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EVIDENCE FOR RED SEA SURFACE CIRCULATION FROM OXYGEN ISOTOPES OF MODERN SURFACE WATERS AND PLANKTONIC FORAMINIFERAL TESTS

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Abstract. Hydrographic data and oxygen isotopic analyses performed on surface waters and planktonic foraminiferal tests, collected during early summer from two succeeding years (1984, 1985) throughout the Red Sea, reveal two different hydrographic regimes. In 1984 the summer "normal" situation prevailed where surface waters from the Red Sea flowed out into the Gulf of Aden, while in 1985 a reversed inflow current occurred. The higher temperatures and salinities observed in 1985 indicate high evaporation rates and increased aridity in the northern Red Sea and caused this inflow of Indian Ocean Surface Water which origins from the active upwelling region in the Arabian Sea. Lower salinities and lower oxygen isotopes were observed up to 18°N. The occurrence of *Globorotalia menardii* during 1985 with its surprisingly constant isotope values up to the Gulf of Suez indicates northward flowing surface currents for the entire Red Sea. Isotope values from *Neogloboquadrina dutertrei* (1985) indicate subsurface shell formation to about 50 m water depth. Oxygen isotope analysis on *Globigerinoides ruber* and *Globigerinoides trilobus* from the 1984 and 1985 tracks suggests that both species calcify in isotopic equilibrium with the surrounding water in the Gulf of Aden and in the northern Red Sea, while an offset from equilibrium values of up to -0.4‰ is found in the Red Sea. Occurrences of *G. menardii* in Red Sea sediments may be useful as a tool for detecting unusual hydrographic situations preserved in the sediment record, when subsurface water was brought to the surface by upwelling in the Arabian Sea and flowed into the Red Sea. As this process is triggered by high evaporation rates in the northern Red Sea region, the appearance of this species in Red Sea sediments may also indicate periods with extreme arid conditions.

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INTRODUCTION

The Red Sea is a semienclosed silled basin (Figure 1) in an arid region, where evaporation exceeds precipitation. This generally leads to an antiestuarine circulation [Seibold and Berger, 1982] in which surface waters from the Gulf of Aden flow into the Red Sea, while "deep water" spills out over the sill of Bab el Mandeb, at a maximum depth of 137 m [Werner and Lange, 1975]. However, the inflow and outflow over the sill also depend on the intensity and direction of the prevailing winds. During winter (November-April), the NE monsoon creates an inflow of surface waters, while deep waters flow out over the sill forming intermediate water in the Arabian Sea (Figure 2a). During summer, the situation is more complex. Between May and October, southwestern winds prevail producing a reversal of the monsoon and a warm, high-salinity surface water flow from the Red Sea south into the Gulf of Aden. In the Strait of Bab el Mandeb, cool subsurface low-salinity water flows into the Red Sea, while deeper, warm, high-salinity water flows out out over the sill [Patzert, 1974]. By this process the structure in the southern part of the Red Sea is made up of three layers (Figure 2b) [Neumann and McGill, 1962; Béthoux, 1980; Maillard and Soliman, 1986]. According to Neuman and McGill [1962] this three-layered circulation scheme begins in July in the southern part of Bab el Mandeb Strait but has not been found farther north in the Red Sea. The northernmost limit of the cold subsurface inflow of Indian Ocean water has been observed up to about 18°N in October by various authors [Jones and Browning, 1971; Robinson, 1973; Maillard and Soliman, 1986].

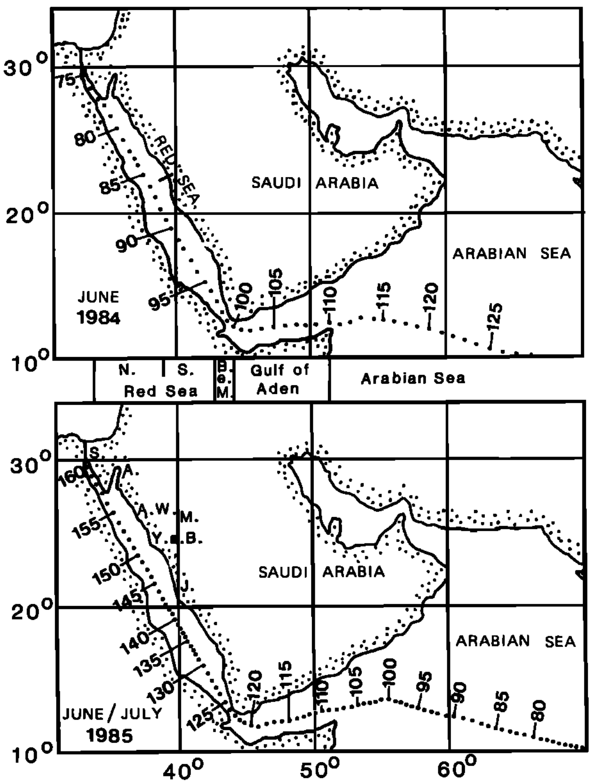

Fig. 1. Location of pump samples from 1984 and 1985. Since foraminiferal samples were obtained by pumping continuously, the mean position of every pump sample is given. S, Suez; A, Aqaba; AW, Al Wajh; M, Medina; YaB, Yanba 'al Bahr; J, Jiddah, indicating the meteorological stations which were used for temperature comparison between June 1985 and 1984. The approximate position of the different areas is indicated., N, indicating the northern and S, the southern part of the Red Sea; BeM, stands for Bab el Mandeb.

Planktonic foraminifers from the Red Sea region are extensively studied to reconstruct hydrographic changes through time as referred to by Auras-Schudnagies et al. [1989]. In this study we present isotope data for modern planktonic foraminifers and oxygen isotopic ratios of surface waters from samples taken during two succeeding summers in the Red Sea and Gulf of Aden. In addition, we discuss calcification of different species with respect to oxygen isotope equilibrium, draw conclusions on the different hydrographic situations which occurred during June 1984 and July 1985, and discuss possible paleoceanographic implications.

MATERIAL AND METHODS

As part of the Indonesian-Dutch Snellius II expedition, the Dutch R/V Tyro crossed the Red Sea twice: June 9-13, 1984, and July 6-11, 1985 (Figure 1). During both cruises, seawater from a depth of 5 m was continuously pumped and filtered over a 75 μm plankton net in order to collect planktonic foraminifera. Temperature and salinity were measured at the beginning and the end of each sampling interval. Precision of these measurements is 0.2°C and 0.3‰, respectively. In addition, water samples were taken to determine the oxygen isotopic composition of the seawater at the beginning and end of each foraminiferal sampling interval. These samples were transferred to infusion bottles and poisoned with potassium iodide. The oxygen isotopic composition of the water was automatically analyzed online with a Finnigan MAT CO_2-H_2O equilibration unit (24 samples) combined with a Finnigan MAT 251 mass spectrometer. Ten milliliters of seawater were equilibrated with CO_2 for three hours at 18°C. Every sixth sample was a standard water with known isotopic value. Reproducibility of the samples was 0.1‰, or better. These measurements are necessary, especially in an area as the Red Sea with its high salinity variability due to the high evaporation rates resulting in large variation of the oxygen isotopic composition of the water, and were used, together with the measured temperature, to calculate calcium carbonate equilibrium values [after Epstein et al., 1953]. Isotope values of the seawater samples expressed in per mil versus V-SMOW were corrected to the PDB scale by - 0.27‰ [Hut, 1987]. From the plankton samples, 20-40 specimens of foraminifera from the >250 μm fraction were hand picked for isotopic analysis after drying the sample residues and removing organic matter by means of a low-temperature asher. Our analysis includes for both years *Globigerinoides ruber* and *Globigerinoides trilobus* from the entire sample transect, and *Globorotalia menardii* and *Neogloboquadrina dutertrei*, where present. At some stations, measurements on bulk samples of *G. ruber* and *G. trilobus* were carried out when not sufficient material of each species was available (see Table 2). Stable isotopes of foraminifers were analyzed, partly at the ^{14}C laboratory, Kiel University, partly at the stable isotope laboratory in Amsterdam. For further methodological details, see Auras-Schudnagies et al. [1989]. Analytical precision of working standards at both laboratories reached during the measurements was 0.07‰. In order to check the reproducibility of the measurements from the two different labs, two samples (*G. menardii*, 94 and 101) were analyzed in Kiel and Amsterdam (see Table 3): the differences were 0.02 and 0.11‰, respectively, which is within the analytical error of each measurement itself.

RESULTS AND DISCUSSION

Hydrography of Surface Waters

By comparing temperature and salinity data from both cruises (Figure 3) two different hydrographic situations for 1984 and 1985 become obvious. In 1985, temperatures in the Western Arabian Sea were lower than comparable 1984 temperatures by 1° - 3°C. At the easternmost part of the Gulf of Aden, temperature was 27°C in 1985 (sample 108) compared to 30°C in 1984 at the same location (sample 110). Moreover, the difference in temperatures between the Western Arabian Sea and Gulf of Aden was greater (6°C)

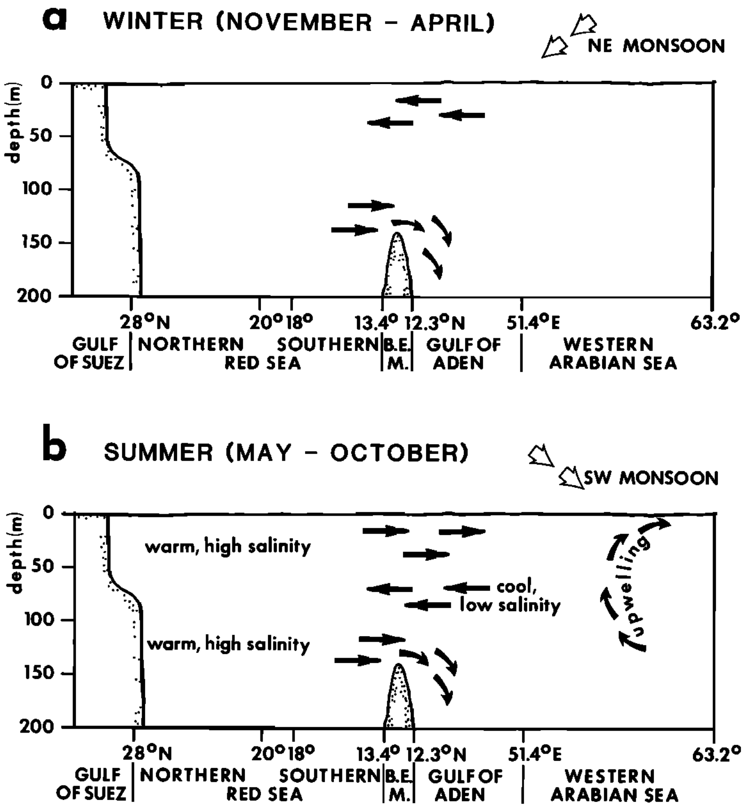

Fig. 2. Generalized models of circulation across the Strait of Bab el Mandeb (BeM) under "normal" (a) winter and (b) summer hydrographic conditions.

in 1985 than in 1984 (4°C) and the temperature transition region was also displaced to a more westerly position. These lower temperatures may indicate stronger upwelling in the western part of the Arabian Sea for 1985. In the Red Sea, between 13.4°N and 18°N, higher temperatures were observed in 1985, with a maximum of 34°C in the Strait of Bab el Mandeb. This temperature compares with the 1984 maximum of 31.5°C. Near 18°N, surface waters had a similar temperature range during both years. North of 20°N, 1985 temperatures were significantly higher as compared to 1984, pointing to more arid conditions in the region of the northern Red Sea for 1985. This observation is confirmed by temperature data from six different land stations (Figure 1) in the region for June 1984 and 1985 (Table 1) [from Die Grosswetterlagen Europas, 1984, 1985]. The mean of all temperatures is 1.1°C higher for June 1985 compared to June 1984. This results in a positive temperature anomaly of 1°C for the Red Sea region north of 20°N compared to the mean temperature values between 1931 and 1960 in this area [Die Grosswetterlagen Europas, 1985]. Salinity values from both cruises do not differ significantly in the Western Arabian Sea except for the most westerly part. There salinities in 1985 (samples 113-110) were about 0.6‰ lower than in 1984, possibly caused by stronger upwelling, leading to a difference of about 1‰ in the Gulf of Aden. In 1984, salinity between the easternmost part of the Gulf of Aden (sample 110) and the central Red Sea at 24°N (sample 84) remained relatively constant where only a slight increase of about 0.5‰ was observed, compared to the significant increase of salinity of more than 2‰ in 1985 between these two positions (samples 108-148).

These observations of temperature and salinity characterize the different hydrographic regimes during 1984 and 1985. In 1984, the "normal" summer situation prevailed (see Figure 2b) and Red Sea surface waters flowed south into the Gulf of Aden, while in 1985, as a result of anomalous high arid conditions in the northern Red Sea region (Table 1), surface waters from the Indian Ocean flowed northward into the Red Sea to about 18°N (Figure 4).

Oxygen Isotopes of Surface Waters

In 1985 oxygen isotopes of surface waters were slightly lower (0.1‰) in the Western Arabian Sea than in 1984 (Figure 5 and Table 2). Although reproducibility of the samples is within 0.1‰ and differences between the 2 years is generally between 0.1 and 0.2‰, we believe that the separation is significant because of the consistantly

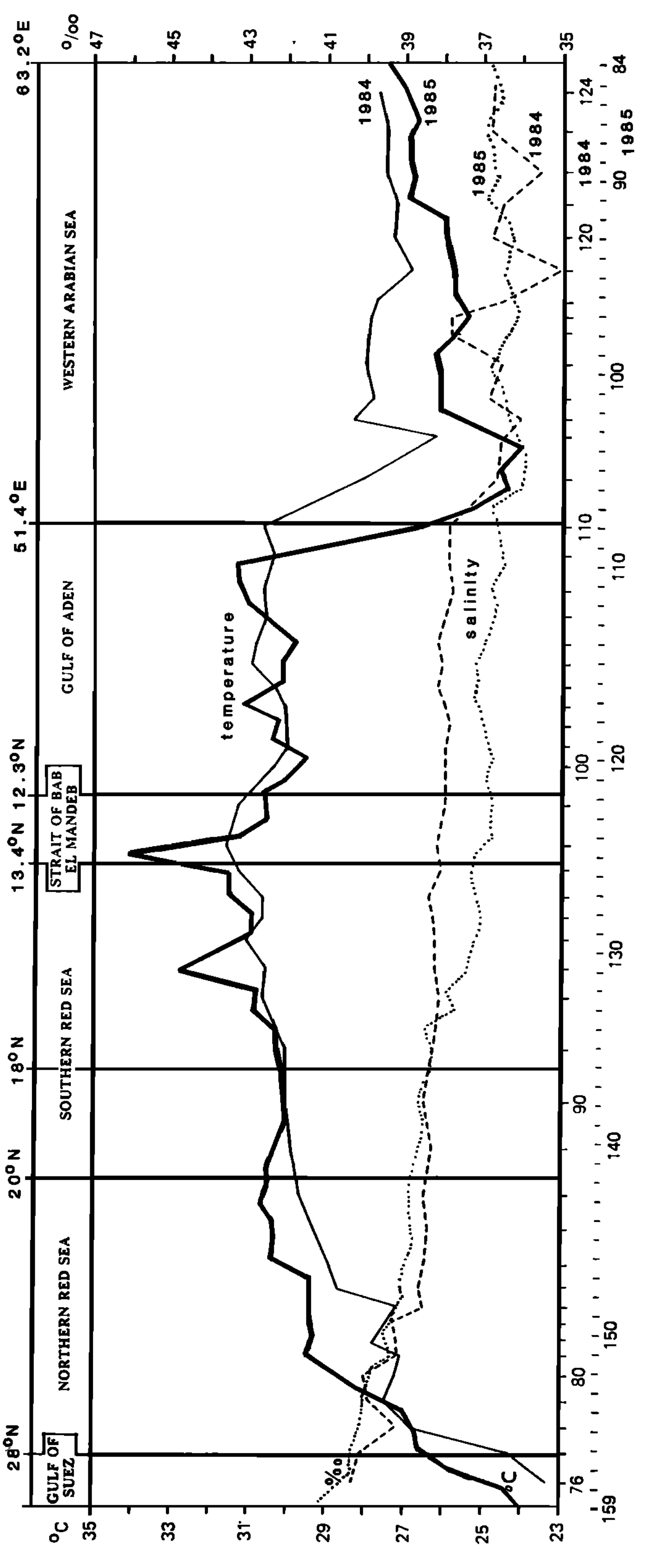

Fig. 3. Surface temperatures (solid curves) and salinities (dashed curves) measured during the 1984 and the 1985 cruise.

TABLE 1. Monthly Mean Temperatures at Six Meteorological Stations (Indicated in Figure 1) in the Northern Red Sea Region for June 1984 and 1985

	T June 1985 °C	T June 1984 °C	Δ T °C
Suez	27.9	26.5	1.4
Aqaba	31.9	29.3	2.6
Al Wajh	28.1	27.5	0.6
Medina	35.7	35.0	0.7
Yanba 'al Bahr	30.8	30.8	0.0
Jiddah	29.3	28.0	1.3
Mean			1.1

From Die Grosswetterlagen Europas [1984,1985].

higher 1984 values. The difference in the data from the 2 years was found until about 18°N. North of this latitude, values from both years are nearly identical. These isotope data confirm our earlier interpretation of the temperature and salinity data: more intense upwelling occurred in the Western Arabian Sea during 1985 and, as a result of higher evaporation rates in the northern Red Sea, Indian Ocean surface waters flowed into the Red Sea northward to approximately 18°N.

Oxygen Isotopes in Planktonic Foraminifers

The distribution of planktonic foraminifera and pteropods from both cruises has been studied and discussed by Auras-Schudnagies et al. [1989]. They show (their Figure 3) that in 1984 *Globorotalia menardii* and *Neogloboquadrina dutertrei* were limited to the Western Arabian Sea, while in 1985 both species occurred up to the northernmost part of the Red Sea. They conclude that the northern distribution of *G. menardii* in the Red Sea is dependent on the continuation of the northward surface current which in turn is caused by the high evaporation rates.

Our isotope data (Table 3) from the 1984 samples (Figure 6) show that *Globigerinoides ruber* and *G. trilobus*, typical surface dwellers [Berger, 1969], follow the trend of oxygen isotope equilibrium values. Both species nearly seem to be in isotopic equilibrium with surface sea water in the Arabian Sea and the Gulf of Aden, but in the Red Sea, they deviate up to -0.4‰. That these species calcify close to or in equilibrium is surprising if we compare our results for *G. ruber* and *G. trilobus* with those of other workers [Kahn, 1979; Duplessy et al., 1981; Fairbanks et al., 1980; Williams et al., 1981; Ganssen, 1983], who report deviations from equilibrium of -0.4 to -0.8‰. The following explanation seems plausible: during the sampling period of early summer, surface water temperatures rise quickly, especially in both the Western Arabian Sea and the Gulf of Aden regions where cool subsurface waters reach the surface caused by upwelling. Probably, the foraminifers did not build their last chambers (which form the majority of their test) during the sampling period, but rather some days before. Due to the rapid warming of surface waters, the registered temperature values used for the equilibrium calculation were too high with respect to the surrrounding temperatures during shell formation. As a result, the calculated equilibrium line may be an artifact showing reduced values compared to the isotopic composition of the foraminiferal tests.

The two other species analyzed from the 1984 samples, *Globorotalia menardii* and *Neogloboquadrina dutertrei*, were restricted to the Western Arabian Sea and have slightly higher values compared to the equilibrium line (Figure 6). Under nonupwelling conditions this would be very likely, because these two species are known to be subsurface dwellers [Berger, 1969], reflecting the lower temperatures of deeper waters. During upwelling, however, these species are brought to the surface and should reflect surface water conditions in the oxygen isotopic composition

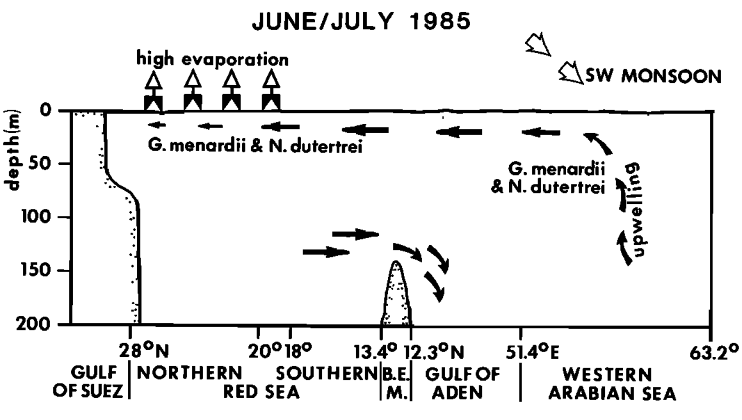

Fig. 4. Summary of the anomalous circulation in the Red Sea/Arabian Sea region during June/July of 1985 indicating the inflow of Arabian Sea surface water and the transport of *Globorotalia menardii* and *Neogloboquadrina dutertrei* into the Red Sea.

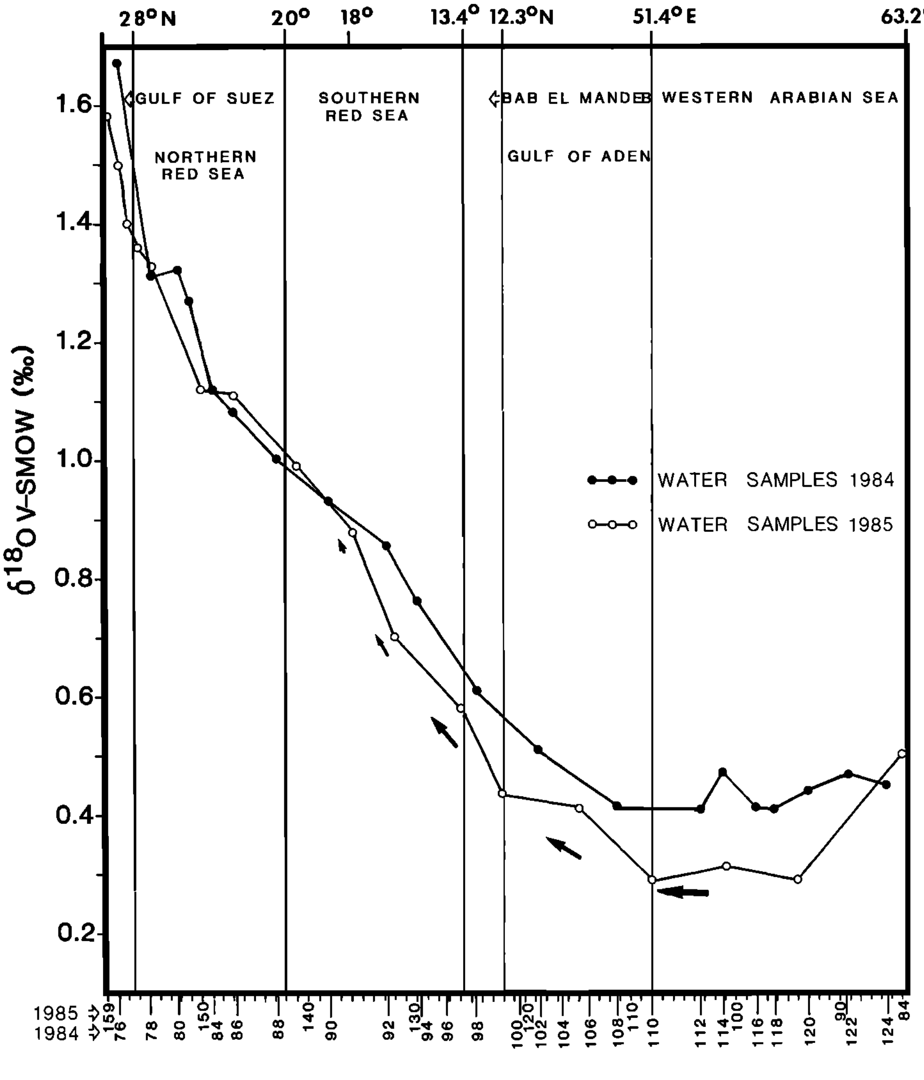

Fig. 5. Stable oxygen isotope composition (SMOW) of the surface waters from both cruises. Arrows indicate inflow of Arabian Sea surface waters.

of their tests. That this is not found may again be attributed to the process of the rapid temperature rise of the cool subsurface waters, when reaching the surface, as explained above.

The isotopic values on *Globigerinoides ruber* and *G. trilobus* from the 1985 samples fall within the calculated equilibrium line for the entire sample transect (Figure 7). *Globorotalia menardii* and *Neogloboquadrina dutertrei* from the Western Arabian Sea have, as in 1984, slightly higher values compared to the equilibrium line. In 1985, the latter two species also were present in most of the Red Sea samples and have their own isotopic signature (Figure 7). The *N. dutertrei* data follow the trend of the surface water equilibrium line. The offset of about 1‰ to higher values indicates calcification at subsurface depths. From temperature [Maillard and Soliman, 1986] and seawater oxygen isotope data [Andrié and Merlivat, 1989] we calculated calcium carbonate equilibrium values at 50 m depth. The values of -1.6‰ for the southernmost part of the Red Sea and -0.7‰ at 20°N are slightly higher than those measured on *N. dutertrei* at the same positions. This indicates that *N. dutertrei* continued to grow in the southern Red Sea at subsurface depths slightly above 50 m. The fact that this species occurred at the sampling depth of 5 m is probably the result of vertical migration. Unlike the isotopic trend of *N. dutertrei* collected in the Red Sea, the values of *G. menardii* from 1985 are nearly constant throughout the Red Sea to the Gulf of Suez (Figure 7).

TABLE 2. Oxygen Isotopes of Surface Waters in Per Mil V-SMOW

1984	$\delta^{18}O$		1985	$\delta^{18}O$	
Sample	Begin	End	Sample	Begin	End
76	1.70	1.63	84	0.23	0.23
78	1.34	1.28	94	0.02	0.01
80	1.41	1.25	101	0.03	0.04
84	1.04	1.17	108	0.01	0.03
86	1.17	0.98	115	0.20	0.07
88	1.02	0.96	122	0.08	0.24
90	0.95	0.91	126	0.29	0.32
92	0.90	0.79	132	0.37	0.49
94	0.84	0.67	136	0.56	0.65
102	0.54	0.47	141	0.74	0.69
108	0.38	0.44	147	0.85	0.82
112	0.37	0.44	150	0.80	0.90
114	0.47	0.40	155	1.05	1.07
116	0.42	0.39	157	1.10	1.15
118	0.39	0.43	159	1.31	1.31
120	0.47	0.44			
122	0.46	0.48			
124	0.48	0.41			

Samples were taken at the beginning and the end of each foraminiferal sampling interval.

This indicates that specimens of *G. menardii* stopped building chambers while entering the Gulf of Aden and were transported with the inflowing surface water throughout the total Red Sea, staying alive but not secreting calcium carbonate. It is remarkable that *G. menardii* still occurred in the extreme north of the Red Sea, while based on the hydrographic data and the oxygen isotopes of the surface waters, the inflowing water could not be traced farther than 18°N. We do not have a clear explanation for this discrepancy, but the numbers of specimens drop significantly farther north [Auras-Schudnagies et al., 1989], which may indicate that the main current did not flow north of 18°N but rather that a subsidiary current was present and remnants of Indian Ocean water mixed with "normal" northern Red Sea water.

Surface current velocities of up to 1 m/s in the Strait of Bab el Mandeb [Siedler, 1968] indicate that it takes about 2 weeks for a planktonic foraminifer to "ride" from the Gulf of Aden to the Northern Red Sea. *G. menardii* survives such a journey in a sort of sleeping stage, when it does not add any more chambers to its test.

Implications for Paleoceanography

The situation in early summer 1985, when specimens of *Globorotalia menardii* occur throughout the Red Sea, is probably exceptional [Auras-Schudnagies et al., 1989]. However, this species has been recorded in sediments of

TABLE 3. Oxygen Isotopes of the Planktonic Foraminifers *Globigerinoides ruber*, *G. trilobus* (tril.), *Globorotalia menardii* (men.) and *Neogloboquadrina dutertrei* (dut.) in Per Mil PDB From the Fraction 250-400 μm

1984		$\delta^{18}O$			1985			$\delta^{18}O$			
Sample	ruber	tril.	men.	dut.	Sample	ruber	tril.	ru./tr.	men.		dut.
76	-0.63	-0.46			84	-2.26*	-2.39*		-1.90		-1.93
78	-1.49	-1.39			94		-1.75*		-1.67	-1.69*	-1.50
80		-1.35			101	-2.04*	-2.09*		-1.88	-1.77*	-1.99
84	-2.11	-1.72			108			-2.34*	-1.83		-1.85
86	-1.88	-1.96			115			-2.44*	-1.86		-1.92
88	-2.29	-2.12			122			-2.40*	-1.79		-2.34
90	-2.58	-2.36			126				-1.87		-1.94
92	-2.86	-2.70			132		-2.51*		-1.91		-1.67
94	-3.04	-2.82			136		-2.31*		-1.97		
102	-2.86	-2.67			141			-2.31*	-1.93		-1.07
108		-2.94			147		-2.26*		-2.25		
112	-2.29	-2.07	-1.63	-1.80	150		-1.93*		-1.98		
114	-2.39	-2.21	-2.23	-2.10	155		-1.36*		-2.00		
116	-2.51	-2.71	-2.05	-2.28	157			-1.20*	-1.75		
118	-2.19	-2.12	-1.95	-1.81	159				-2.24		
120	-2.10	-2.07	-1.88	-1.75							
122	-2.23	-2.08	-1.89	-1.82							
124	-2.46	-2.27	-2.09	-2.15							

*Analyzed in Amsterdam.

ru./tr., bulk sample of *G. ruber* and *G. trilobus*.

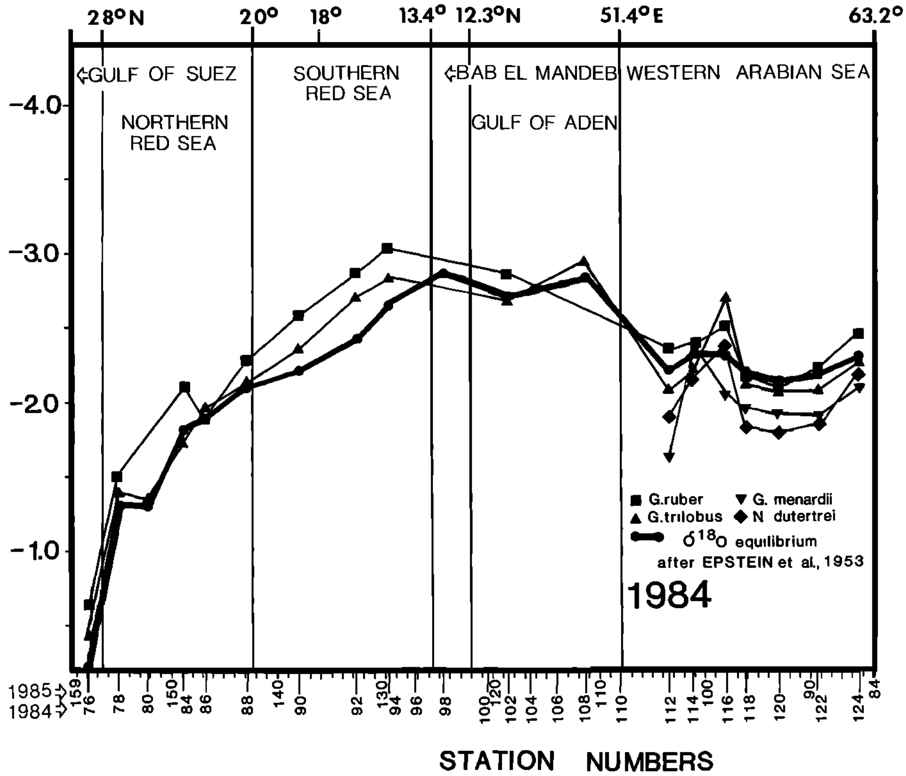

Fig. 6. Isotopic composition of the analyzed tests of living planktonic foraminifers from the 1984 cruise, compared with the oxygen isotopic equilibrium curve (PDB).

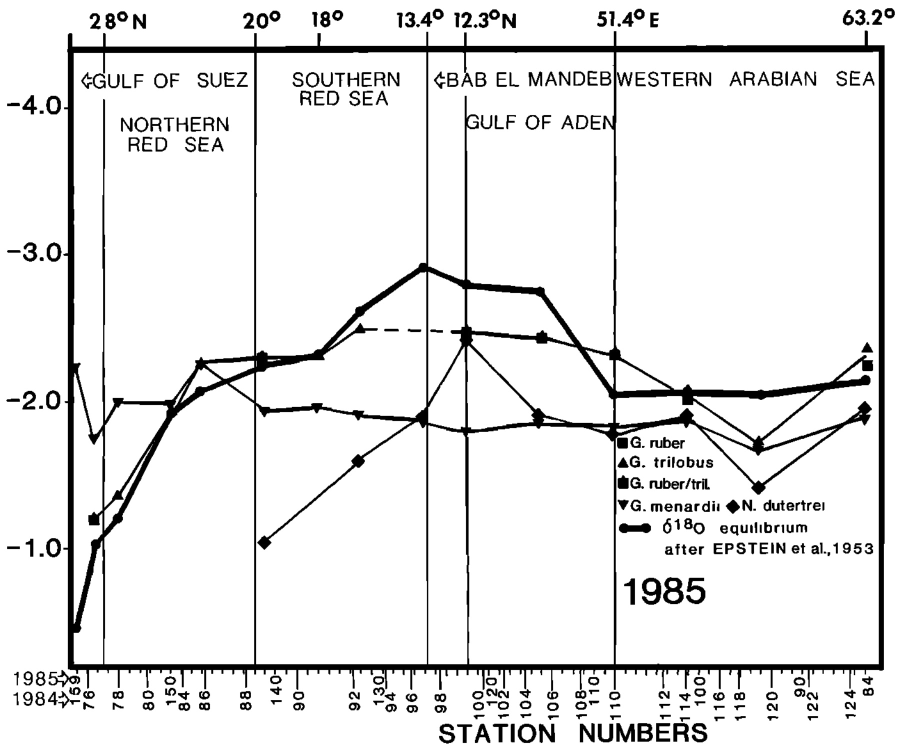

Fig. 7. Isotopic composition of the analyzed tests of living planktonic foraminifers from the 1985 cruise, compared with the oxygen isotopic equilibrium curve (PDB).

Holocene age up to nearly 24°N [Rosenberg-Herman, 1965]. Locke and Thunell [1988] also report at 18°N a sporadically occurrence of *G. menardii* in sediments from the socalled "aplanktonic zone" around 16,000 years B.P. These and possibly other appearances of *G. menardii* in the Red Sea probably can be interpreted as being the result of inflowing waters from the Arabian Sea caused during exceptionally high arid conditions in the northern Red Sea area and intense upwelling in the Western Arabian Sea. Parallel isotope analysis of this species from sediment samples from the Red Sea, bearing the isotopic signature of the Arabian Sea, and for example, *Globigerinoides ruber* as a real Red Sea surface water species, can thus provide a tool for reconstructing hydrographic differences between the Red Sea and the Arabian Sea. Unfortunately, up to now no isotope data from *G. menardii* from Red Sea sediments are available, and some questions remain unresolved:

For instance, does *G. menardii* occur in the Red Sea during these exceptional summer situations when intensive upwelling in the western Arabian Sea occurred simultaneous with high evaporation rates in the Northern Red Sea causing an inflow of Arabian Sea surface water? Are other species also expatriated from the Indian Ocean into the Red Sea during winter?

CONCLUSIONS

On the basis of our interpretation of hydrographic data, isotope values of surface waters and planktonic foraminifera from the same waters of the Gulf of Aden and the Red Sea, we make the following conclusions:

1. In July 1985 an exceptional hydrographic situation occurred in the Red Sea, caused by high evaporation in the northern Red Sea area. Anomalous high arid conditions in this region are confirmed by meteorological observations. Inflow of Indian Ocean Surface Water is suggested by temperature, salinity, and oxygen isotope data of surface water northward to 18°N; isotope data from *Globorotalia menardii* indicate that patches of water continued to flow to the north as far as the Gulf of Suez. This situation was not observed in June 1984 when normal summer circulation with outflowing Red Sea surface water dominated.

2. In 1985, *Neogloboquadrina dutertrei* was expatriated from the Gulf of Aden but continued to grow in the Red Sea down to approximately 50 m water depth. *G. menardii* probably "rode" with the inflowing water and survived its journey in a sort of "sleeping" stage when it did not add chambers to its test.

3. *Globigerinoides ruber* and *G. trilobus*, analyzed in samples from 1984 and 1985, seem to calcify nearly in oxygen isotopic equilibrium with the surrounding water, namely, in the Gulf of Aden and Arabian Sea area. However, calculated isotopic equilibrium values may have been too low because of rapidly increasing temperatures of the water during early summer.

4. Foraminiferal distribution and stable isotope data from Red Sea sediments have to be interpreted with care. Since our data for the modern situation can be interpreted in terms of exceptional hydrographic situations of inflowing Indian Ocean Surface Waters caused by the anomalous high arid conditions in the northern Red Sea area and intense upwelling in the Arabian Sea during the early summer, the fossil record can be used as a paleoclimatic tool to detect past extreme arid conditions of the northern Red Sea area.

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