Anthropogenic CO_2 penetration in the northern Red Sea and in the Gulf of Elat (Aqaba)

Red Sea
Gulf of Elat (Aqaba)
Anthropogenic carbon dioxide

Mer Rouge
Golfe d'Eilat (Aqaba)
CO_2 anthropogénique

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ABSTRACT

The penetration of anthropogenic carbon dioxide in the northern Red Sea and in the Gulf of Elat (Aqaba) was studied using data obtained during the *Tiran*-02 cruise (February 1982). The results obtained demonstrated that the entire water column of the Gulf of Elat was saturated with an excess of anthropogenic CO_2, indicating winter overturning. In the Red Sea, the upper 200 m are very young with a very uniform excess carbon dioxide signal close to zero (0 ± 7 µmol kg^{-1}). The $\Delta\Sigma CO_2^0$ values (the signal of anthropogenic CO_2 penetration, after reaching maximum negative values *ca.* -28 ± 5 µmol kg^{-1} at 600 ± 100 m, increase and remain almost constant at *ca.* -15 ± 6 µmol kg^{-1} from 800 to 1 500 m. The increase of $\Delta\Sigma CO_2^0$ values below 600 ± 100 m in the northern Red Sea was explained by the influence of the overflow of younger waters from the Gulf of Elat over the sill in the Strait of Tiran and by the inflow of young waters from the Gulf of Suez. The tongue of these young waters spreads at a depth of about 800-1 500 m from the Strait of Tiran southward. Relatively old waters, characterized by maximum negative $\Delta\Sigma CO_2^0$ values at a depth of *ca.*600 ± 100 m, are sandwiched between younger waters.

Comparison of the obtained results with the existing data from other expeditions proves that the mechanism of deep water formation in the northern Red Sea is seasonally independent and did not change from the GEOSECS expedition of 1977.

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RÉSUMÉ

Pénétration du CO_2 anthropogénique dans le nord de la Mer Rouge et le golfe d'Eilat (Aqaba)

La pénétration du CO_2 anthropogénique dans le nord de la Mer Rouge et dans le golfe d'Eilat (Aqaba) est étudiée à partir des données de la campagne *Tiran*-02 (février 1982). Les résultats montrent que toute la colonne d'eau du golfe d'Eilat est saturée en CO_2 anthropogénique, par suite du renouvellement hivernal. Dans la Mer Rouge, les 200 premiers mètres sont très jeunes, l'excès de CO_2 étant uniforme et voisin de zéro (0 ± 7 µmol kg^{-1}). Les valeurs de $\Delta\Sigma CO_2^0$ passent par un minimum négatif d'environ -28 ± 5 µmol kg^{-1} à 600 ± 100 m, puis se stabilisent à environ -15 ± 6 µmol kg^{-1} de 800 à 1 500 m. L'augmentation de $\Delta\Sigma CO_2^0$ au-dessous de 600 ± 100 m dans le nord de la Mer Rouge est due à l'apport des eaux plus jeunes du golfe d'Eilat qui franchissent le seuil du détroit de Tiran, et à l'apport d'eaux jeunes en provenance du Golfe de Suez. Ces eaux jeunes se répandent vers le Sud, au-delà du détroit, entre 800 et 1 500 m de profondeur. Une couche d'eaux relativement vieilles, caractérisées par des valeurs négatives extrêmes de $\Delta\Sigma CO_2^0$, est observée à une profondeur de l'ordre de 600 ± 100 m. Les résultats obtenus et les données d'autres campagnes montrent que, dans le nord de la Mer Rouge, le mécanisme de formation des eaux profondes ne dépend pas de la saison, et n'a pas varié depuis la campagne GEOSECS de 1972.

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INTRODUCTION

Since the beginning of the Industrial Revolution in the middle of the last century, the amount of carbon dioxide in the earth's atmosphere has drastically increased due to burning of fossil fuel and deforestation, especially during the last century. The partial carbon dioxide pressure in the atmosphere has increased from a pre-industrial value in the range of either 260-290 ppm (Dyrssen and Wedborg, 1982) or 268 ± 13 µatm (Poisson and Chen, 1987, who gave an extensive review of past atmospheric CO_2 values) to the present value of approximately 335 ppm (Dyrssen and Wedborg, 1982). It has been estimated that by the year 2 000 the CO_2 level in the atmosphere will be doubled (Anderson and Malahoff, 1977). The ecological effects of this phenomenon can hardly be overestimated, but the greatest danger seems to be of global climatic changes. Mercer (1978), Stuiver (1978) and many others have predicted that an increase in the atmospheric CO_2 level with lead to a warming of the globe ("greenhouse effect") which will cause the melting of polar ice (Kellogg, 1979; Thompson and Schneider, 1981; Bently, 1983; Revelle, 1983). This could raise the sea level by as much as several meters (Hoffman *et al.*, 1983) and lead to major catastrophes in coastal cities (Chen and Lin, 1987). Intensive studies of the various aspects of the global carbon system are thus a matter of urgency and are being conducted in many countries. One of the most probable ways of the neutralization of the CO_2 increase in the atmosphere is its penetration to the deep oceans, accompanied by the dissolution of $CaCO_3$, resulting in the increase of total carbonate in the ocean waters. The deep oceans may thus be considered as a major sink for excess carbon dioxide (Moore, 1987). According to various estimations, the residence time of the deep water ranges from 700-1 000 years (Southam and Peterson, 1985) to 1 600 years (Broecker, 1974); therefore, the sunken CO_2 is effectively removed from the atmosphere during this time interval. Evidence of anthropogenic CO_2 penetration in the world ocean has been reported during the last decade by numerous scientists (Brewer, 1978; Broecker *et al.*, 1979; Chen and Millero, 1979; Jones and Levy, 1981; Broecker and Peng, 1982; Chen and Drake, 1986; *etc.*).

The northern Red Sea-Gulf of Elat system has no water input from the surrounding land. Changes in the carbonate chemistry parameters of this system are consequently controlled by carbon dioxide penetration from the atmosphere to the seawater, by chemical processes in the water column, and by the water body formation mechanism. The study of this limited area cannot solve quantitatively the problem of the global ocean's role in the regulation of atmospheric carbon dioxide content. However, the anthropogenic carbon dioxide excess signal will be computed for use as a geochemical tracer.

The Red Sea – Gulf of Elat system, part of the Syrian-African rift valley, is an embryonic ocean in the process of opening by sea floor spreading, in which the Gulf of Elat constitutes a deep and wide open fracture zone (Ben-Avraham *et al.*, 1979), separated from the Red Sea by a shallow still (253 m, Anati, 1980) at the Strait of Tiran. The gulf itself reaches a maximum depth of *ca.* 1 800 m. Its width is roughly 14-26 km and its length is *ca.* 180 km. The general winter circulation pattern in the Red Sea-Gulf of Elat has been studied during the past two decades and is described in Klinker *et al.* (1976) and Paldor and Anati (1979) for the Gulf of Elat, and in Morcos (1970), Manins (1973), Maillard (1974), Ross (1983), Poisson *et al.* (1984), Cember (1988) and Metzl *et al.* (1989) for the northern Red Sea.

The circulation pattern in the Gulf of Elat is driven mainly by thermohaline gradients and wind stress. Surface water of the northern Red Sea enters the Gulf of Elat through the Strait of Tiran and flows northward against the prevailing northern winds. These surface waters become cooler and more saline, hence denser. In the northern part of the Gulf of Elat, these dense waters sink and a return flow, developed above sill depth, forms part of the deep saline water in the northern Red Sea. Clearly the deep water in the northernmost Red Sea is formed by the overflow of cool and saline waters from both the gulfs of Elat and Suez. Therefore we can expect that various patterns of signal of anthropogenic CO_2 penetration in these two water bodies (the Gulf of Elat and the Red Sea) will be observed.

RESULTS AND DISCUSSION

A method for the calculation of the anthropogenic CO_2 signal has been documented in Chen and Millero (1979) and Poisson and Chen (1987). Although the method is subject to large uncertainties (sometimes reaching ± 20 µmol kg^{-1} according to Chen, 1982), the precision of the method is adequate to show the excess CO_2 signal. Therefore the CO_2 data can be very useful for tracing waters formed in the last 140 years (Chen, 1980). A portion of the surface seawater in contact with the air has a certain steady state carbon dioxide concentration. The amount of total dissolved carbon dioxide (ΣCO_2) in this water is defined as ΣCO_2^0, which depends on the partial CO_2 pressure in the air as well as the salinity and the temperature of the water. As the seawater portion sinks, the *in situ* decomposition of organic carbon and the dissolution of particulate $CaCO_3$ add dissolved CO_2 to this seawater portion. Consequently the measured ΣCO_2 at each depth becomes larger than ΣCO_2^0. The values of ΣCO_2^0 can be calculated from the measured ΣCO_2 values for any particular depth by correcting them for carbon dioxide originating from organic carbon decomposition and $CaCO_3$ dissolution. The chemically-added CO_2 can in turn be calculated by the modified Redfield *et al* (1963) model using the total titration alkalinity (TA) and the apparent oxygen utilization (AOU) data. The biological material decay model (Redfield *et al.*, 1963) with the addition of $CaCO_3$ dissolution can be presented as:

$$(CH_2O)_{106}(NH_3)_{16}H_3PO_4 + 138\,O_2 + CaCO_3 \rightleftarrows 106\,CO_2 + 16\,HNO_3 + H_3PO_4 + Ca^{2+} + CO_3^{2-} + 122\,H_2O. \quad (1)$$

According to equation 1, the combined effect of the dissolution of x moles of $CaCO_3$ and decomposing y moles of organic matter in 1 kg of seawater on the changes of the concentrations of carbon, nitrogen, phosphorus, oxygen and TA can be represented as (Chen and Millero, 1978; Chen *et al.*, 1982*a*):

$$\Sigma CO_2 - \Sigma CO_2^0 = \Delta\Sigma CO_2 = x + 106y \quad (2)$$

$$TA - TA^0 = 2x - 17y \quad (3)$$

$$AOU = 138y \quad (4)$$

where TA^0 is the titration alkalinity of the surface seawater portion, and AOU is the apparent oxygen utilization defined as the difference between the saturation values calculated for the potential temperature of the sample by the Weiss (1970) formula and the measured value at each depth:

$$AOU = O_{2(sat)} - O_{2(meas)}. \quad (5)$$

Eliminating x and y from the equations 2-4 yields:

$$\Delta\Sigma CO_2 = 0.5[TA - TA^0] + 0.83\,AOU. \quad (6)$$

The right part of equation 6 represents the amount of total dissolved carbon dioxide originating from organic matter decomposition and $CaCO_3$ dissolution. Thus, having the experimental values of total dissolved carbon dioxide ($\Sigma CO_{2,calc}$) for each depth, we can calculate the total dissolved carbon dioxide content in this seawater portion at the time it was on the sea surface ($\Sigma CO^0_{2,\,old}$):

$$\Sigma CO^0_{2,\,old} = \Sigma CO_{2,calc} - \Delta\Sigma CO_2$$
$$= \Sigma CO_{2,calc} - 0.5[TA - TA^0] - 0.83\,AOU. \quad (7)$$

Then the signal of anthropogenic CO_2 penetration will be defined as follows:

$$\Delta\Sigma CO_2^0 = \Sigma CO^0_{2,\,old} - \Sigma CO^0_{2,\,present} \quad (8)$$

where $\Sigma CO^0_{2,\,old}$ and $\Sigma CO^0_{2,\,present}$ are the total dissolved carbon dioxide values for water formed some time ago and for water formed between 1981 and 1982, respectively. Thus, the values $\Sigma CO^0_{2,\,present}$ are total dissolved carbon dioxide content for surface sea water at the sampling time.

The above scheme is based on the Redfield stoichiometry $C:N:P:O_2 = 106:16:1:(-138)$ for organic matter suggested by Redfield *et al.* (1963) for the western Atlantic waters, and has been shown to be correct also in some other locations of the world ocean (*e.g.* Kumar, 1985). However, during recent years some data (*e.g.* Anderson and Dyrssen, 1981; Broecker and Peng, 1982; Takahashi *et al.*, 1985; Naqvi *et al.*, 1986; Papaud and Poisson, 1986; Minster and Boulahdid, 1987; Peng and Broecker, 1987; Boulahdid and Minster, 1989) demonstrated that coefficients characterizing the ratio $C:N:P:O_2$ sometimes differ from those suggested by equation (1). The variations in the $C:N:P:O_2$ ratios reported for world ocean waters resulted in the variability of the coefficient connected to AOU in equations (6) and (7) (RKR factor) from 0.75 (Kroopnick, 1985) to 0.865 (Naqvi *et al.*, 1986). The item RKR.AOU in equation (7) is a minor item, compared to the others, and the use of one particular RKR value instead of another can result in only a minor bias in the calculated $\Delta\Sigma CO_2^0$ values. Therefore the variation of the RKR factor, even between its extreme values, causes no appreciable changes in the conclusions.

The limitations of the $\Delta\Sigma CO_2^0$ calculation method have been described in detail elsewhere (Chen and Millero, 1979; Chen and Pytkowicz, 1979; Chen *et al.*, 1982*b*; Shiller, 1981; Chen, 1982). Summarizing equations (7)-(8) gave results with a precision ranging from ± 5 to ± 20 μmol kg^{-1} for various data sets, as stated by Chen (1982). Taking into account the experimental precision of our data (discussed below) and the scatter of the data, the uncertainties of the $\Delta\Sigma CO_2^0$ values are actually as good as *ca.* ± 10 μmol kg^{-1} for all the *Tiran*-02 cruise stations.

The calculations of the signal of anthropogenic CO_2 penetration in the Red Sea and in the Gulf Elat were carried out using pH, total titration alkalinity (TA) and dissolved oxygen content, measured on board R/V *Shikmona* during the *Tiran*-02 cruise in February 1982. The whole track of the cruise is presented in Figure 1 with station description in Table 1. The experimental

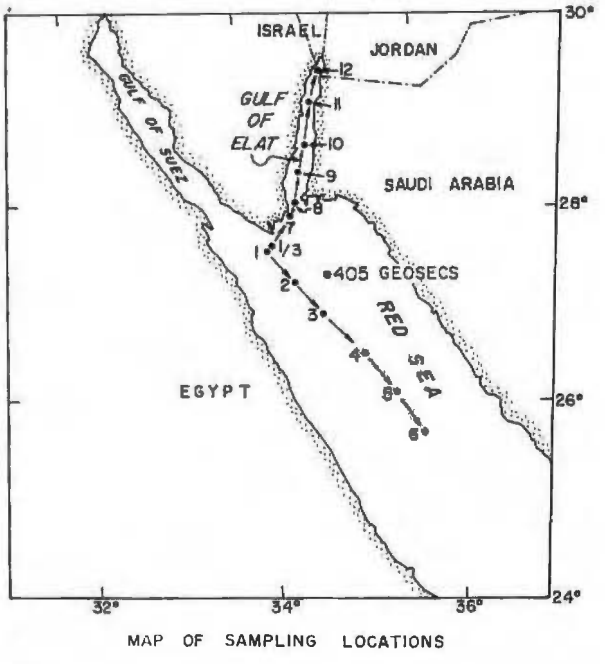

Figure 1
Map of sampling locations for the Tiran-02 *cruise.*

Table 1
Station description.

Stn No.	Sampling date	Sampling time (local)	Station position
1	1 Feb. 82	13^{00}	27°33′N, 34°14′E
2	1 Feb. 82	20^{30}	27°12′N, 34°32′E
3	2 Feb. 82	06^{10}	26°54′N, 34°46′E
4	2 Feb. 82	15^{35}	26°31′N, 35°09′E
5	3 Feb. 82	01^{00}	26°05′N, 35°25′E
6	3 Feb. 82	10^{45}	25°43′N, 35°46′E
1/3 (*)	5 Feb. 82	10^{30}	27°35′N, 34°13′E
7	5 Feb. 82	19^{20}	27°55′N, 34°26′E
8	6 Feb. 82	01^{30}	27°59′N, 34°27′E
9	6 Feb. 82	07^{35}	28°18′N, 34°31′E
10	6 Feb. 82	17^{35}	28°40′N, 34°37′E
11	6 Feb. 82	23^{15}	29°05′N, 34°43′E
12	7 Feb. 82	07^{15}	29°26′N, 34°53′E

(*) Sampling was conducted after a strong storm.

Table 2
Hydrographic data and carbonate chemistry parameters for the Tiran-02 cruise in the Gulf of Elat and the northern Red Sea in 1982.

	Depth (m)	$pH_{in\ situ}$	TA, (meq kg^{-1})	$\Sigma CO_{2,calc.}$ (mmol kg^{-1})	AOU, (μmol kg^{-1})
Station 1	3.1	8.270	2.501	2.102	0.8
	74.4	8.269	2.502	2.101	−1.3
	149.5	8.255	2.504	2.115	7.1
	199.6	8.210	2.494	2.139	41.6
	249.6	8.177	2.493	2.159	77.0
	349.1	8.133	2.481	2.173	90.6
	449.1	8.066	2.469	2.200	143.4
	547.1	8.071	2.477	2.203	134.6
	645.7	8.071	2.461	2.186	134.6
	746.5	8.080	2.467	2.184	123.8
	841.9	8.087	2.468	2.179	117.0
	939.9	8.106	2.485	2.182	109.3
Station 3	2.4	8.274	2.495	2.092	2.4
	18.8	8.276	2.502	2.096	2.3
	59.1	8.270	2.507	2.108	2.6
	120.4	8.244	2.504	2.125	24.2
	198.7	8.200	2.490	2.143	55.5
	299.0	8.130	2.487	2.182	107.4
	496.8	8.090	2.464	2.180	133.7
	644.4	8.075	2.472	2.194	136.6
	743.7	8.094	2.474	2.183	123.9
	843.5	8.117	2.480	2.172	100.4
	941.6	8.115	2.476	2.168	91.7
	1 076.9	8.108	2.483	2.176	90.8
Station 4	2.3	8.263	2.492	2.091	2.5
	48.7	8.260	2.503	2.100	4.2
	88.8	8.263	2.506	2.107	0.4
	148.9	8.248	2.510	2.125	14.9
	202.7	8.198	2.496	2.149	54.5
	302.9	8.093	2.476	2.194	130.8
	470.3	8.050	2.476	2.215	156.0
	694.7	8.055	2.471	2.203	145.3
	841.4	8.078	2.481	2.196	120.0
	982.9	8.108	2.480	2.176	98.8
	1 088.8	8.114	2.483	2.173	93.0
	1 178.1	8.112	2.484	2.172	91.9
Station 5	2.8	8.272	–	–	2.4
	58.6	8.274	–	–	4.4
	88.5	8.259	–	–	11.8
	117.9	8.261	–	–	9.9
	148.1	8.231	–	–	33.8
	248.8	8.164	–	–	88.0
	397.8	8.069	–	–	153.2
	546.9	8.057	–	–	156.0
	694.2	8.077	–	–	137.6
	842.5	8.088	–	–	125.9
	1 040.3	8.106	–	–	99.7
	1 172.3	8.106	–	–	97.7
Station 6	3.0	8.271	2.496	2.092	3.8
	58.8	8.264	2.507	2.109	1.9
	178.1	8.205	2.495	2.144	53.6
	239.1	8.149	–	–	90.0
	298.5	8.114	–	–	117.2
	399.6	8.066	2.484	2.215	152.2
	496.5	8.059	2.477	2.210	143.1
	594.8	8.065	2.480	2.209	145.3
	794.4	8.084	2.474	2.188	130.7
	1 090.0	8.103	2.476	2.173	107.3
	1 239.6	8.107	2.477	2.167	101.4
Station 1/3	3.2	–	2.506	2.052	−2.0
	3.2	–	2.506	2.052	3.8
	3.2	–	2.506	2.052	2.8
	204.9	–	2.503	2.073	19.7
	204.9	–	2.503	2.073	21.7
	407.1	–	2.492	2.106	–
	407.1	–	2.492	2.106	–
	609.0	–	2.478	2.156	125.8
	801.6	–	2.478	2.111	126.7
	1 077.5	–	2.497	2.140	–
	1 077.5	–	2.496	2.139	–
Station 7	2.9	8.295	2.503	2.087	4.7
	75.1	8.295	2.516	2.097	5.5
	148.3	8.291	2.507	2.090	6.4
	148.3	8.295	2.507	2.087	5.5
	198.7	8.264	2.523	2.125	23.9
	248.0	8.245	2.511	2.128	37.4
	298.4	8.250	2.508	2.120	
	496.8	8.195	2.508	2.154	–
	694.1	8.085	2.505	2.218	145.2
	891.9	8.126	2.478	2.163	110.2
	1 139.6	8.137	2.493	2.166	97.6
Station 8	3.4	8.322	2.524	2.086	4.9
	149.5	8.309	2.517	2.090	8.7
	368.9	8.284	2.510	2.099	19.4
Station 9	2.9	8.296	–	–	6.0
	48.9	8.295	–	–	6.8
	89.4	8.285	–	–	10.4
	118.0	8.284	–	–	2.7
	159.5	8.282	–	–	10.8
	249.2	8.277	–	–	12.8
	299.5	8.264	–	–	17.4
	399.5	8.244	–	–	35.2
	497.9	8.234	–	–	41.2
	595.7	8.227	–	–	44.3
	743.2	8.222	–	–	45.3
	950.5	8.212	–	–	47.1
Station 10	3.6	8.271	2.512	2.118	4.8
	99.8	8.267	2.510	2.117	5.7
	200.1	8.261	2.514	2.122	5.7
	299.1	8.237	2.506	2.131	22.9
	399.7	8.218	2.512	2.149	36.5
	791.2	8.190	–	–	45.6
	990.6	8.182	2.502	2.152	43.6
	1 138.5	8.177	2.505	2.153	45.4
	1 285.7	8.174	2.500	2.149	44.4
	1 384.8	8.178	2.497	2.141	45.3
	1 505.5	8.161	2.498	2.151	46.2
Station 11	3.4	8.281	–	–	6.0
	59.8	8.283	–	–	5.8
	118.7	8.279	–	–	5.8
	301.6	8.264	–	–	12.1
	337.0	8.248	–	–	26.9
	380.7	8.231	–	–	40.3
	447.5	8.223	–	–	42.3
	498.1	8.224	–	–	43.3
	595.6	8.213	–	–	44.3
	689.4	8.209	–	–	46.3
	790.1	8.201	–	–	48.2
Station 12	2.2	8.278	2.510	2.112	5.2
	98.9	8.281	2.511	2.108	6.1
	198.2	8.278	2.507	2.105	6.0
	296.4	8.274	2.506	2.104	4.9
	347.5	8.248	2.508	2.122	21.1
	397.1	8.225	2.506	2.139	40.5
	446.0	8.217	2.507	2.145	41.7
	595.1	8.185	2.500	2.156	45.7
	694.3	8.203	2.506	2.148	46.6
	807.0	8.200	2.494	2.137	48.5

results and the calculated total dissolved carbon dioxide are summarized in Table 2. The pH values presented in the table were calculated for *in situ* conditions according to Millero (1979).

Total alkalinity measurements were carried out by the method developed by Edmond (1970). The end-point of titration was determined by an automatic digital titration system (Radiometer DTS-833) using a glass electrode (G2040C) and a calomel electrode (K4040). The total alkalinities in volumetric scale were converted to weight units using the seawater densities calculated by the one atmosphere International Equation of State

of Seawater 1980 (UNESCO, 1981). The precision of the total alkalinity determination was *ca.* 0.003 meqv kg^{-1}. pH measurements of seawater samples were carried out at 25°C with a precision of ±0.002 pH in the water as soon as the samples were taken from the Niskin bottles, immediately after sampling for oxygen, in special vessels similar to those described in the UNESCO report (1983). A combined glass electrode (GK2401C) with a Radiometer pH meter (PHM64) were used for pH measurements. Oxygen analysis was conducted using the modified Winkler method (Strickland and Parsons, 1972) with a precision of ±0.5% (one standard deviation). Details of the experimental part and calculations of the carbonate chemistry parameters have been reported earlier (Millero, 1979; Millero *et al.*, 1979; Krumgalz and Erez, 1984). All these parameters were calculated under *in situ* conditions, taking into account the temperature, pressure and salinity corrections. The apparent dissociation constants of carbonic and boric acids, valid for the high salinities encountered in the Red Sea, were taken from Mehrbach *et al.* (1973) and from Takahashi *et al.* (1970), respectively.

The TA^0, $\Delta\Sigma CO_2^0$ and other chemical properties, except AOU, have been normalized on a constant 35 salinity basis (to take account either evaporation or precipitation effects) as:

$$(\text{Property})_{\text{norm}} = (\text{Property})_{\text{meas}} \times 35.000/S_{\text{meas}} \qquad (9)$$

where subscripts "norm" and "meas" relate to the normalized and measured properties, respectively.

Chen and Pytkowicz (1979) and Kroopnick (1985), using the GEOSECS expedition data for world oceanic waters, reported that TA^0 and ΣCO_2^0 showed linear temperature dependence in the natural temperature interval. As may been seen from Figure 2, based on our data for the surface waters of the northern Red Sea and the Gulf of Elat, such a relationship exists also in the area under study. The following equations represent the best fit of the *Tiran*-02 cruise surface TA^0 and $\Sigma CO^0_{2,\,\text{present}}$ values:

$$TA^0\,(\mu\text{eq kg}^{-1}) = 2\,698 - 8.5 \times \Theta(\pm 7) \qquad (10)$$

$$\Sigma CO^0_{2,\,\text{present}}\,(\mu\text{mol kg}^{-1}) = 2\,297 - 8.8 \times \Theta(\pm 9) \qquad (11)$$

where Θ is the potential temperature, and the numbers in parenthesis are one standard deviation of the least squares fits. However, since temperature in the studied area changed in a very narrow range, we feel that the temperature normalization in this study can introduce only a negligible effect in the calculations and may therefore be omitted.

The calculated excess carbon dioxide signals ($\Delta\Sigma CO_2^0$) based on *Tiran*-02 cruise data (Krumgalz and Erez, 1984) for the Gulf of Elat and the northern Red Sea are presented in Figure 3. The $\Delta\Sigma CO_2^0$ values are close to zero for surface waters and for the mixed layer and become negative for deeper and older waters, because at the time when these waters were formed, their performed $\Sigma CO^0_{2,\,\text{old}}$ values were lower than the present-day $\Sigma CO^0_{2,\,\text{present}}$ values. In the northern Gulf of Elat (station 12), the entire water column seems to be saturated with excess anthropogenic CO_2, indicating winter overturning of the water column. However, in the central part of the Gulf of Elat (station 10), and even in

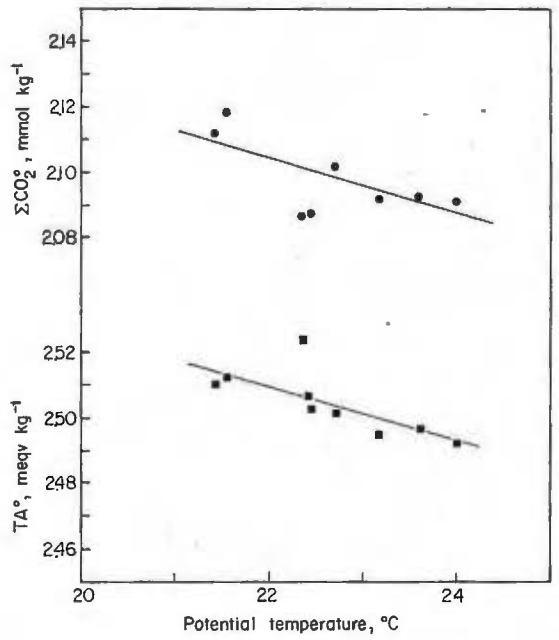

Figure 2
Surface ΣCO_2^0 and TA° values normalized to 35 salinity at various potential temperatures.

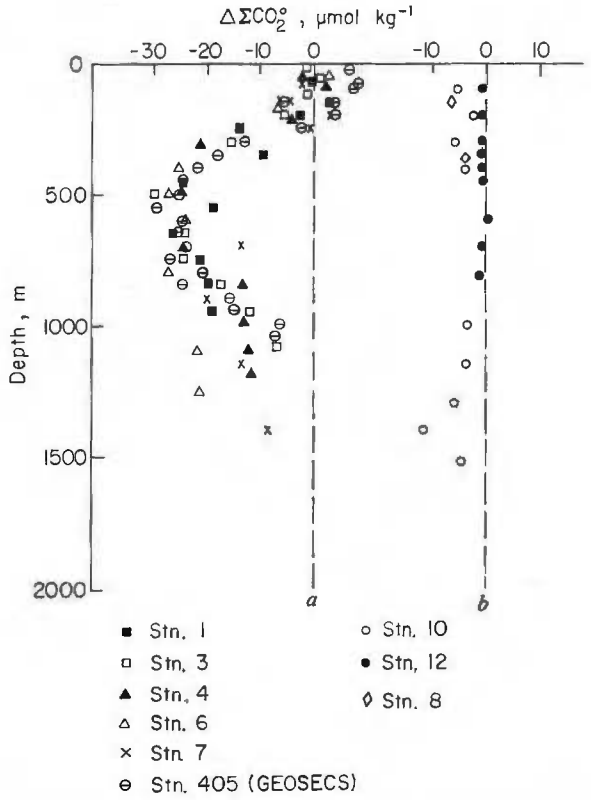

Figure 3
Depth profiles of $\Delta\Sigma CO_2^0$ for the Red Sea (a) and for the Gulf of Elat (b). The $\Delta\Sigma CO_2^0$ values for station 405 (GEOSECS) *were calculated from Weiss* et al. (1983).

the vicinity of the Strait of Tiran (station 8), old waters (negative values of $\Delta\Sigma CO_2^0$) can be observed at all depths. The results obtained for station 8, situated in the Strait of Tiran, are in good agreement with a well-developed two-layered gravitational convection circulation between the Red Sea and the Gulf of Elat (Murray *et al.*, 1984). The values of $\Delta\Sigma CO_2^0$ for the northern Red Sea decrease from about 3 to -30 μmol kg^{-1} (with uncertainties ± 10 μmol kg^{-1}) from surface to the maximum studied depth *ca.* 1 500 m, close to the sea floor. At depths of 600 ± 100 m, the $\Delta\Sigma CO_2^0$ reaches a maximum negative value, showing the strong excess CO_2 penetration in the Red Sea. These results, namely the general pattern of excess CO_2 penetration in the Red Sea, are in very good agreement with those obtained by Papaud and Poisson (1986) in the Red Sea in summer 1982.

We could expect the anthropogenic CO_2 tracer to have a distribution pattern similar to nuclear bomb tracers. In fact, the depth distribution pattern of the $\Delta\Sigma CO_2^0$ signal for the northern Red Sea (Fig. 3) is similar to the tritium and $\Delta\ ^{14}C$ vertical profiles from GEOSECS Red Sea stations (Cember, 1988), and to the helium-3 data of Andrie and Merlivat (1989) for the *Merou* cruise (July 1982) in the Red Sea. After reaching maximum negative values, -28 ± 5 μmol kg^{-1}, the $\Delta\Sigma CO_2^0$ values increase and remain almost constant (in the uncertainty range), *ca.* -15 ± 6 μmol kg^{-1}, from 800 to 1 500 m, the lowest sampling depth close to the sea floor. The increase of $\Delta\Sigma CO_2^0$ values below 600 ± 100 m can be explained by the outflow of younger waters from the Gulf of Elat (Cember, 1988) over the sill at the Straits of Tiran and from the Gulf of Suez (Morcos, 1970). A cross-section of the anthropogenic CO_2 signal in the Gulf of Elat and in the northern Red Sea (Fig. 4) demonstrates very clearly the influence of the overflow of young waters from the Gulf of Elat over the sill at the Strait of Tiran and the inflow of young waters from the Gulf of Suez in the deepening of old waters at stations 1 and 7, closest to the Gulf of Suez and Strait of Tiran, respectively. The tongue of these young waters from the gulfs of Suez and Elat spreads at a depth of about 800-1 500 m from the Strait of Tiran to the south. Relatively old waters, characterized by maximum negative $\Delta\Sigma CO_2^0$ values at a depth of *ca.* 600 ± 100 m, are sandwiched between younger waters.

Maximum of the anthropogenic CO_2 signal found around 600 m is also related to the extremes of other properties such as nutrients (silicate, nitrate, phosphate), $\Delta\ ^{14}C$, helium, tritium and oxygen (Weiss *et al.*, 1983; Krumgalz and Erez, 1984; Papaud and Poisson, 1986; Cember, 1988) at approximately the same depth. The specific features of this water layer at about 600 m depth is conditioned by three processes acting simultaneously in this area:

(*a*) intensive penetration of various geochemical tracers to depth;

(*b*) the intermediate return flow of seawater from the south in accordance with the circulation scheme presented by Manins (1973), Cember (1988) and Metzl *et al.* (1989).

(*c*) the outflow of younger waters from the Gulfs of Elat and Suez.

Thus, the intermediate return flow leads to helium maximum owing to helium enrichment from the south, while the nutrient maximum and oxygen minimum are the results of the decline of the ventilation of this water layer. The simultaneous actions of the three above-mentioned processes are also responsible for the maximum of the anthropogenic CO_2 signal at about 600 m.

Just four years before the *Tiran*-02 cruise, a GEOSECS expedition took place in the Mediterranean Sea and the Indian Ocean. One of the cruise stations (station 405) was situated not far from our station 3 in the Red Sea (*see* Fig. 1). Since station 405 (GEOSECS) was sampled in December 1977, it can be considered that this was during the same winter season as the *Tiran*-02 cruise. Therefore, a comparison of the results obtained for these stations during various cruises would be of great interest, especially concerning any changes (if any) which may have occurred between 1977 and 1982. The $\Delta\Sigma CO_2^0$ values for station 405 (GEOSECS) have been calculated by us from the GEOSECS cruise data (Weiss *et al.*, 1983) and plotted together with the *Tiran*-02 data in Figure 3. We used for calculation purposes ΣCO_2 values measured exper-

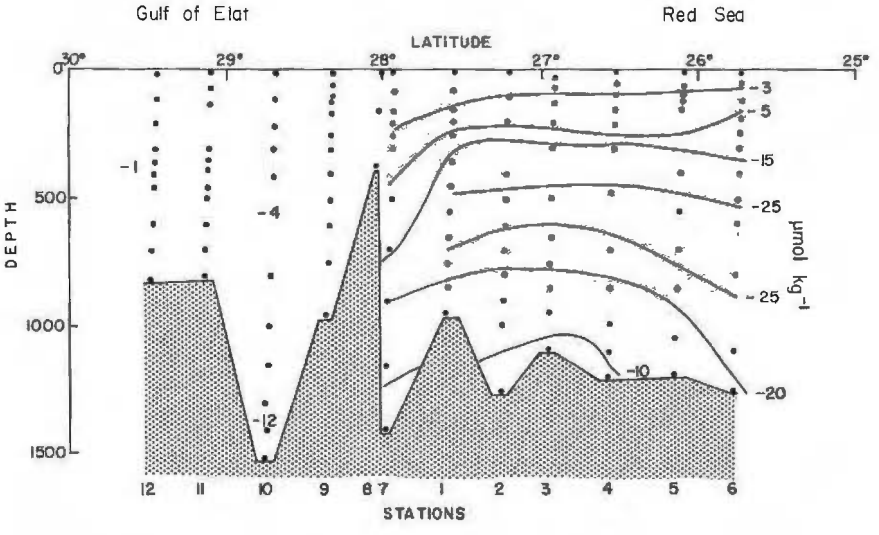

Figure 4
$\Delta\Sigma CO_2^0$ (μmol kg^{-1}) cross-section in the Gulf of Elat and in the northern Red Sea. All $\Delta\Sigma CO_2^0$ values have uncertainties ± 10 μmol kg^{-1}.

imentally during the GEOSECS cruise with a correction on -0.015 mmol kg^{-1} as was recommended by Taro Takahashi on page 7 in Weiss *et al.* (1983). However, we would like to emphasize here that this correction is responsible only for the very negligible difference in $\Delta\Sigma CO_2^0$ values (*ca.* 0.06 μmol kg^{-1}) calculated with and without this correction. Even when we used the ΣCO_2 values obtained by the same computing procedure as for our cruise, a similar depth profile of $\Delta\Sigma CO_2^0$ for station 405 (GEOSECS) was obtained within the uncertainty stated above as ± 10 μmol kg^{-1}. As may be seen from Figure 3, the maximum negative $\Delta\Sigma CO_2^0$ values for both the cruises are the same and situated at the same depth. The agreement between these two sets of data is excellent, showing that the excess CO_2 values did not change over a period of four years, and perhaps longer, since there is no evidence that this signal did not exist much earlier than 1977.

Therefore, even though the excess anthropogenic CO_2 signal reported in this article can be considered only as a qualitative one, owing to uncertainties in the calculations, it can be used as a valuable tracer for water mass formation and deep circulation in the northern Red Sea.

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