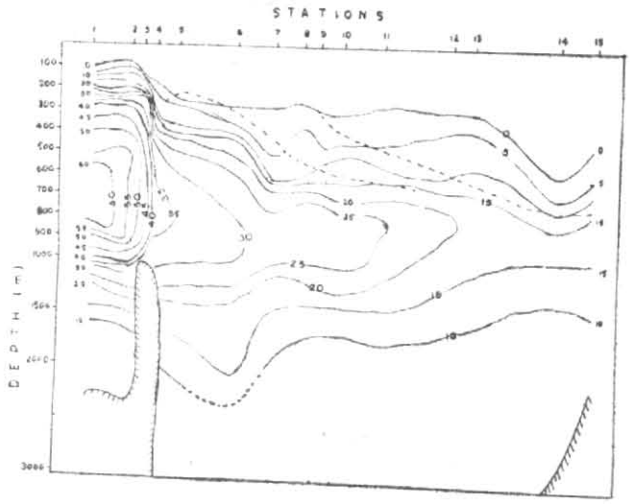



Fig. 6. Percentage composition of RSW along the African coast (along Section II, Fig. 1)

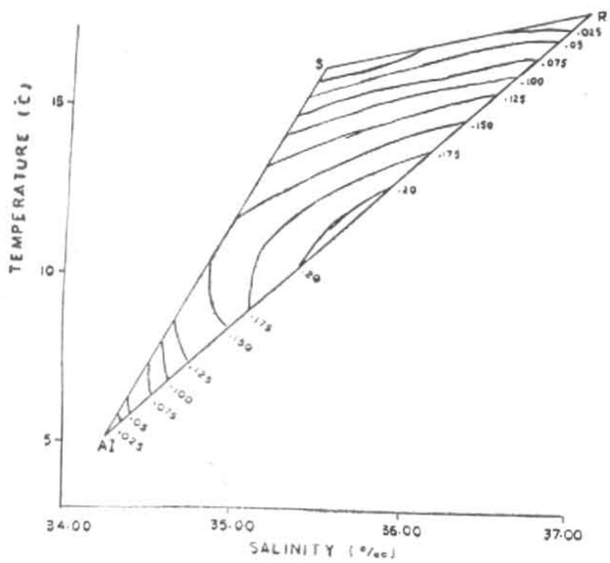



Fig. 7. Triangle of densification of mixing of Red Sea Water (R), Subtropical Subsurface Water (S) and Antarctic Intermediate Water (AI)

#### 6. Percentage composition of Red Sea Water (RSW)

The percentage composition of RSW along the African coast has been evaluated taking into cosideration the various aspects of the watermass structure in southwest Indian Ocean mentioned above. As RSW flows out into the Gulf of Aden, it penetrates the 'Indian Ocean Common Water' and a layer of salinity minimum (designated as $H_2$, Part I) develops between the core of RSW and the high salinity surface waters. For the evaluation of the percentage composition of RSW in the Gulf of Aden the thermohaline indices of the Arabian Sea High Salinity Water (ASHSW), Hypothetical Water ($H_2$), RSW and the Bottom Water are considered (Premchand 1981). Only three watermasses are considered at a time.

The percentage composition at the core exceeds 60 at station 1 in the Gulf of Aden and gets diluted to 40 at station 3 (Fig. 6). The vertical extent increases in the Gulf of Aden and its influence could be seen in the depth range of 100-1500 m. Along the African coast the percentage composition of this watermass progressively decreases. At about 7° S the core layers of RSW and AIW come into contact giving rise to a uniform salinity layer which appears as a weak salinity maximum south of about 15° S (especially in the Malagasy channel). Since RSW is poorly oxygenated, the oxyty (associated with the salinity maximum) shows a relatively low concentration. In Fig. 6 eventhough the presence of the watermass is shown upto 16° S it is felt that the boundary of this water should be limited to around 7°-10° S.

The dashed lines in Fig. 6 show the upper and lower branches of the salinity minima. These minima are clearly located at the upper levels of the influence of RSW when it penetrates into the layer of the Subtropical Subsurface Water and explains the occurrence of the salinity minimum at different depths (usually shallowing towards north).

Wyrtki (1971) mentions an upper and lower salinity minimum at about 10° S. The data presented here shows two minima that can be associated with Wyrtki's single upper minimum layer. He suggests that the influence of upper minimum layer is felt at 10° S whereas the lower minimum comes under the influence of Banda Sea Water and is located at a depth of 1000 m between 27.4 and 27.5 $\sigma_t$ (60-90 cl/t) and that salinity occurring between 600 and 1200 m is very nearly uniform. Along the vertical section off the African coast (depicted in IIOE Atlas), the salinity minimum appears in the depth range of 500-800 m bounded by the 34.9‰ isohaline around 5° S. Below this salinity minimum appears a zone of maximum salinity extending upto 20° S. In Fig. 3(b), we see clearly a lower (1000 m, 34.85‰ contour) and an upper (600 m) salinity minima around station 13. The percentage composition of the Red Sea Water (Fig. 6) shows that the core of the Red Sea Water when penetrates further south gives rise to an upper and lower minimum. Only the upper minimum is of considerable significance. This section is located close to the African coast and it is unlikely that the Banda Sea Water penetrates upto this region. The *percentage composition* of the Bottom Water along this section shows that its influence extends to 12° N and in the vertical upto about 800 m from the bottom. However, in the Gulf of Aden, its influence could be seen upto about 300 m depth.

#### 7. Densification upon mixing of RSW

When Red Sea Water penetrates into the 'Common Water' in the Gulf of Aden (where the Persian Gulf Water is absent) the densification is negligible since the core of RSW generally appears on the side $H_2$ R of the mixing triangle A $H_2$ R. The same is true when bottom water is considered for the mixing process.

Fig. 7 shows the triangle of densification when RSW penetrates the layer of Subtropical Subsurface Watermass (S). With the core of RSW at the same steric level as that of AIW, the densification is maximum when RSW and AIW mix ( $\sigma_t$ units 0.2). When mixing progresses between RSW and S, the increase in density is insignificant. When AIW is absent at any place, and when mixing progresses between the watermasses, S, RSW and B the maximum increase in density ($\sigma_t$) would occur when equal proportions of RSW and B mix (0.4 along the side BR). As the cores of RSW and AIW were observed on the same steric level the resulting mixture will increase in density ($\sigma_t$) of about 0.2. If the mixture contains a component of B, the densification could be still more. It may be mentioned that below 800 m the *T-S* curves run parallel to the side RB of the mixing triangle. In the zone of 7°-10° S mixing of these watermasses takes place on a large scale leading to densification. In the Mozambique Channel, this increase in density ($\sigma_t$) would be between 0.2 and 0.3.

#### 8. Discussion

As the Red Sea Water flows out into Gulf of Aden, it sinks to deeper levels and considerable dilution due to vertical mixing takes place. The spreading of RSW in the Indian Ocean extends from about 16° N in the Arabian Sea to about 10° S (except along the African coast). Off the Arabian coast the presence of this watermass could be identified upto about 20° N while in the Mozambique Channel, its influence could be seen south of 10°S. The core of this watermass progressively deepens during its spread in the Mozambique Channel whereas it shallows up towards the west coast of India. The percentage composition of this watermass shows that its influence is felt over a larger thickness in the Gulf of Aden and as it spreads further south its thickness (zone of its influence) progressively reduces. The core of this watermass and that of the Antarctic Intermediate Water lie at the same steric level and these two watermasses mix isopycnally to form an isohaline layer at about 10° S in the southwest Indian Ocean. The salinity minimum in the Somali basin in the depth range of 200-400 m is attributed to the penetration of RSW into the layer of the Subtropical Subsurface Water overlying the core of the Antarctic Intermediate Water. While the core of RSW lies below the layer of the Subtropical Subsurface Water the percentage composition of RSW shows the presence of this watermass in the layer of the Subtropical Subsurface Watermass giving rise to the upper salinity minimum appearing at different depths. The distribution of the density flux function and of the thermosteric anomaly reveal that vertical mixing is a predominant process in the Gulf of Aden and upto about 7° S and further south, isopycnal mixing is predominant. The southern limit of RSW is placed at the zone of isopycnal mixing between the cores of RSW and Antarctic Intermediate Water where the formation of the isohaline layer is noticed. Due to the low oxyties in RSW, the mixture of RSW and AIW will have a low oxyty. When this watermass spreads southwards, it would appear at deeper levels due to densification on mixing and appears as a weak salinity maximum with low oxyty below the core of the Antarctic Intermediate Water.

An analysis of the watermass structure in the southwest Indian Ocean has shown that the magnitude of salinity minimum of the core of the Antarctic Intermediate Water progressively increases northward whereas the thickness of the Subtropical Subsurface Water progressively decreases to the north. These features are due to the mixing of RSW with AIW and Subtropical Subsurface Water.

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