

Environmental and biological effects on the stable oxygen isotope records of corals in the northern Gulf of Aqaba, Red Sea

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ABSTRACT: Monthly $\delta^{18}\text{O}$ records of 2 coral colonies (*Porites cf. lutea* and *P. cf. nodifera*) from different localities (Aqaba and Eilat) from the northern Gulf of Aqaba, Red Sea, were calibrated with recorded sea surface temperatures (SST) between 1988 and 2000. The results show high correlation coefficients between SST and $\delta^{18}\text{O}$. Seasonal variations of coral $\delta^{18}\text{O}$ in both locations could explain 91 % of the recorded SST. Different $\delta^{18}\text{O}$ /SST relations from both colonies and from the same colonies were obtained, indicating that $\delta^{18}\text{O}$ from coral skeletons were subject to an extension rate effect. Significant $\delta^{18}\text{O}$ depletions are associated with high extension rates and higher values with low extension rates. The relation between coral skeletal $\delta^{18}\text{O}$ and extension rate is not linear and can be described by a simple exponential model. An inverse relationship extends over extension rates from 1 to 5 mm yr⁻¹, while for more rapidly growing corals and portions of colonies the relation is constant and the extension rate does not appear to have a significant effect. We recommend that $\delta^{18}\text{O}$ values be obtained from fast-growing corals or from portions in which the isotopic disequilibrium is fairly constant (extension rate >5 mm yr⁻¹). The results show that interspecific differences in corals may produce a significant $\delta^{18}\text{O}$ profile offset between 2 colonies that is independent of environmental and extension-rate effects. We conclude that the rate of skeletal extension and the species of coral involved have an important influence on coral $\delta^{18}\text{O}$ and must be considered when using $\delta^{18}\text{O}$ records for paleoclimatic reconstructions.

KEY WORDS: Stable oxygen isotopes · Coral extension rate · Coral calcification rate · *Porites* spp. · Gulf of Aqaba · Red Sea

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INTRODUCTION

Massive-growing corals can be used as environmental recorder because their annual growth bands allow the reconstruction of accurate chronologies (Knutson et al. 1972). Massive hermatypic coral skeletons are excellent monitors of tropical water environments. Corals of this type live in the surface-ocean mixed layer, grow continuously at rates of several mm to cm per yr, and during growth incorporate isotopic species into their skeleton.

The stable oxygen isotopic composition ($\delta^{18}\text{O}$) of hermatypic corals has been utilised in numerous reconstructions of past sea surface temperatures (SST) and salinities (e.g. Charles et al. 1997, Gagan et al. 2000). Coral $\delta^{18}\text{O}$ reflects a combination of local SST and the $\delta^{18}\text{O}$ value of ambient seawater (Epstein et al. 1953, Wefer & Berger 1991). However, changes in coral growth rates may change the absolute isotopic values. Variations in the extension and calcification rates have an impact on the fractionation of stable isotopes and have long been a subject of discussion (Land et al. 1975, Goreau 1977, Weil et al. 1981, Pätzold 1986, McConnaughey 1989, de Villiers et al. 1995, Allison et al. 1996, Leder et al. 1996, Cohen & Hart 1997). Signif-

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icant skeletal $\delta^{18}\text{O}$ depletion in faster-growing areas of coral skeleton compared to slower-growing areas were reported for the first time by Land et al. (1975). Allison et al. (1996) observed in *Porites lutea* from Phuket, south Thailand, that the growth rate/ $\delta^{18}\text{O}$ relationship is linear at all extension rates, while McConnaughey (1989) found this relation in *Pavona clavus* from Galápagos only in parts of corals extending at a rate of less than 5 mm yr^{-1} . For more rapidly growing parts of the coral, extension rate does not appear to have a significant effect on $\delta^{18}\text{O}$.

Few studies have examined skeletal $\delta^{18}\text{O}$ variations within and among species. From studies on corals from Kaneohe Bay, Hawaii, Grottoli (1999) found that $\delta^{18}\text{O}$ values are constant over variable depths for a given species, and that this parameter exhibits interspecific variability. Species-specific offsets in $\delta^{18}\text{O}$ have also been reported by Weil et al. (1981) and Wellington et al. (1996).

In this study we examined skeletal $\delta^{18}\text{O}$ composition of 2 *Porites* colonies collected from the northern end of the Gulf of Aqaba: from Aqaba at a depth of 19 m (*Porites* cf. *lutea*) and from Eilat at 15 m (*P.* cf. *nodifera*). To evaluate the effect of extension rate that is independent of *in situ* temperature, variations in the $\delta^{18}\text{O}$ of seawater and specific-species effects, samples for $\delta^{18}\text{O}$ analysis were taken from each specimen along synchronous growth profiles with different extension rates. Previously published and unpublished coral $\delta^{18}\text{O}$ data from the area are also included in this study for comparison. However, the results from this study can be used to evaluate and correct coral $\delta^{18}\text{O}$ values from modern and fossil corals for extension rate effects.

MATERIALS AND METHODS

The study area is located at the northern end of the Gulf of Aqaba (Fig. 1), which is the northward extension of the desert-enclosed Red Sea. The maximum depth of the Gulf is 1830 m; its 180 km long and 5 to 26 km wide. Oligotrophic conditions prevail in the Gulf waters, and evaporation (350 cm yr^{-1}) greatly exceeds precipitation (3 cm yr^{-1}) (Reiss & Hottinger 1984).

A column of a *Porites* cf. *nodifera* colony was collected in front of the Interuniversity Institute in Eilat ($29^\circ 31' \text{ N}$, $34^\circ 56' \text{ E}$) at a depth of 15 m in April 1996 (El-15), while another column of a *P.* cf. *lutea* colony (Aq-19) was collected in front of the Marine Science Station in Aqaba ($29^\circ 27' \text{ N}$ and $34^\circ 90' \text{ E}$) at a depth of 19 m in April 1999. Both coral columns were sectioned along their longitudinal axes to obtain slabs of about 4 mm thickness. X-radiographs were prepared to reveal annual density bands for determining sampling

profiles (Fig. 2). Aragonite sub-samples were collected by low-speed drilling using a dentist drill with a 0.6 mm diameter bit. Distance between samples was about 1 mm and the drilling depth was 3 mm. A number of 7 to 12 samples (average 9) yr^{-1} from both corals were obtained along the maximum growth axis (main profile). In addition, we continuously sampled stable isotopic profiles drilled along lateral corallites from the sides of both colonies that showed low growth rate (Fig. 2).

The isotopic composition of the samples was measured with a Finnigan MAT 251 mass spectrometer at Bremen University. All values are reported in per mil relative to VPDB. The average measurement precision for $\delta^{18}\text{O}$ was $\pm 0.07\%$.

The chronologies of both corals were constructed by designating the maximum $\delta^{18}\text{O}$ value within each year as mid-March (the coldest month in the year according to recent SST records from Eilat and Aqaba). Linear interpolation of 12 equidistant values for the main profiles (6 for the side profiles) yr^{-1} between these maxima was applied, using AnalySeries 1.1 software package (Paillard et al. 1996). This procedure provided a monthly and bimonthly sampling resolution.

Absolute bulk density was measured by gamma-densitometry on a Multi Sensor Core Logger (Geotek) with a Cs^{137} source and 1 mm collimator at the Ocean Drilling Core Repository in Bremen. The method is based upon the attenuation of a gamma photon beam,

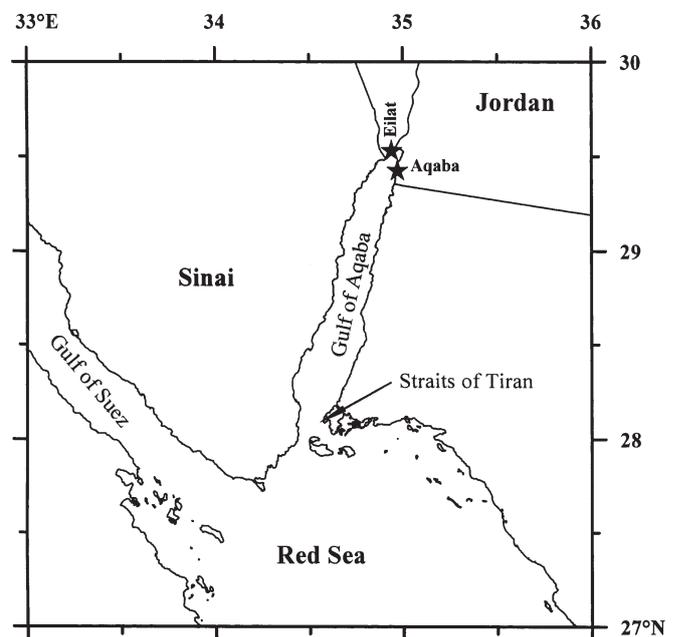


Fig. 1. Location map of the Gulf of Aqaba showing collection sites (★) of *Porites* spp. coral colonies from Aqaba and Eilat, northern Gulf of Aqaba

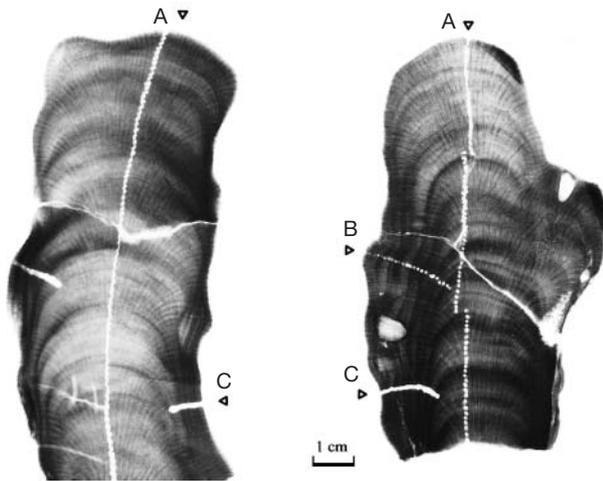


Fig. 2. *Porites* spp. X-radiograph-positive prints of the 2 coral slabs (Left: Aq-19; right: El-15) showing the skeletal density bands and the sampling profiles used for stable isotope analysis (Profiles A, B, and C) as indicated by the arrowheads

depending on the thickness and density of the skeleton material (Chalker & Barnes 1990). Annual mean bulk densities were calculated from the seasonal cycles of density variations which were measured along adjacent profiles near the drilled profiles.

The monthly temperature record from Aqaba was obtained between 1997 and 2000 (R. Manasreh pers. comm.). The measurements were based on biweekly measurements in the upper 1 m of the water column using an OS200 CTD instrument (precision 0.001°C). The measurements were performed in front of the Marine Science Station, 300 m away from the coral site.

Monthly measurements of SST from Eilat between 1988 and 2000 were used for comparison (A. Genin pers. comm.). The measurements were based on daily observations in the upper 20 cm of the water column (200 m distant from the site where the coral was collected) with a pre-calibrated mercury thermometer (precision 0.1°C) fixed in a bucket.

RESULTS

Seawater temperature records

No major significant differences were observed between the SST recorded in Aqaba and Eilat. At both locations, SST show the same regular seasonal cycle and have the same seasonal amplitude (5.5°C). They average 23.6°C, with maximum temperatures of 26.4°C (on average) in August–September, and minimum temperatures of 20.9°C (on average) in February–March (Fig. 3).

Salinity and $\delta^{18}\text{O}$ of seawater

Seawater $\delta^{18}\text{O}$ ($\delta^{18}\text{O}_w$) is related to changes in salinity as a response to changes in evaporation, precipitation and mixing of waters from different sources. This relation between $\delta^{18}\text{O}_w$ and salinity differs from ocean to ocean. In the Red Sea a change of 1‰ salinity causes a change of 0.29‰ in $\delta^{18}\text{O}_w$ according to Craig (1966) and Andrié & Merlivat (1989). At the northern end of the Gulf of Aqaba the salinity of the surface waters is close to 40.5‰, and varies by less than 0.5‰ throughout the year (Wolf-Vecht et al. 1992).

Manasreh (1998) reported that average minimum salinities of 40.34‰ occur during winter (February) and maximum salinities of 40.56‰ during summer (June). These minor variations in the surface seawater salinity throughout the year are considered to have little effect on the seasonal variation of the seawater $\delta^{18}\text{O}$ (Klein et al. 1992) (0.225‰ salinity = 0.065‰ $\delta^{18}\text{O}$: Craig 1966). Therefore, the seasonal $\delta^{18}\text{O}$ variation in the coral skeleton of the northern Gulf of Aqaba should be mainly controlled by SST (Heiss et al. 1999).

Calibration of $\delta^{18}\text{O}$ in coral skeletons

The x-radiograph-positive prints of the coral slabs reveal a clear and regular skeletal density-banding pattern. The alternating bands of high and low densities are annual, as confirmed by the strong seasonal cycle in $\delta^{18}\text{O}$.

The comparison between local SST records and the coral $\delta^{18}\text{O}$ time series is a necessary first step in the calibration of coral $\delta^{18}\text{O}$ records. The oxygen isotope profiles of both corals showed well-organized cyclic variations along the axis of maximum extension rate (fast-growing tops) (Profiles Aq-19A and El-15A; Fig. 4). $\delta^{18}\text{O}$ in the Aqaba coral ranged between -2.45 and -3.55‰ (average -3.10‰) and in the Eilat coral between -2.10 and -3.28‰ (average -2.79‰). Each $\delta^{18}\text{O}$ profile showed strong seasonal variations with similar amplitudes. These were on average 0.80‰ in Aqaba and 0.83‰ in Eilat. Both profiles correspond remarkably well to the monthly SST measurements in Aqaba and Eilat (Fig. 5). The correlation coefficients are rather high and range between -0.84 in the Eilat coral (in the time interval 1988 to 1995) and -0.81 in the Aqaba coral (in the time interval 1995 to 1999). Unfortunately no instrumental temperature data were available from Aqaba during the period 1988 to 1995.

Monthly records of $\delta^{18}\text{O}$ in both locations from the main growth profile (Aq-19A and AEI-15A) were cali-

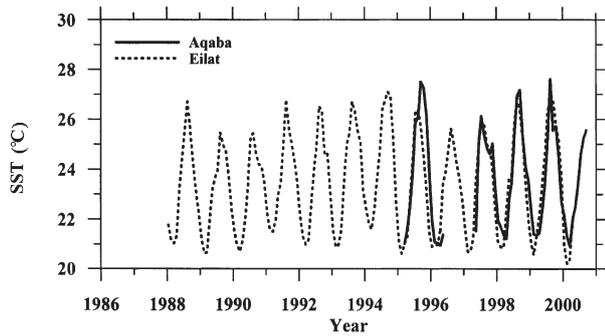


Fig. 3. Monthly recorded sea surface temperatures (SST) in Aqaba between 1997 and 2000 (R. Manasreh unpubl. data) and in Eilat between 1988 and 2000 (A. Genin unpubl. data)

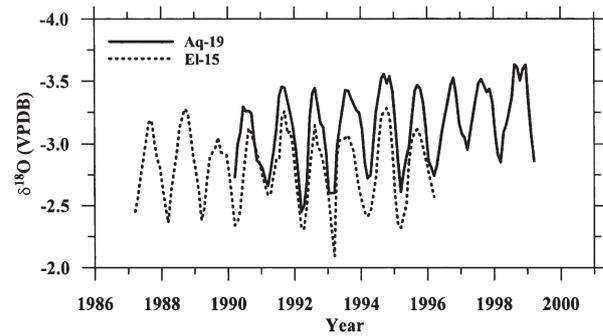


Fig. 4. *Porites* spp. Stable oxygen isotope profiles from samples drilled vertically along the axis of maximum extension rate of *P. cf. lutea* from Aqaba and *P. cf. nodifera* from Eilat between 1987 and 1999

brated with recorded SST, and the following equations are the results of the calculations:

$$\begin{aligned} \text{SST } (^{\circ}\text{C}) &= -5.93 (\delta^{18}\text{O}_{\text{coral}}) + 4.63 \\ r &= -0.81 \text{ (99.5\% level) Aqaba coral} \\ \text{SST } (^{\circ}\text{C}) &= -5.75 (\delta^{18}\text{O}_{\text{coral}}) + 7.30 \\ r &= -0.84 \text{ (99.5\% level) Eilat coral} \end{aligned}$$

The $\delta^{18}\text{O}/\text{SST}$ relationship from these equations varies between 0.168‰/°C from Aqaba and 0.174‰/°C from Eilat coral. The correlations from the annual averages of the $\delta^{18}\text{O}$ record and the annual average SST of the 2 corals were low (−0.25 to −0.31) despite the fact that the annual $\delta^{18}\text{O}$ record follows that of the annual SST record.

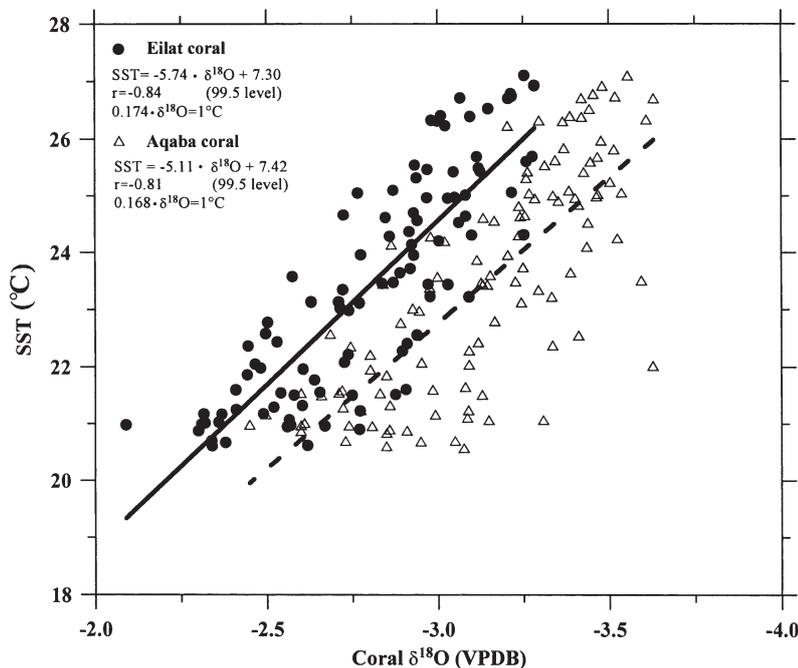


Fig. 5. *Porites* spp. Comparison of monthly variations in coral $\delta^{18}\text{O}$ (from profiles drilled vertically along axis of maximum extension rate) with monthly recorded sea surface temperatures (SST) at Aqaba and Eilat

Extension rate and skeletal $\delta^{18}\text{O}$

Comparison of the $\delta^{18}\text{O}$ records from Aqaba and Eilat (from the main profiles, Aq-19A and El-15A) for the period 1990 to 1995 shows that the Aqaba coral is several degrees more depleted in $\delta^{18}\text{O}$ than the Eilat coral. The offset between the 2 colonies ranged between 0.27 and 0.36‰ with an average of 0.29‰, and appears to be constant over the length of all years covered (Fig. 4).

Annual extension rates were determined from the seasonal cycle of $\delta^{18}\text{O}$ as the distance from the maximum $\delta^{18}\text{O}$ value (which represents the minimum recorded temperature) in a given year to the maximum value in the following year. The Eilat coral showed lower mean annual extension rates, ranging between 7 to 13 mm yr^{−1} (11.2 mm yr^{−1} on average), compared to 12 to 21 mm yr^{−1} (15.2 mm yr^{−1} on average) in the Aqaba coral.

We examined the relationship between annual extension rates and mean annual $\delta^{18}\text{O}$ in Aqaba and Eilat corals. The $\delta^{18}\text{O}$ values obtained along the slower extension rate profile (El-15A) were more enriched in $\delta^{18}\text{O}$ than the faster extension rate profile (Aq-19A).

Coral $\delta^{18}\text{O}$ from synchronous growth profiles

To evaluate the extension rate effect that is independent of the *in situ* temperature and variations in $\delta^{18}\text{O}$ of the seawater, $\delta^{18}\text{O}$ samples were taken from each specimen along synchronous growth profiles with different extension rates.

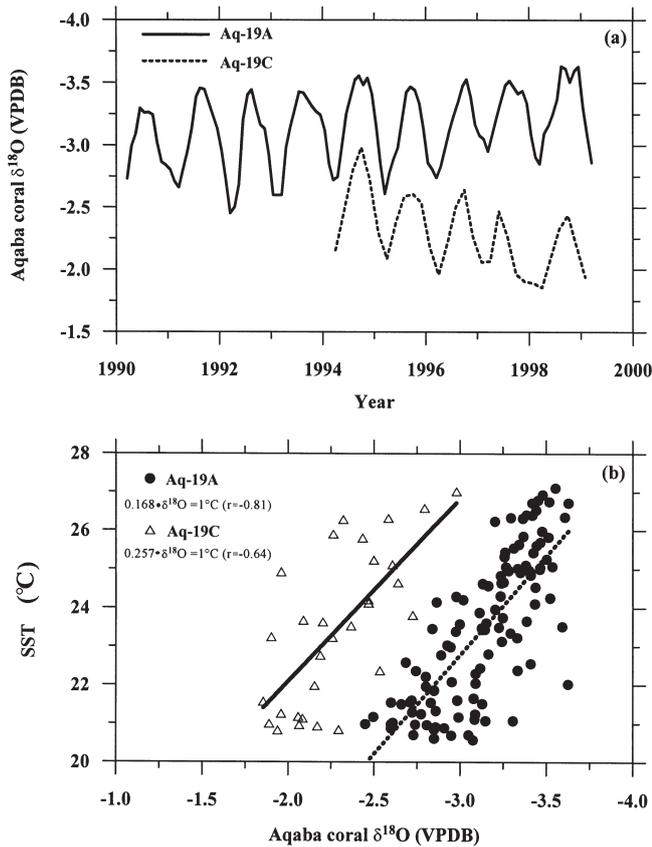


Fig. 6. *Porites cf. lutea*. (a) Seasonal variation in $\delta^{18}\text{O}$ (VPDB) composition of Aqaba coral along 2 different profiles; (b) linear relation between $\delta^{18}\text{O}$ and recorded sea surface temperatures (SST) along 2 different coral extension rate profiles (Aq-19A, 15.2 mm yr^{-1} ; Aq-19C, 1.9 mm yr^{-1})

The bimonthly $\delta^{18}\text{O}$ profile from the Aqaba coral (Aq-19C) with extension rates between 1 and 2.5 mm yr^{-1} (average 1.9 mm yr^{-1}) showed a seasonal amplitude of 0.73‰ . Values ranged between -1.85 and -2.98‰ (average -2.29‰), similar to that obtained from the slowest growth profile of the Eilat coral (El-15C), 0.81‰ higher than the average value of the main profile from the same colony (Aq-19A) (Fig. 6a).

The bimonthly $\delta^{18}\text{O}$ profiles from the slower-growing sides of the Eilat coral (El-15B and El-15C) show strong seasonal variations of 0.82 and 0.89‰ seasonal amplitude, similar to that obtained from the main profile from the same colony (El-15A).

The $\delta^{18}\text{O}$ values from Profile El-15B ranged between -2.04 and -3.30‰ , with an average of -2.68‰ , which is 0.11‰ higher than that obtained from the main profile (Fig. 7a). The extension rate in this profile ranged between 2 and 5 mm yr^{-1} (average 3.9 mm yr^{-1}). Also, $\delta^{18}\text{O}$ values from the El-15C profile ranged between -1.75 and -2.87‰ (average -2.23‰), 0.15‰ higher

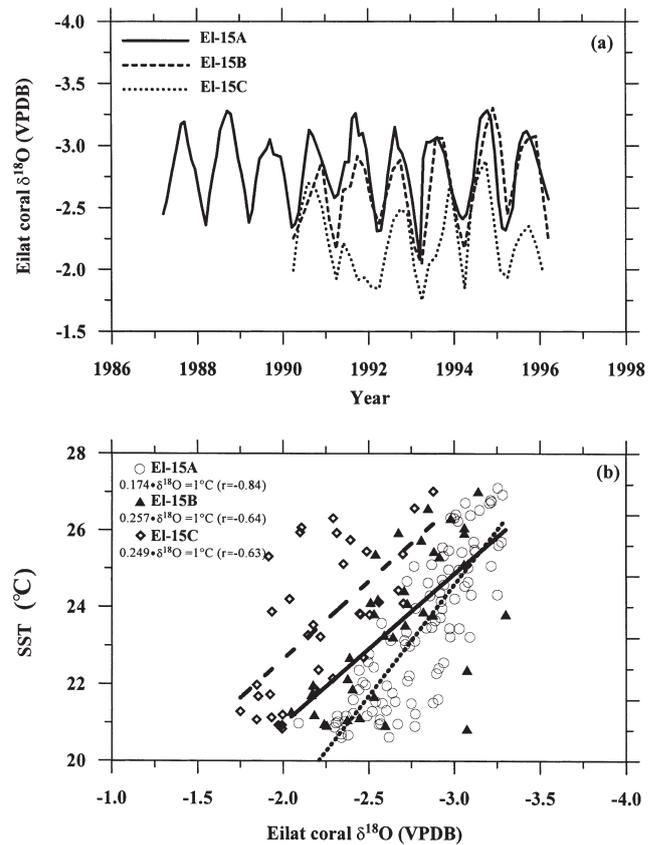


Fig. 7. *Porites cf. nodifera*. (a) Seasonal variation in $\delta^{18}\text{O}$ (VPDB) composition of Eilat coral along 3 different profiles; (b) linear relation between $\delta^{18}\text{O}$ and recorded sea surface temperatures (SST) along 3 different coral extension-rate profiles (El-15A, 11.2 mm yr^{-1} ; El-15B, 3.9 mm yr^{-1} ; El-15C, 2.3 mm yr^{-1})

than that from El-15B (Fig. 7a). The extension rate in this profile ranged between 1.5 and 3 mm yr^{-1} (average 2.3 mm yr^{-1}).

Calibration of $\delta^{18}\text{O}$ from these profiles with recorded SST at bimonthly intervals, produced different $\delta^{18}\text{O}/\text{SST}$ equations (Figs. 6b & 7b) that varied between $0.21\text{‰ } ^\circ\text{C}^{-1}$, $0.25\text{‰ } ^\circ\text{C}^{-1}$ and $0.24\text{‰ } ^\circ\text{C}^{-1}$, with correlation coefficients of 0.69 , 0.64 and 0.63 from Aq-19C, El-15B, El-15C, respectively.

Relation between growth variables

Calcification rate was calculated as a product of linear extension and skeletal density (Chalker et al. 1985, Lough & Barnes 2000). Calcification values along all profiles ranged between 2.2 and $0.157 \text{ g cm}^{-2} \text{ yr}^{-1}$, with an average of $0.92 \text{ g cm}^{-2} \text{ yr}^{-1}$, and decreased from the top to the sides of the colonies due to decreases in the extension rates.

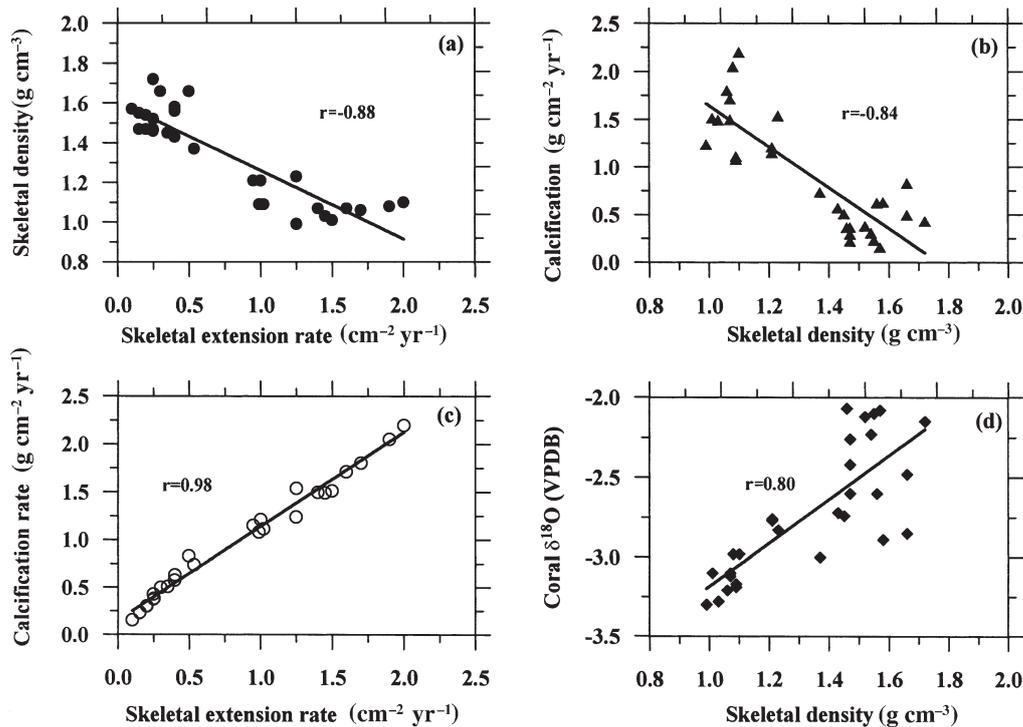


Fig. 8. *Porites* spp. Scatter diagram of average annual growth data for Aqaba and Eilat corals (combined data). (a) Density vs extension; (b) calcification vs extension; (c) calcification vs density; (d) density vs skeletal stable oxygen isotopes. Regression lines and correlation coefficients are shown

The relations between density, extension and calcification rate in this study (Fig. 8) are similar to the growth relations reported for other studies (Wellington & Glynn 1983, Dodge & Brass 1984, Scoffin et al. 1992, Lough & Barnes 2000). Average annual extension was inversely correlated with average annual density ($r = 0.88$) and significantly correlated with average annual calcification ($r = 0.98$). Average skeletal density was inversely correlated with average annual calcification ($r = 0.84$) and skeletal oxygen isotope ($r = 0.80$). Thus, we conclude that variations in average annual calcification were mostly caused by variations in extension rate, as found by Barnes & Lough (1993) and Lough & Barnes (2000).

DISCUSSION

Calibration of coral δ¹⁸O

Our δ¹⁸O/SST slopes from the main profiles of the Aqaba and Eilat corals (0.168 and 0.174‰/°C) are less than the widely accepted values of 0.22‰ for calcite (Epstein et al. 1953) and 0.23‰/°C for aragonite (Grossman & Ku 1986), and are similar to values determined by Gagan et al. (1994) for *Porites* sp. at a weekly resolution from the Great Barrier Reef (0.18‰/°C) and

by Quinn et al. (1998) for a New Caledonia *Porites* sp. on a monthly scale (0.172‰/°C).

Felis et al. (1998) and Moustafa (2000) determined a value of 0.165‰/°C as the most reasonable for calibration for *Porites* sp. from Ras Umm Sid, Red Sea (using the IGOSS temperature data set). Heiss et al. (1999) also found a value of 0.166 and 0.187‰/°C from monthly resolution in horizontal and vertical profiles of a *P. lutea* colony from Aqaba.

On an annual timescale, the correlation coefficient decreased to -0.25 and -0.31 . For New Caledonia corals, Quinn et al. (1998) reported that the correlation coefficient decreased from -0.87 on a seasonal timescale to -0.53 on an annual timescale. They explained this decrease as being due to salinity changes, whereby seasonal variations in salinity are small compared to those for temperature, while inter-annual changes in salinity are proportionally larger than their seasonal changes.

This may also be the situation in the northern Gulf of Aqaba. A regular measurement of seawater salinity over 4 yr (1997 to 2000) showed no systematic annual pattern (R. Manasreh, pers. comm. [2000]) and the average annual values differed from year to year. The interannual variations during this period were as much as 0.4‰, compared to 0.225‰ on a seasonal scale. The potential impact of 0.4‰ interannual salinity variation

on $\delta^{18}\text{O}$ of Red Sea water and hence on coral $\delta^{18}\text{O}$ is 0.12‰ (after Craig 1966). This effect could explain part of the difference in the seasonal and mean annual slopes of $\delta^{18}\text{O}/\text{SST}$.

The measured SST in Aqaba and Eilat reveal an average annual cycle of about 5.5°C. Using the gradient of 0.165‰/°C for coral $\delta^{18}\text{O}$ -temperature dependence from the northern Red Sea (Felis et al. 1998, Moustafa 2000), the average seasonal coral $\delta^{18}\text{O}$ variation of 0.83‰ would reflect a temperature change of about 5.0°C, which is about 91% of the average seasonal SST amplitude. The expected variation of 0.065‰ $\delta^{18}\text{O}$ in seawater (related to a 0.225‰ change in salinity) constitutes 7.8% of the average seasonal coral $\delta^{18}\text{O}$ variation. This indicates that a large majority of the variations in coral oxygen isotope data can be explained by variations in the SST, and only a small fraction can be attributed to $\delta^{18}\text{O}$ variations of surface water.

It is obvious from our results that different $\delta^{18}\text{O}/\text{SST}$ relations exist in different colonies and in different parts of the same colony. These variations are most probably biologically mediated, as outlined in the following subsection.

Effect of extension rate on skeletal $\delta^{18}\text{O}$ composition

Both main $\delta^{18}\text{O}$ profiles for the 2 colonies (Aq-19A and El-15A) show similar amplitudes (0.83 and 0.80‰, respectively), which implies that both corals respond similarly to environmental signals. The offset between the $\delta^{18}\text{O}$ profiles (~0.29‰ on average, with lower $\delta^{18}\text{O}$ values in the Aqaba coral) does not reflect changes in temperature and/or salinity between the 2 sites (similar physical environment) and is probably a biologically mediated signal.

Although the profiles from the coral sides (Aq-19C and El-15B, C) were sampled at lower resolution, they displayed roughly the same seasonal amplitude as the

main profiles with a monthly sampling resolution. Analysis of $\delta^{18}\text{O}$ along the main and synchronous growth profiles revealed different trends in the $\delta^{18}\text{O}$ values (Figs. 5, 6b, 7b). These results indicate that the $\delta^{18}\text{O}$ values are subject to extension and calcification rate effects, i.e. the faster-growing profile (Aq-19A) is 0.29‰ more depleted in $\delta^{18}\text{O}$ than the slower-growing profile (El-15A). A trend of higher $\delta^{18}\text{O}$ content with slower extension rate was also observed in the synchronous growth profiles of both colonies (Aq-19C, El-15B, El-15C).

The relation between coral $\delta^{18}\text{O}$ and skeletal growth rate determined in this study is not linear and can be explained by a simple exponential model (Fig. 9):

$$\text{Coral } \delta^{18}\text{O} = -3.067 + \exp [1.069 + (-0.744) \times \text{ER}]$$

Aqaba coral $r = 0.96$

$$\text{Coral } \delta^{18}\text{O} = -2.795 + \exp [1.016 + (-0.757) \times \text{ER}]$$

Eilat coral $r = 0.97$

where ER is the coral extension rate (mm yr^{-1}), and $\delta^{18}\text{O}$ is ‰VPDB.

Coral $\delta^{18}\text{O}$ data from Aqaba and Eilat and from the same genus (*Porites*) with different extension rates—Coral S4 (6.8 mm yr^{-1}), Coral MB30 (3.3 mm yr^{-1}), Coral IS50 (2.0 mm yr^{-1}) and Coral S6 (14.8 mm yr^{-1}) (Klein et al. 1993, J. Pätzold & R. Klein unpubl. data), Aq-193 (20 mm yr^{-1}), Coral Aq-292 (5.3 mm yr^{-1}) and Coral Aq-424 (3.5 mm yr^{-1}) (Al-Rousan unpubl. data)—are also plotted in Fig. 9. The data fit the curve and support the reliability of the exponential model.

The inverse relationship between $\delta^{18}\text{O}$ and extension rate revealed by this model applies to growth rates of 1 to 5 mm yr^{-1} (Profiles Aq-19C, Aq-292, Aq-424, El-15B, El-15C, MB30, and IS50). For more rapidly growing corals and portions of corals (as in Profiles Aq-19A, Aq-193, El-15A, S4 and S6; Fig. 9), the relation is constant, and the extension rate does not appear to have a significant effect on coral $\delta^{18}\text{O}$.

These results are similar to those of McConnaughey (1989), who found an inverse relationship for Galápa-

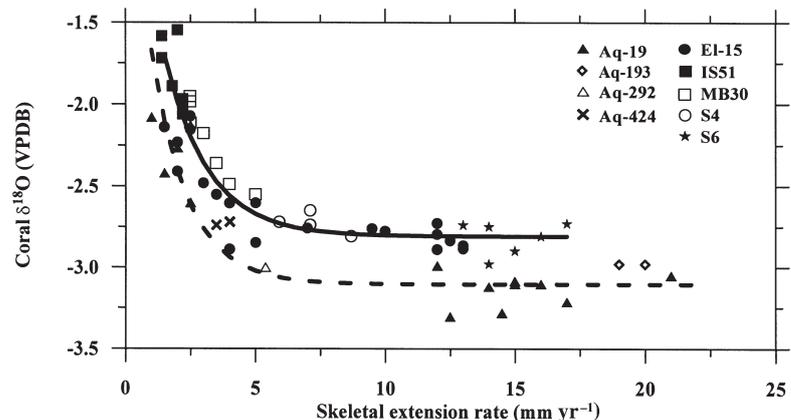


Fig. 9. *Porites* spp. Exponential relationship between skeletal $\delta^{18}\text{O}$ and skeletal extension rate of colonies sampled along vertical (main axis) and horizontal (coral sides) profiles of corals collected from the northern Gulf of Aqaba, Red Sea. Data for Corals IS51, MB30 and S4 are from Klein et al. (1993), data for S6 from J. Pätzold and R. Klein (unpubl. data), and for Aq-193, Aq-292 and Aq-424 from S. Al-Rousan (unpubl. data)

gos *Pavona clavus* corals that grew at rates of $<5 \text{ mm yr}^{-1}$, and extension rate did not appear to have any significant effect on $\delta^{18}\text{O}$ composition at growth rates of $>5 \text{ mm yr}^{-1}$. Quinn et al. (1998) also found a negative correlation in New Caledonia corals, and Allison et al. (1996) in corals from Phuket, South Thailand—but at all extension rates. Higher $\delta^{18}\text{O}$ and Sr/Ca values in slower growing transects were reported by de Villiers et al. (1995) for *Pavona clavus* from Galápagos. In contrast, Leder et al. (1996) found that the $\delta^{18}\text{O}$ content of rapidly growing portions (8 mm yr^{-1}) of a colony was 0.1 to 0.2‰ higher than that of the slowest growing portions (1.1 mm yr^{-1}), and explained this as a result of reduced sampling resolution in slower growing portions of the coral and not a result of variable kinetic effects.

We conclude that growth rate has an important effect on the isotopic composition of coral skeletons. Our results support the conclusion drawn by McConnaughey (1989) that the depletion of $\delta^{18}\text{O}$ is characteristic for kinetic fractionation associated with rapid calcification, and that isotope disequilibria tend to be fairly consistent in rapidly growing parts of photosynthetic corals. For this reason, we suggest that $\delta^{18}\text{O}$ should be measured in fast-growing portions where the extent of isotopic disequilibria is largest, since isotopic disequilibria are too variable in slow-growing parts.

Calcification rate and species-specific effects

As shown in Fig. 9, a $\delta^{18}\text{O}$ offset between Aqaba and Eilat colonies does exist. We calculated the calcification rate along the drilled profiles. Due to the high correlation between extension and calcification rate (Fig. 8c) the relation between calcification and $\delta^{18}\text{O}$

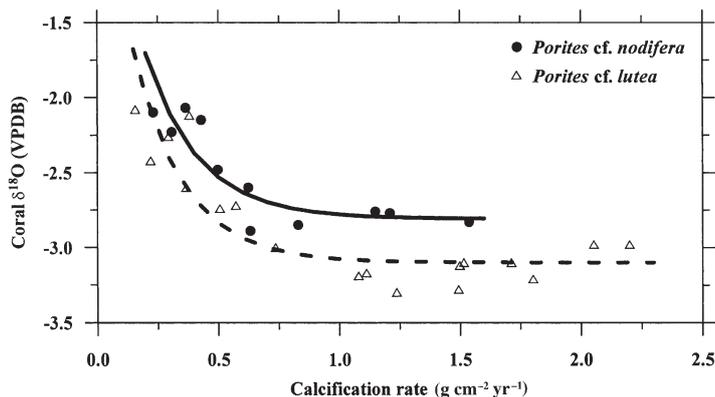


Fig. 10. *Porites* spp. Exponential relationship between skeletal $\delta^{18}\text{O}$ and skeletal calcification rate for 2 species collected from the northern Gulf of Aqaba, Red Sea

failed to explain the offset between the main $\delta^{18}\text{O}$ profiles for the 2 colonies. A similar exponential equation was produced (Fig. 10). We found that high extension profiles revealing low skeletal densities (Aq-19A) were depleted in $\delta^{18}\text{O}$ compared to low extension profiles showing high densities (El-15A) which may have had the similar calcification rate.

The offset between $\delta^{18}\text{O}$ profiles cannot always be explained as a function of extension and/or calcification rate. For this reason, both corals were taxonomically identified. Aq-19, Aq-193, Aq-292 and Aq-424 (which are depleted in $\delta^{18}\text{O}$ by $\sim 0.29\%$ compared to El-15) are *Porites cf. lutea*, while El-15 is *P. cf. nodifera*. Wellington et al. (1996) found that certain species are enriched or depleted in $\delta^{18}\text{O}$ relative to other species of the same genus living under the same environmental conditions, whereas Grottoli (1999) found for Hawaii corals that $\delta^{18}\text{O}$ varies among species. Species-specific offsets in $\delta^{18}\text{O}$ have been also reported by Weil et al. (1981). The $\delta^{18}\text{O}$ offset between coral species may reflect some genetic differences which alter the extent of isotopic disequilibria (Allison et al. 1996).

The results of this study show that the linear extension rate and species variation should be considered when interpreting coral $\delta^{18}\text{O}$ data for paleoclimatic studies. Further studies are also needed to study the variation of $\delta^{18}\text{O}$ of other *Porites* species.

CONCLUSIONS

The high correlation between coral $\delta^{18}\text{O}$ and recorded SST (-0.84) in both Aqaba and Eilat in the northern Red Sea suggests that the great majority of the seasonal variations in coral oxygen isotopes can be explained by the SST variations, and only a small fraction can be attributed to $\delta^{18}\text{O}$ variations in the surface

water. These results support the concept of using northern Red Sea corals as recorders of variability in SST. Interannual salinity variations in the Gulf of Aqaba (as recorded in recent studies) seem to be responsible for decreasing the correlation between coral $\delta^{18}\text{O}$ and SST on the annual timescale.

Different $\delta^{18}\text{O}$ /SST relations from 2 different colonies and also from the same colonies were obtained, indicating that $\delta^{18}\text{O}$ of coral skeletons is subject to an extension rate effect. Significant $\delta^{18}\text{O}$ depletion occurs at high extension rates, and higher values at low extension rates. The relation between $\delta^{18}\text{O}$ and extension rate is not linear, and can be explained by a simple exponential model in which the inverse function extends over extension rates of 1 to 5 mm yr^{-1} . For more rapidly growing corals and portions

of coral colonies, the relation is constant, and the extension rate did not appear to have any significant effect on coral $\delta^{18}\text{O}$. The offset in $\delta^{18}\text{O}$ profiles cannot always be explained as a function of extension and/or calcification rate, and may result from interspecific differences between corals.

We suggest that $\delta^{18}\text{O}$ values from *Porites* spp. corals should be measured from fast-growing corals or portions of the colonies (growth rate of $>5\text{ mm yr}^{-1}$), in which the isotopic disequilibrium is fairly constant. Skeletal extension rate and coral species should be considered when interpreting and comparing coral paleoclimatic data from various coral species with different extension rates.

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