

Property-property relations: 22° and 9° discontinuities in the Arabian Sea

Conservative properties
Discontinuity layers
Water masses
Arabian Sea

Propriétés conservatives
Couches de discontinuité
Masses d'eau
Mer d'Oman

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ABSTRACT

Property-property relations, mostly of conservative chemical parameters, are used in this attempt in tracing various discontinuities in the Arabian Sea and to reveal *in situ* processes together with potential temperature-salinity plots. Plots of salinity, PO, NO, oxygen and water stability (E) against potential temperature reveal that two discontinuity layers, one at 22.2°C (22 DD) and the other at 9.1°C (9 DD) are found in the Arabian Sea. 22 DD seems to have been formed due to the mixing of shallow salinity maximum water (SSMW) and Persian Gulf water (PGW). This discontinuity is situated in the centre of the mixing depth interval. Red Sea water (RSW) mass contributes chiefly for 9 DD. Various physico-chemical characteristics of these two discontinuity layers are elucidated, along with those of other water masses and density surfaces.

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RÉSUMÉ

Discontinuités dans la mer d'Oman (isothermes 22°C et 9°C) d'après les relations entre les paramètres physiques et chimiques

Cette étude utilise les relations entre les paramètres chimiques conservatifs et les relations entre la température potentielle et la salinité pour déterminer les couches de discontinuité dans la mer d'Oman et décrire les phénomènes *in situ*. Les valeurs de salinité, PO, NO, oxygène et la stabilité de l'eau (E) en fonction de la température potentielle révèlent deux couches de discontinuité, l'une suivant l'isotherme 22,2°C (22 DD) et l'autre suivant l'isotherme 9,1°C (9 DD). La couche 22 DD semble résulter du mélange des eaux du Golfe (PGW) avec des eaux peu profondes de salinité maximale (SSMW). Cette discontinuité se situe à mi-profondeur de la couche de mélange. La masse d'eau de la Mer Rouge (RSW) contribue à la discontinuité 9 DD. Nous déterminons aussi différentes caractéristiques physico-chimiques de ces deux couches de discontinuité, ainsi que celles des autres masses d'eau et des surfaces isopycnes.

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INTRODUCTION

Property-property relations are most important in determining the physical and chemical processes, that take place in the sea. Potential temperature (θ)-Salinity (S) plots have been found to be good indicators of various mixing processes (Wyrski, 1971; Broecker *et al.*, 1976; Harvey, 1982). θ -S relation is also shown to depict the 2° discontinuity in the Atlantic deep waters (Broecker *et al.*, 1976). Discontinuity is referred to a point where two lines of evidently different slopes intersect in θ versus a property diagram. Besides the

θ -S diagram, the conservative chemical parameters, such as PO and NO proposed by Broecker (1974), can also be used in tracing various water bodies and to reveal the physical processes which occur *in situ*. There has so far been no study of property-property relations and the occurrence of any discontinuity in the Arabian Sea waters. In the present attempt, potential temperature-property relations in the water of the Arabian Sea are used to deduce any eventual discontinuity and to establish its physicochemical characteristics.

MATERIAL AND METHODS

The physical and chemical data were collected on board R.V. Gaveshani during a Monex Cruise in June 1979 and also on board ORV Sagar Kanya. The study area lies essentially between the 68°00' and 71°32'E longitudes and 11°00' and 15°26'N latitudes, in the Arabian Sea (Fig. 1). TPN Hydrobios water samplers fitted with reversing thermometers were used for collecting samples. Some stations were sampled by rosette sampler fitted with CSTD probes. Nutrients, dissolved oxygen and salinity were measured immediately after collection on board ship. Temperature was measured with reversing thermometers and salinity analysis was

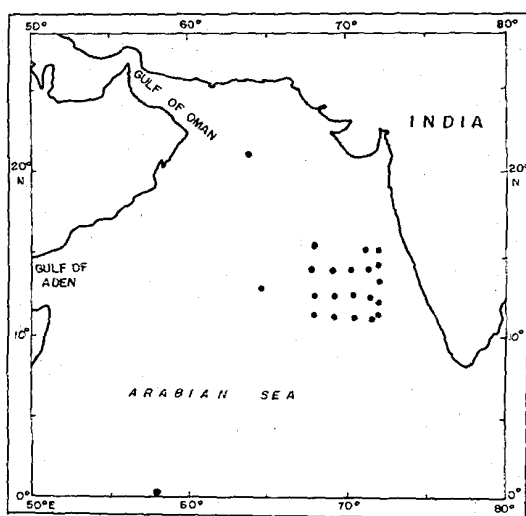


Figure 1
Map showing station locations.

conducted on board using an Autosol salinometer with a precision of $\pm 0.003 \times 10^{-3}$. Inorganic phosphate was determined by the method of Murphy and Riley (1962) and nitrate by the method of Morris and Riley (1963) as modified by Grasshoff (1964). Dissolved oxygen was measured by the Winkler method as modified by Carpenter (1965). Potential temperatures were calculated using the polynomials of Fofonoff and Millard (1983), the accuracy of these equations being $\pm 6.0 \times 10^{-3} \text{ } ^\circ\text{C}$. θ values were calculated according to Veronis (1972). For the evaluation of NO and PO, the observed ratios for O_2/NO_3 and O_2/PO_4 were found to be 8.5 and 164.5, respectively, and with these values, the NO and PO equations were formulated as

$$\text{NO} = 8.5 (\text{NO}_3)_{\text{obs.}} + (\text{O}_2)_{\text{obs.}}$$

and

$$\text{PO} = 164.5 (\text{PO}_4)_{\text{obs.}} + (\text{O}_2)_{\text{obs.}}$$

At the experimental standard error of oxygen $\pm 1.5 \mu\text{mol} \cdot \text{dm}^{-3}$, $\text{NO}_3 \pm 0.2 \mu\text{mol} \cdot \text{dm}^{-3}$ and $\text{PO}_4 \pm 0.02 \mu\text{mol} \cdot \text{dm}^{-3}$ the standard errors estimated for NO and PO are $\pm 4.6 \mu\text{mol} \cdot \text{dm}^{-3}$ and

$\pm 4.79 \mu\text{mol} \cdot \text{dm}^{-3}$, respectively. Stability of the water bodies were calculated for some selected stations from the relation

$$E = \frac{\partial \rho}{\partial S} \cdot \frac{\partial S}{\partial z} + \frac{\partial \rho}{\partial v} \left(\frac{\partial v}{\partial z} - \frac{\partial \theta}{\partial z} \right)$$

given by Sverdrup *et al.* (1942), and used as one of the properties in our plots. Each E value showing the stability of water between two geopotential depths (D1 and D2) has been plotted with corresponding potential temperatures, respectively.

RESULTS AND DISCUSSION

From the enormous data collected during the International Indian Ocean Expedition, Wyrcki (1971) has selected, after carefully considering various factors, the sigma- θ surfaces which coincide roughly with the density most typically found along major core layers. His selection elaborately deals with the sigma- θ surfaces of 25.0, 25.8, 26.6, 27.2 and 27.4, and these cover all the important core layers found in the Indian Ocean with the exception of the deep salinity maximum near sigma- $\theta = 27.75$. The data plots in this present study are well in agreement with those presented in Wyrcki's atlas and essentially describe all those core layers occurring in Arabian Sea. For example, shallow salinity maximum water (SSMW) in the Arabian Sea above 25.0, salinity maximum in Persian Gulf Water (PSW) at 26.6 and salinity maximum in Red Sea Water (RSW) at 27.2. In addition, our plots of potential temperature (θ) against salinity, oxygen, PO, NO and water stability (E) show some interesting results which are discussed in terms of mixing of different water bodies with the consequent formation of discontinuity layers.

Figures 2-5 show the relations between the potential temperature (θ) and other properties; it can be seen from them that abrupt changes occur in slopes of property-property relations at 22°C and 9°C potential temperatures. Hence, these two points of intersection are referred to as 22°C discontinuity (22 DD) and 9°C discontinuity (9 DD). 22 DD is characterized with an average salinity of $35.859 \pm 0.094 \times 10^{-3}$ and potential temperature of $22.191 \pm 0.3547^\circ\text{C}$ whereas 9 DD has $35.327 \pm 0.066 \times 10^{-3}$ salinity and $9.080 \pm 0.3075^\circ\text{C}$ potential temperature. Shaded areas in Figures 2-5 show the standard deviation limits for the two discontinuities.

The 22 DD falls just above the surface of 25.00 σ_θ salinity maximum. This is evident from Figure 3, which shows oxygen minimum values occurring slightly below 22 DD region. Wyrcki (1971) noted coincidence of the first oxygen minimum with 25.8 σ_θ surface, whereas in the present work these oxygen minimum values are observed above 25.8 surface and below 22 DD (Fig. 3). Figures 4 and 5 also reveal the minimum values of NO and PO just below the 22 DD in agreement with oxygen minimum (Fig. 3). The 22 DD might have been

Figure 2
 θ -S plot for the study area. Different marks show the data from different stations.

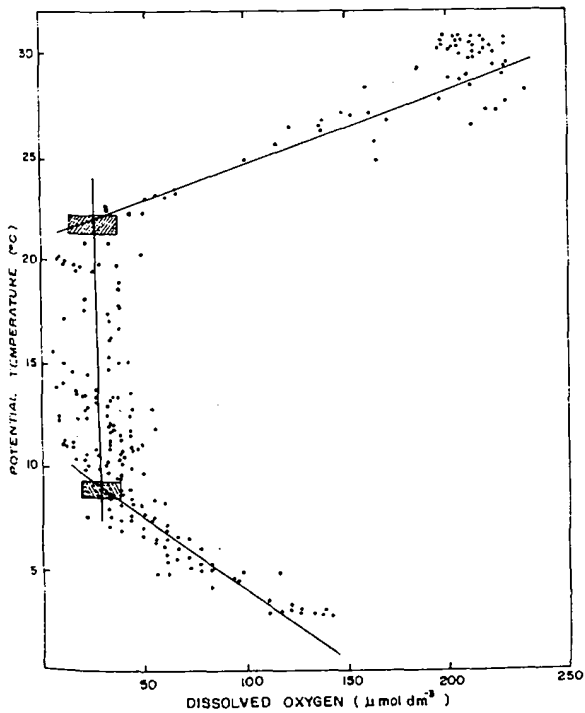
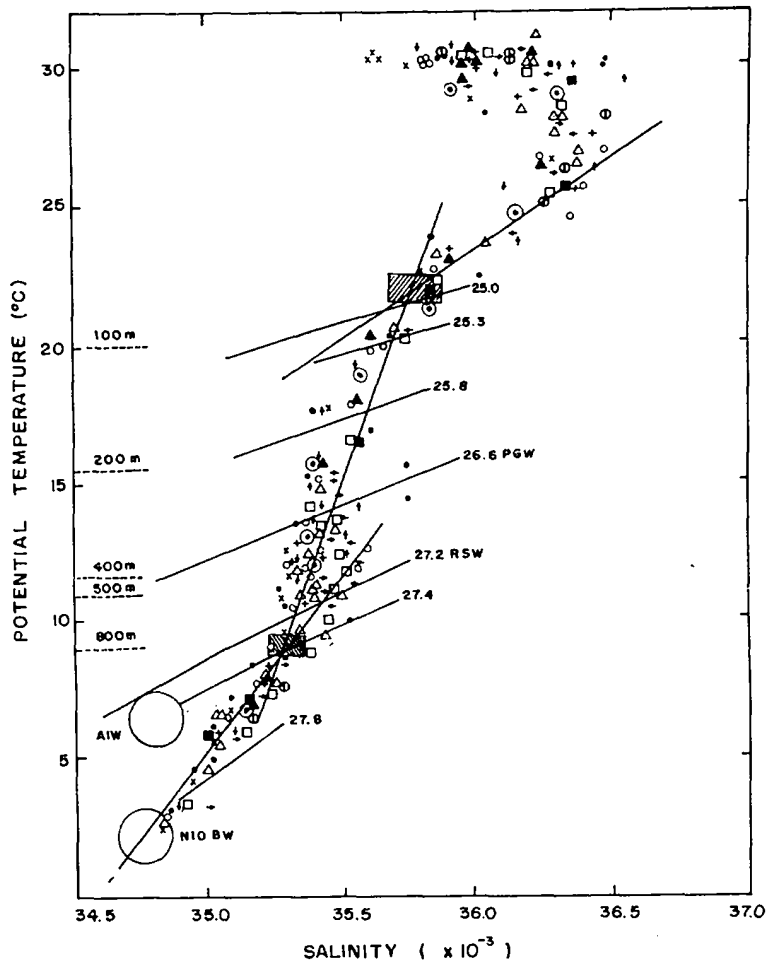


Figure 3
 θ -O₂ plot for the study area.

formed due to mixing between Shallow Salinity Maximum Water (SSMW) having a θ of 27°C and S of 36.4×10^{-3} and Persian Gulf Water with a θ of 15°C and S of 35.8×10^{-3} and found at the centre of the mixing depth interval (Fig. 2). The SSMW is originated in the northern Arabian Sea surface layers and is also termed as Arabian Sea High Salinity water (Wyrтки, 1971). The PGW contribution to the origin of 22 DD can be ascertained from the fact that the original PGW with high oxygen content loses its property as it spreads into the oxygen minimum in the northern Arabian Sea, leading to the oxygen concentrations to even $< 10 \mu\text{mol.dm}^{-3}$ (Wyrтки, 1971), mostly around 100 m with oxygen minimum lying below discontinuity (Fig. 2, Tab. 1).

9 DD lying between σ_θ surfaces of 27.3 and 27.4 (Fig. 2) mostly occurs around a depth of 800 m (Tab. 1), and Red Sea Water (RSW) is reported to be present at this depth (Wyrтки, 1971; Rajendran *et al.*, 1980). Hence, RSW with a σ_θ surface of 27.2 seems to contribute chiefly to 9 DD (Fig. 2). Occurrence of 9 DD, exactly 27.4 σ_θ surface, reveals that 9 DD might have been originated due to the linear mixing between RSW and North Indian Ocean Bottom Water

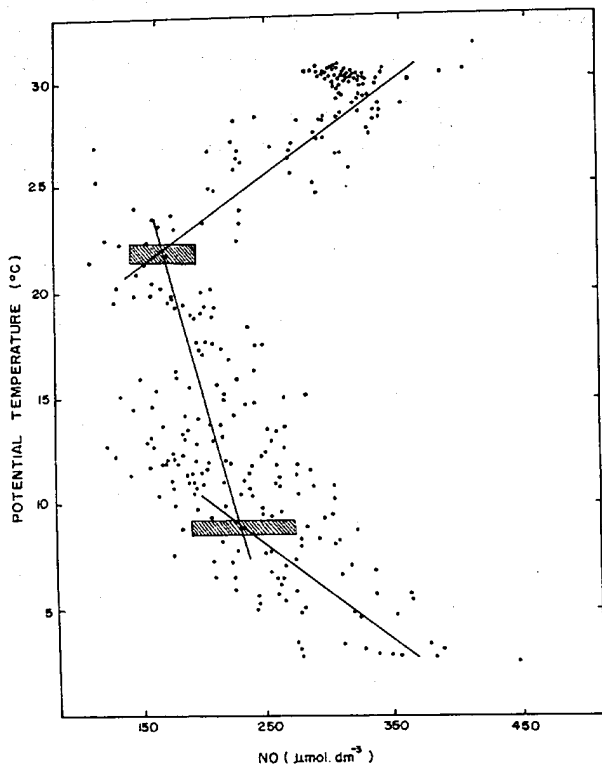


Figure 4
 θ -NO plot for the study area.

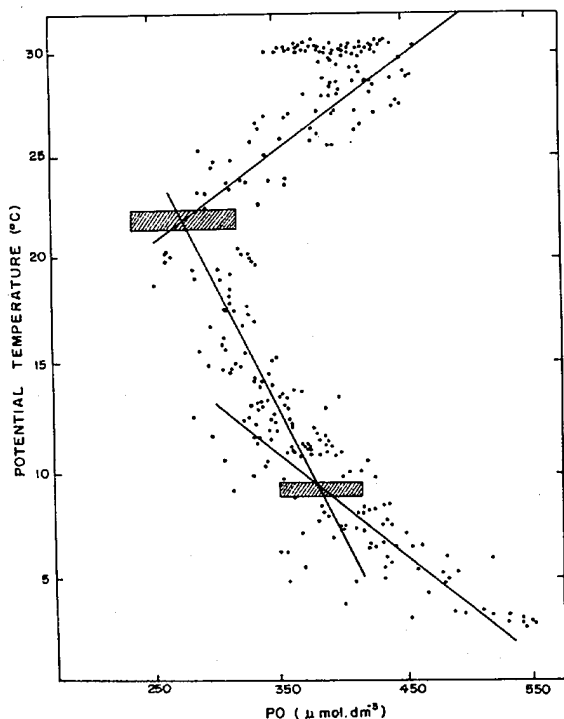


Figure 5
 θ -PO plot for the study area.

(NIOBW or NIBW) of Ivanenkov and Gubin (1960). Gordon (1983) ascertained that NIO deep water may be formed to some extent by vertical processes, since the potential temperature-salinity curve is nearly linear between the salinity maximum at 10°C which is due to RSW and the cold end member. Below this 9 DD, the

Table 1

Physicochemical characteristics of 22 DD and 9 DD.

Station No.	Depth (m)	θ (°C)	S ($\times 10^{-3}$)	NO ($\mu\text{mol.dm}^{-3}$)	PO ($\mu\text{mol.dm}^{-3}$)	O ₂
22° discontinuity						
86	108	22.008	35.84	148	293	24.3
96	100	22.570	35.80	148	294	29.2
99	96	22.670	38.85	—	337	63.3
102	125	22.344	35.91	158	266	38.9
115	125	22.715	35.75	174	311	34.4
125	115	22.237	35.85	136	392	24.6
128	135	21.488	35.81	110	288	24.6
132	113	22.497	36.01	124	257	44.3
Mean		22.191	35.859	142.5	304.7	35.57
Standard deviation		± 0.3457	± 0.094	± 21.3	± 42.3	± 13.5
9° discontinuity						
79	728	9.495	35.32	257	362	14.6
80	796	8.999	35.35	282	416	34.1
83	743	9.433	35.33	298	400	34.1
86	869	8.653	35.28	228	400	29.2
93	733	8.808	35.21	320	415	38.9
96	668	9.601	35.29	249	354	19.5
99	739	9.036	35.24	285	433	38.9
109	798	9.387	35.44	207	298	24.6
119	775	9.082	35.32	197	314	24.6
125	890	8.760	35.39	247	392	39.3
128	845	8.904	35.35	202	413	34.5
132	935	8.804	35.40	185	395	24.6
Mean		9.080	35.327	250.6	391	29.74
Standard deviation		± 0.3075	± 0.066	± 44.3	± 32.5	± 8.2

θ -S curve agrees with linear mixing between RSW and NIOBW (Fig. 2) rather than RSW mixing with Antarctic Intermediate Water (AIW) of Wyrki (1971). The North Indian Ocean Bottom Water (NIOBW) with σ_{θ} of approximately 27.8 and the Arabian Sea Deep Water (ASDW; Gallagher, 1966) seem to refer to the same water mass. The origin of the deep water (NIOBW) according to Sen Gupta *et al.* (1976) is due to Antarctic Circumpolar Water, but to the mixing between RSW, south Indian Ocean Intermediate Water and Indian Ocean Bottom Water according to Gallagher (1966). However in the Central Indian Basin near 12°S Warren (1982) noted the effect of RSW outflow producing a weak salinity maximum of 34.75×10^{-3} between 1200 and 2000 m. Alternately, Kolla *et al.* (1976) and Warren (1978) found the entry of Antarctic Bottom water (AABW) into the Arabian Sea Basin through the Crozet Basin. Kolla *et al.* (1976) also observed a rise in potential temperature from 0.20°C near 40°S to 1.2°C near 10°N for AABW. In the light of these recent studies (Kolla *et al.*, 1976; Warren, 1978; 1982), it could be presumed that NIOBW ($\theta \sim 2^{\circ}\text{C}$) must have been formed, due to mixing between the outflowed southward moving RSW and northward moving AABW ($\theta \sim 1.2^{\circ}\text{C}$) south of Arabian Sea basin. Wyrki (1971) also found that AIW would be blocked by RSW, rather near the same density surface around 10°S. Taft (1963) noted the absence of "line of flow" between the Arabian Sea salinity minimum and the Antarctic Intermediate Water and in concurrence with this, Premchand and Sastry (1975) observed that Antarctic Intermediate Water flow is limited to the south and does not cross the equatorial region northward. A deep oxygen minimum is found

mostly about 600 m depth and is due to RSW (Wyrki, 1971). The oxygen minimum is found to occur slightly deeper in the present study. With the exception of some extreme cases, the occurrence of 9 DD was found to vary between 728 m and 869 m (Tab. 1) and the deep oxygen minimum closely lies above 9 DD. NO and PO (Fig. 4 and 5, respectively) also show low values near 9 DD as is found for oxygen (Fig. 3). The observed 9 DD is found to occur well on top of the linear mixing curve between RSW and NIOBW (Fig. 2).

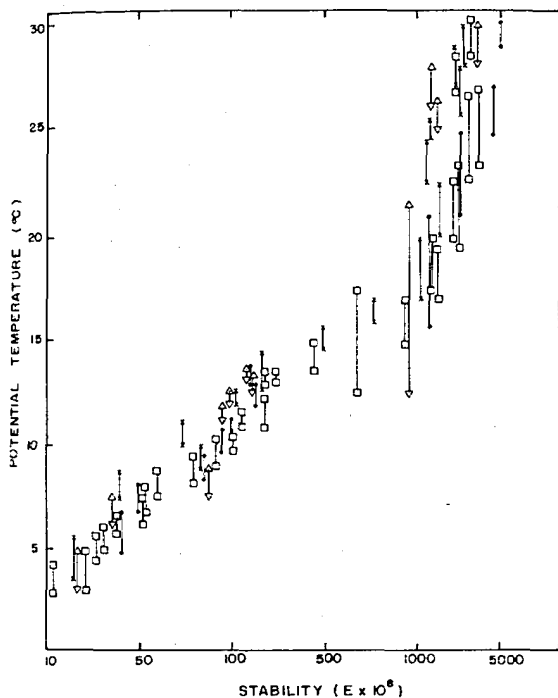


Figure 6
Stability plot for the study area. Different marks show the data from different stations.

Figure 6 shows the relation between potential temperature and water stability ($E \times 10^8$). It was anticipated that stability (E) values calculated for the entire water column in the Arabian Sea would exhibit the discontinuity at the depths where 22 DD and 9 DD are occurring. However, E being a measure of vertical stability between two depths assuming that a water mass is displaced vertically upward from the geopotential depth D_2 to the geopotential depth D_1 , it does not give the sharp discontinuity exactly at depths where 22 DD and 9 DD are occurring. Despite this, E also showed some discontinuity features in these depths (Fig. 6).

The physical and chemical characteristics of 22 DD and 9 DD are given in Table 1. The 22 DD occurred between 90 and 150 m whereas 9 DD is between 660 and 950 m. 22 DD has slightly high standard deviation values of salinity ($\pm 0.094 \times 10^{-3}$) and potential temperature ($\pm 0.346^\circ\text{C}$) compared to 9 DD values of salinity ($\pm 0.066 \times 10^{-3}$) and potential temperature ($\pm 0.308^\circ\text{C}$). This is probably due to the major contribution of a specific water mass (RSW) in 9 DD formation. Relatively high oxygen minimum concentration occurs nearer 22 DD than near 9 DD. In 22 DD oxy-

gen varied from 24.3 to $63.3 \mu\text{mol.dm}^{-3}$ (mean $35.57 \mu\text{mol.dm}^{-3}$), whereas in 9 DD the oxygen range is from 14.6 to $38.9 \mu\text{mol.dm}^{-3}$ (mean $29.74 \mu\text{mol.dm}^{-3}$). Figure 3 shows that between the two discontinuities (22 DD and 9 DD) there occurs a continuous oxygen minimum though the occurrence of slight oxygen maximum between the two minima does not have much effect. NO value ranges from 110 to $174 \mu\text{mol.dm}^{-3}$ in 22 DD and from 185 to $320 \mu\text{mol.dm}^{-3}$ in 9 DD. The standard deviations calculated show higher values in 9 DD than 22 DD (Tab. 1). PO varied from 257 to $392 \mu\text{mol.dm}^{-3}$ in 22 DD with a standard deviation of $\pm 42 \mu\text{mol.dm}^{-3}$, whereas it varied from 314 to $433 \mu\text{mol.dm}^{-3}$ in 9 DD with $\pm 33 \mu\text{mol.dm}^{-3}$ standard deviation. As expected with respect to vertical distributions of nutrients, 9 DD has higher NO_3 and PO_4 values (average being 27.74 ± 1.60 and $2.47 \pm 0.20 \mu\text{mol.dm}^{-3}$, respectively) than 22 DD (13.20 ± 0.94 and $1.76 \pm 0.37 \mu\text{mol.dm}^{-3}$, respectively). Sen Gupta *et al.* (1976), Deuser *et al.* (1978) and Naqvi *et al.* (1982) noted a positive nitrate anomaly (ΔN) between 150 and 1200 m depth and used this to calculate the rate of denitrification in this water column. In the upper layers of this depth range, the positive ΔN can be ascribed to PGW which has lost its high oxygen concentration as well as to the denitrification process. The observed low standard deviation values for all parameters, except NO_3 and NO in 9 DD than 22 DD (Tab. 1) are consistent with the fact that the origin of 9 DD is due to the major contribution of RSW. Moreover, poor correlations are observed among O_2 , NO_3 and PO_4 for both the discontinuities, as the linear regression equations deduced are:

22 DD

$$\text{NO}_3 = 0.004 \text{O}_2 + 3.571, \quad r = 0.12$$

$$\text{PO}_4 = -0.008 \text{O}_2 + 2.295, \quad r = 0.54$$

$$\text{NO}_3 = 0.909 \text{PO}_4 + 2.263, \quad r = 0.36$$

9 DD

$$\text{NO}_3 = 0.016 \text{O}_2 + 7.172, \quad r = 0.162$$

$$\text{PO}_4 = 0.004 \text{O}_2 + 2.24, \quad r = 0.32$$

$$\text{NO}_3 = 1.984 \text{PO}_4 + 3.21, \quad r = 0.25.$$

The observed r values for 22 DD and 9 DD indicate the absence of any major biochemical reaction in these layers, and indirectly support our view that these two discontinuity layers are the result of chiefly physical mixing processes.

Table 2 lists physical and chemical characteristics for some of the water masses (SSMW, PGW, RSW and NIOBW), two density surfaces (25.0 and 25.8) and also for 22 DD and 9 DD discontinuity layers. These values are deduced from Figures 2-3 at appropriate potential temperature, characteristic of the water mass/density surface. Conservative chemical properties (NO and PO) show relatively lower values for 25.0 σ_θ surface (Tab. 2) compared to all other water masses, other density surfaces and two discontinuity layers. Though NO and PO are found to behave as good conservative

Table 2
 Characteristics of water masses, density surfaces and observed discontinuities in the study area.

Water masses/ Density surfaces	θ °C	S ($\times 10^{-3}$)	O ₂	NO ($\mu\text{mol}\cdot\text{dm}^{-3}$)	PO
SSMW	27.00	36.40	180	300	388
22 DD*	22.19	35.86	35.6	142.5	304.7
25.0	21.5	35.75	30	95	283
25.8	17.5	35.60	28	100	317
PGW (26.6 σ_θ)	14.0	35.36	28	107	343
RSW (27.2 σ_θ)	10.31	35.33	27	112	375
9 DD* (27.4 σ_θ)	9.08	34.75	29.7	250.6	391
NIOBW	2.0	35.75	130	287	538

* Average values from Table 1.

properties, the superiority of one over the other is not clearly understood (Broecker, 1974). However PO- θ plot (Fig. 5) shows more distinguishable discontinuity layers than NO- θ plot in this present study.

Despite the present finding of 22 DD and 9 DD in the centre of the Arabian Sea, the same do not occur in the southern or northern regions because of the presence or absence of characteristic water masses. In the north, the main break is observed around a potential temperature of 15°C and salinity of $\sim 36 \times 10^{-3}$, which are the characteristics of Persian Gulf Water. Hence at 19°N latitude neither 22 nor 9 DD are found (Fig. 7). The absence of 9 DD is evidently due to the non-occurrence of RSW north of 12°N. 22 DD also does not occur in this area, possibly due to the lower temperatures generally occurring in this area. Due to the decrease in temperature, the density of the surface waters increases and hence sinks downward. This

highly saline surface water might be forming a mixed layer while mixing with the almost equally saline PGW. In the middle latitudes of the Arabian Sea, the occurrence of both the 22 DD and 9 DD is obvious (Fig. 7). Both PGW and RSW are found to be present, but further south the PGW completely loses its characteristics. The presence of these two water masses along with others result in the formation of these discontinuities. At 12°N, 22 DD is very clear because the surface temperature increases compared to that of 21°N, making the density differences between SSMW and PGW layers more distinct a process which is also aided by the loss of characteristic PGW salinity maximum by the time it reaches this latitude (Fig. 7). 22 DD does not occur near the Equator, obviously because of the absence of SSMW and PGW, whereas 9 DD occurs as a consequence of the presence of RSW and NIOBW. The presence of various water masses at their characteristic potential temperatures are also depicted schematically (Fig. 7). However, the possible presence of NIOBW north of 15°N is not known.

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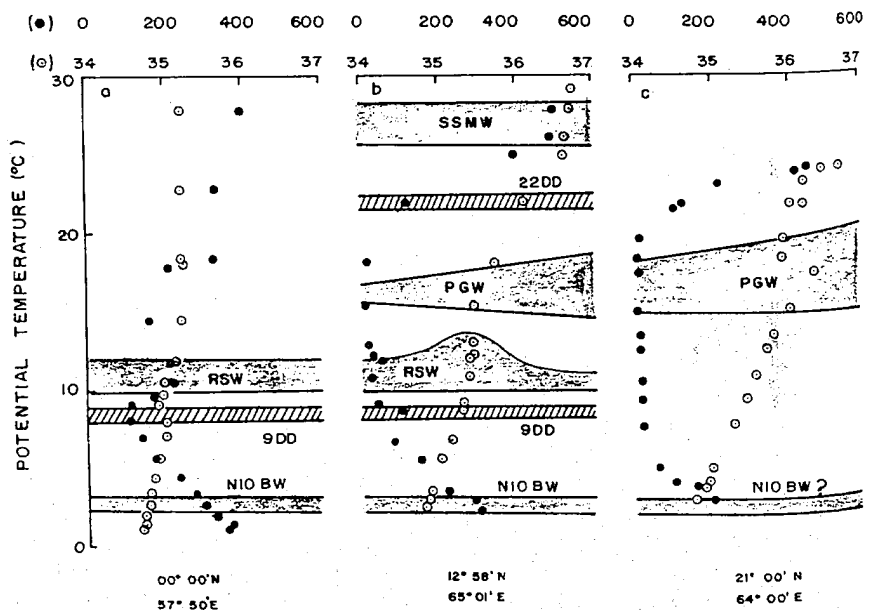


Figure 7
 Latitudinal variations in the profiles of salinity (O) and oxygen (●) with the schematic representation of water masses and discontinuities.

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