

Chemical Oceanography of the Arabian Sea: Part I—Hydrochemical & Hydrographical Features of the Northern Basin

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Three water masses in the Arabian Sea have been identified from their physical and chemical characteristics: (i) water mass which originates in the surface layer and has high salinity, low oxygen and high pH; (ii) water mass below it which has its origin in the Persian Gulf and has high salinity and low oxygen; and (iii) deep water which has low salinity, low temperature, lower nutrients but high oxygen and pH. Two oxygen minima are observed the 1st at depths between 100 and 400 m and the 2nd between 800 and 1500 m. Denitrification is observed at the level of the 1st oxygen minimum resulting in $\Delta N : \Delta P$ ratio of 6:1 by atoms in water.

CHEMICAL oceanographic studies help in understanding characteristics of water masses in the oceans and problems such as potential fertility and oxidation of organic matter in them.

An oceanographic expedition to the northern Arabian Sea was undertaken on board INS *Darshak* between December 1973 and May 1974. Sea water samples were collected from depths up to 3000 m and from a total of 210 stations occupied within the block area (Fig. 1). The present paper reports a generalized study of the analytical data on salinity, temperature, dissolved oxygen, inorganic phosphate, nitrate-nitrogen, nitrite-nitrogen, ammonia nitrogen, pH and total alkalinity, in relation to the hydrochemical and hydrographical features of the area.

Materials and Methods

Transparent TPN water samplers (type Hydro Bios, Kiel, West Germany) and metallic Nansen reversing bottles were used for obtaining water samples.

Salinity was measured using a Bisett-Berman type inductive salinometer. Deep-sea reversing thermometers were used for measuring temperature. Dissolved oxygen was determined by the Winkler method as modified by Carritt and Carpenter¹.

Inorganic phosphate was determined by the ascorbic acid-potassium antimonyl tartrate method of Murphy and Riley². Turbidity blanks were made by adding 3.5 ml of the reagent without ascorbic acid to 25 ml of the samples. These were run at all depths of the stations on the continental shelf and at selected depths of the deeper stations.

Nitrate was estimated by the cadmium-amalgam reduction method of Morris and Riley³ as modified by Grasshoff⁴. Nitrite was determined by the method of Bendschneider and Robinson⁵. Turbidity blanks were made by adding 0.5 ml sulphanimide solution to 25 ml of the samples. These were run in a similar manner as for the inorganic phosphate. Ammonia was determined by the indophenol blue method of Koroleff⁶, using a citrate buffer to avoid precipitation. Total alkalinity was measured by the pH-method of Anderson and Robinson⁷.

Results and Discussion

Three stations in the north-south transect 05, along 60°45'E longitude (Nos. 01, 07 and 15) in the northern basin were selected to study the progress of the high saline water flowing out of the Persian Gulf. A salinity maximum was observed at about 300 m depth (Fig. 2, stn 05-01). The depth of the salinity maxima decreased southwards. It is present at 200 m (Fig. 2, stn 05-07) and also at about 100 m (Fig. 2, stn 05-15). This water mass was associated with low oxygen and low nutrient concentrations as can be seen from the figures. Station 19-01 (24°00'N; 64°35'E), off the Pakistan coast, was selected to study the eventual eastward flow of this water mass, if any. There was a salinity maximum at about 70 m depth (Fig. 2, stn 19-01) associated with a progressive decrease of oxygen and nutrient concentrations. The same feature can be observed in Fig. 3 [stations 33-12 (20°40'2N; 66°22'5E), 51-13 (19°00'5N; 69°27'E) and 57-13 (17°26'1N; 70°56'E)] off the Indian coast.

The occurrence of a salinity maximum at about 75 m at almost all the stations studied, except at

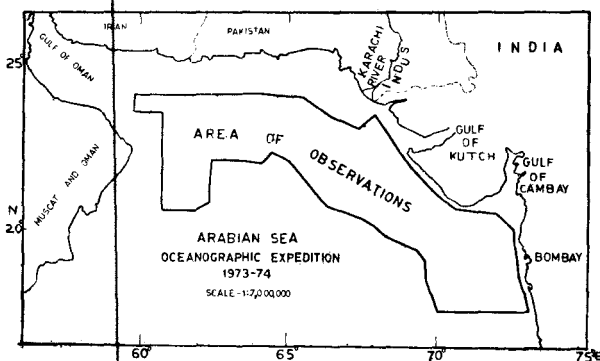


Fig. 1 — Area of observation

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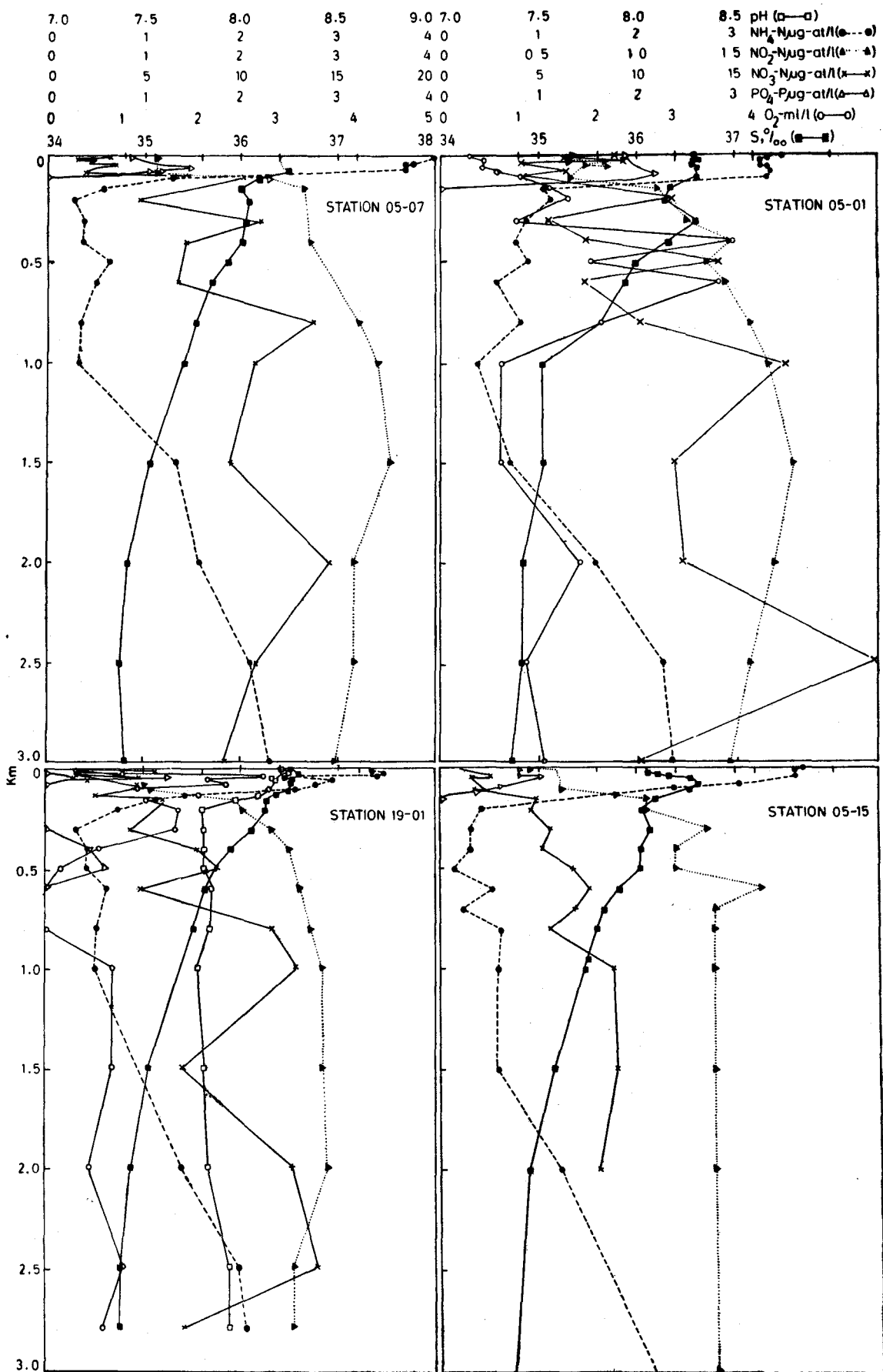
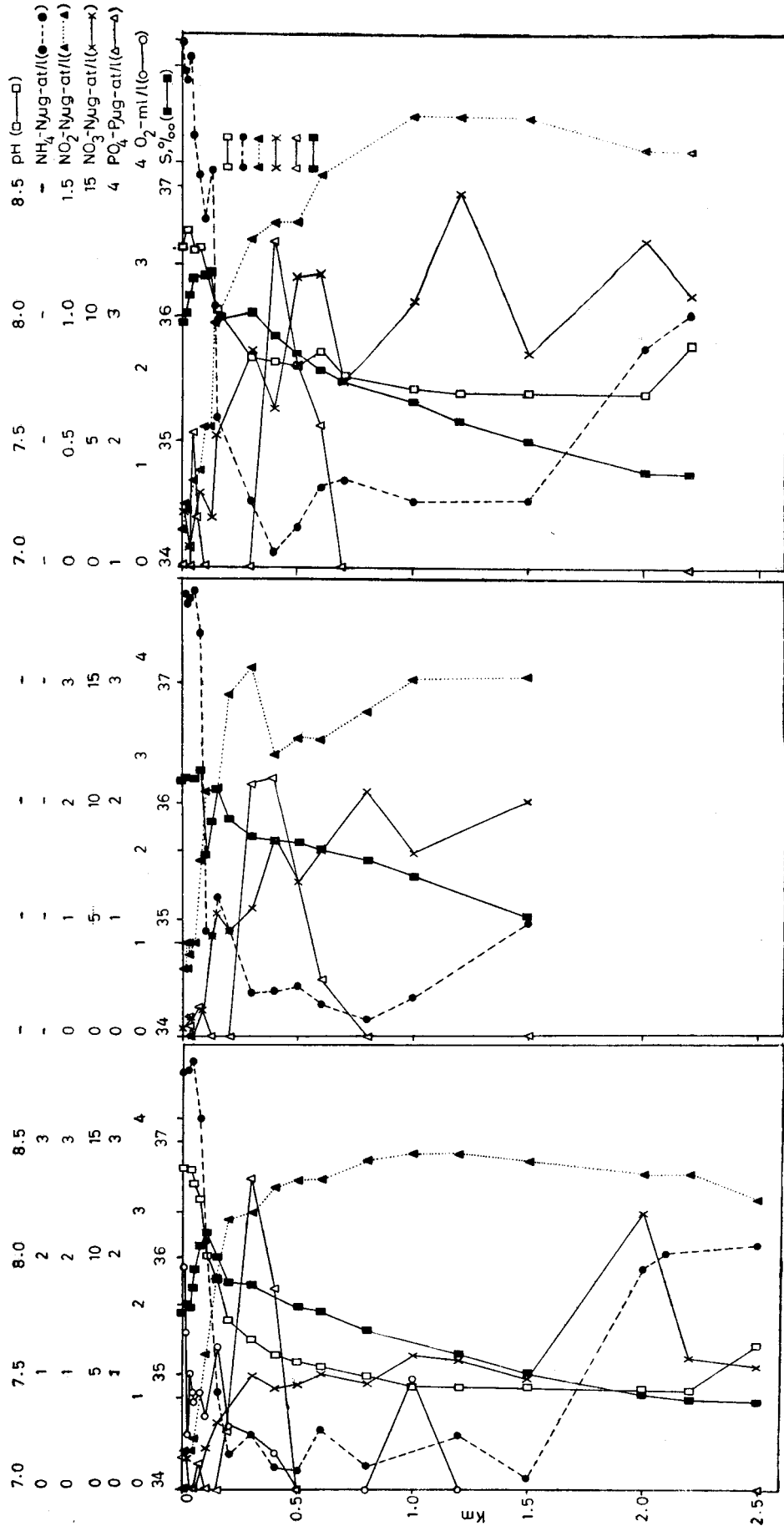


Fig. 2— Vertical distribution of properties at stations 05-01, 05-07, 05-15 and 19-01



STATION 33-12

STATION 51-13

STATION 57-13

Fig. 3 — Vertical distribution of properties at stations 33-12, 51-13 and 57-13

station 05-01, indicates that this water mass must have an origin similar to that described by Schott⁸. The Arabian Sea is an area of negative water balance. The annual excess of evaporation over precipitation and runoff varies between 7 and 10 km³ and one of the 2 maxima in evaporation occurs during December-February⁹. Therefore, this water mass is formed at the surface during the periods of intense evaporation and later on seeks its own density level and has been named Arabian Sea high salinity water¹⁰. Being formed during the periods when evaporation is in excess, this water mass has low oxygen concentration.

The maximum at around 300 m (Fig. 2 stn 05-01 and Fig. 3 stn 33-12) seems to have its origin in the Persian Gulf, according to the criteria outlined by Sastry and D'Souza⁹. From these and from the STD observations during the *Darshak* cruises¹¹, it is apparent that this is the surface water from the Persian Gulf, formed as a result of excess evaporation. It sinks and flows out over the 50 m sill in the Hormuz Strait and then through the Gulf of Oman. It reaches its density level at about 300 m and then spreads mostly in a south-easterly direction.

Two oxygen minima can be seen in Figs. 2 and 3. The first is between 100 and 400 m associated with low nitrate but increasing phosphate concentrations. The second is between 800 and 1500 m associated with increasing nitrate and phosphate concentrations. It can be also observed from the figures, that at the first minimum level, some ammonia is present along with nitrate, while nitrite is almost absent. Lower down at the second minimum level, nitrite attains a maximum while ammonia is either very low or absent. Below 1000 m, and occasionally below 1500 m, nutrients decrease with depth. This decrease is associated with an increase in oxygen and a decrease in both salinity and temperature. A nitrate maximum is present from 2000 to 2500 m at all the stations but below 2500 m nitrate decreases. These features give some idea about the mechanism of oxidation of organic matter in the Arabian Sea. During decomposition phosphate released from the decaying organisms does not undergo oxidation through different stages before it is finally returned to water; whereas nitrogen is released first as ammonia which is converted to nitrate with nitrite as an intermediate stage in the process. The process starts at about 100 m, or just below the thermocline, and gets nearly completed at about 1000 m as in most other oceanic areas. The first stage in the organic decomposition process is the utilization of available oxygen. The intensity of this process depends on the amount of organic material available which seems to regulate the oxygen minima. From the very low values of oxygen at the minimum levels, it can be deduced that the production of organic matter in the Arabian Sea should be fairly high. It has been observed during October-March 1960 that photosynthetic productivity in the Arabian Sea is between 50 and 120 mg C m⁻² day⁻¹ (ref. 12). It has also been observed during the *Darshak* cruises that zooplankton population was fairly high in the northern basin during February and got almost totally depleted

in early April. The second stage in the oxidation process is the utilization of nitrate for bacterial decomposition of decaying organisms. This process results in nitrite as an intermediate and ammonia and nitrogen gas as the end products. This is the reason for the appearance of the nitrite maxima at the first oxygen-minimum level with low concentrations of nitrate in water. (Preliminary assessment of the photosynthetic productivity values in the northern Arabian Sea carried out during the *Darshak* cruises indicate a range of variation between 100 and 500 mg C m⁻² day⁻¹ during January-February 1974.)

It can, thus, be concluded that the top oxygen deficient layer in the Arabian Sea is caused by the decomposition of organic matter while the deeper one is predominantly due to the effect of other water masses. An oxygen minimum of about 1.5 ml/litre has also been observed in the equatorial region of the Indian Ocean during *Monex* 1973 cruises at about 1500 m. The decrease in the level of this minimum layer northwards in the Arabian Sea is most probably caused either by mixing or by other physical processes such as vertical and horizontal turbulent or molecular diffusion.

During the later period of observation, nitrate disappeared totally from the surface layers while phosphate was always present in measurable quantities. This suggests that in the Arabian Sea, as in almost all other oceanic regions, nitrate has a stronger influence than phosphate in regulating the phytoplankton productivity. Lower values of photosynthetic productivity were recorded during October-March 1961, the cause of which was attributed to the deficiency of nutrients particularly nitrogen compounds, leading to the conclusion that algal production in the Arabian Sea is largely controlled by nitrogen compounds¹³. Observations during March-April 1974 indicated comparatively lower values for photosynthetic productivity with decreasing concentrations of inorganic nitrogen compounds in the surface layers. The present data, thus, agree well with earlier findings.

Since the oxygen concentrations at the levels of the shallow minimum in the northern Arabian Sea lie between 0.1 and 0.3 ml/litre this area seems to be well suited for the process of denitrification. It has been calculated from statistical analysis of the data that $\Delta N:\Delta P$ ratio in water above 200 m is only 6:1 by atoms compared to 16:1 in deeper layers, which is the same as the theoretical value of this ratio¹⁴.

An interesting feature was observed during the 1st and 2nd cruises (during December-January). In the surface layers at stations along the mouth of the Gulf of Cambay, nutrient concentrations were higher than in the region south of the mouth of the Gulf. Average concentrations of phosphate and nitrate in the upper 50 m at the stations along the continental shelf in transects 45, 47 and 49 were calculated. Transect 45 covers the mouth of the Gulf and slightly northwards of it, while transects 47 and 49 are to the south of Gulf mouth. The average concentrations of phosphate and nitrate respectively are 1.26 and 5.13 μg at/litre for transect 45, 0.94 and 1.11 μg at/litre for transect 47 and 0.18 and 0.77 μg at/litre for transect 49.

The decrease in nutrients in the upper layers southwards from the mouth of the Gulf of Cambay may be due to one or more of the following reasons: (i) nutrients added by river runoff, which might largely be utilized till December and January when the observations were taken; (ii) higher rate of photosynthetic activity south of the Gulf; and (iii) the Gulf itself may act as an ecological barrier, as has been suggested from earlier marine biological observations in the area¹⁵.

High ammonia concentrations were occasionally observed in the surface layers. This may be due to (i) ammonia added by precipitation, (ii) fixation of nitrogen by blue green algae, and (iii) notable absence of nitrification activity. The presence of considerable amount of nitrate in the surface layers during most of the observations rules out the 3rd possibility. Therefore, ammonia in the surface layers may be the result of either or both of the 1st two possibilities. This, again, is in agreement with observations in surface layers in oligotrophic areas where an excess of ammonia was often observed when nitrate and nitrite were absent¹⁶.

pH and total alkalinity values show trends as can be expected in oceanic environments (Fig. 2 stn 19-01 and Fig. 3 stn 33-12 and 57-13). High pH in the surface layers is due to photosynthetic activity. Higher pH values at intermediate depths (Fig. 2 stn 19-01 and Fig. 3 stn 33-12) probably result from dissolution of carbonate. Below 2000 m, pH values increase, suggesting dissolution of calcium carbonate at the sediment-water interface.

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References

1. CARRITT, D. E. & CARPENTER, J. H., *J. mar. Res.*, **24** (1966), 286.
2. MURPHY, J. & RILEY, J. P., *Anal. chim. Acta*, **27** (1962), 31.
3. MORRIS, A. W. & RILEY, J. P., *Anal. chim. Acta*, **29** (1963), 31.
4. GRASSHOFF, K., *Kieler Meeresforsch.*, **20** (1964), 5.
5. BENDSCHNEIDER, K. & ROBINSON, R. J., *J. mar. Res.*, **2** (1952), 87.
6. KOROLEFF, F., *International Council for the Exploration of the Sea, Charlottenlund, Denmark, No. C.M. 1969/C9*, 4 (mimeo).
7. ANDERSON, D. H. & ROBINSON, R. J., *Ind. Engng Chem., Anal. Ed.*, **18** (1946), 757.
8. SCHOTT, G., *Geographie des Indischen und Stillen Ozeans* (Verlag Boysen, Hamburg), 1935.
9. SASTRY, J. S. & D'SOUZA, R. S., *Indian J. Met. Geophys.*, **23** (1972), 479.
10. ROCHFORD, D. J., *Aust. J. mar. Freshwat. Res.*, **15** (1964), 25.
11. GANGADHARA RAO, L. V., unpublished data.
12. KABANOVA, J. G., *Okeanologicheskie Issledovania*, **4** (1961), 72.
13. KABANOVA, J. G., *Okeanologia*, **8** (1968), 270.
14. SEN GUPTA, R., unpublished data.
15. WAGH, A. B., *personal communication*.
16. RILEY, J. P. & CHESTER, R., *Introduction to marine chemistry* (Academic Press, London), 1971.