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Seasonal rainfall in the Sinai Desert during the late Quaternary inferred from fluorescent bands in fossil corals

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SKELETAL bands of alternating high and low density in massive coral species have been used to record their growth history[1,2]. In the Red Sea, living colonies of the genus *Porites* deposit low-density skeletal bands during summer and high-density bands during winter[3]. Additionally, yellow-green fluorescence can sometimes be seen in these massive corals, imparted to them by the incorporation of humic material carried by coastal runoff[4]. Annual banding of fluorescent sequences in living scleractinian corals has proved to be useful in the study of terrestrial runoff in the near-shore environment[5,6]. Here we report the finding of similar yellow-green fluorescent bands in fossil *Porites* from late Quaternary reef terraces in southern Sinai, which are absent from living *Porites* in the nearby fringing reefs. The periodic sequences of the fluorescing humics were found to be superimposed on the low-density sub-bands of the fossil corals. We interpret our observations as evidence that, during the late Quaternary reef-forming peaks, the climate was wetter than the extreme desert conditions now prevailing, with a possible summer rainfall regime.

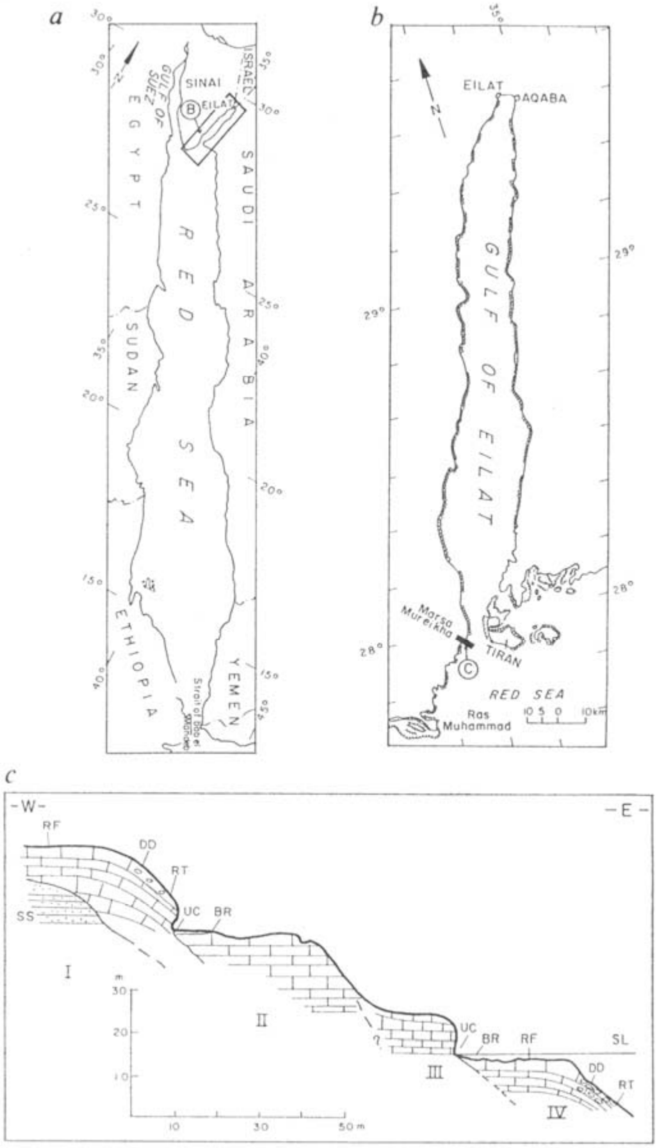

FIG. 1 Location map of *a*, the Red Sea; *b*, the Gulf of Eilat and its belt of fringing reefs; and *c*, a cross-section of the elevated late Quaternary fossil reefs, along the coastal belt in Marsa Mureikha. The reefs form morphological terraces labelled I–IV, from the oldest to the youngest, respectively. BR, beach rock; DD, depositional dips; RF, reef flat; RT, reef talus; SL, sea level; SS, sandstone substrate; UC, fossil shoreline undercut (modified after ref. 12). W, west; E, east.

The coastline along the Gulf of Eilat and the southern Sinai Peninsula is fringed by a narrow belt of modern coral reefs[7,8] (Fig. 1*a*,*b*). A well preserved belt of three elevated fossil-reef terraces, up to 35 m above mean sea level, stretches along the coast of southern Sinai[9] (Fig. 1*c*). Samples were dated as follows: the Upper Terrace (labelled I in Fig. 1*c*) as older than 250 kyr (1 kyr = 1000 years); the Middle Terrace (II) as ~140–200 kyr the Lower Terrace (III) as 108–140 kyr; and the modern offshore fringing reef (IV) as 10,000 years and younger[10–12]. These terraces were formed during periods of late Quaternary high-stand sea levels (G.G., J. Kronfeld and B. Buchbinder, manuscript in preparation).

Of 26 samples of the fossil *Porites* collected from the three elevated coral terraces, 22 samples showed degrees of fluorescent banding when sections were irradiated with long-wave (~360 nm) ultraviolet light. A comparable number of living *Porites* from the modern reef did not have distinct fluorescent banding.

High-performance liquid chromatography analysis[13] (Table 1) indicated that the source of fluorescence was humic acid that had been incorporated into the coral skeleton, as already found in in-shore corals from the Great Barrier Reef of Australia[4]. Fluorometric analysis of the fossil corals showed that the emitted light spectrum of a solid coral skeletal sample had the broad-band shape characteristic of organic luminescence, rather than the sharp bands associated with purely inorganic luminescence. These results indicate that the luminescence of fossil corals is governed by the humic acid in the coral skeletal matter.

Fossil corals exhibiting the best fluorescent banding sequences were selected for detailed analysis and compared with a randomly selected coral from the modern reef (Table 1). Quantitative analysis of humic acid by HPLC (Table 1) showed that the fluorescent bands of the fossil coral samples (labelled Fos4 and 1389) were richer in humic acid than the adjacent non-fluorescent bands. This contrasted with a living coral (labelled S21) that had only low levels of incorporated humic acid (Table 1). Results for individual fluorescent and non-fluorescent bands of the fossil coral Fos4 are illustrated in Fig. 2.

Most of the fossil corals that we investigated were phosphorescent. After irradiation with ultraviolet light, fossil corals glowed for tens of seconds, which is far longer than the modern corals. We examined the crystal fabric of a phosphorescent and non-phosphorescent fossil coral, and found rhombs of low-Mg calcite present in the pores of the phosphorescent coral (Table 1). The trace-element record supports this finding in that there are low amounts of magnesium in the inner part of the phosphorescent coral, which are not detected in the non-phosphorescent coral. The mineral composition of the corals by X-ray diffractometry (Table 1) indicates that the fossil corals underwent only initial stages of diagenesis, in which 85–90% of the aragonite was not replaced. Sample Fos4 underwent initial void-filling of low-Mg calcite, whereas sample 1389 had initial replacement of the aragonitic skeleton. The Sr content, from direct-current plasma spectometry (Table 1), reconfirms our assertion that the fossil corals were not significantly affected by diagenesis, because the Sr content (in the range of 6,900–7,800 $\mu g\ g^{-1}$) is still typical of aragonitic corals[14,15]. These results

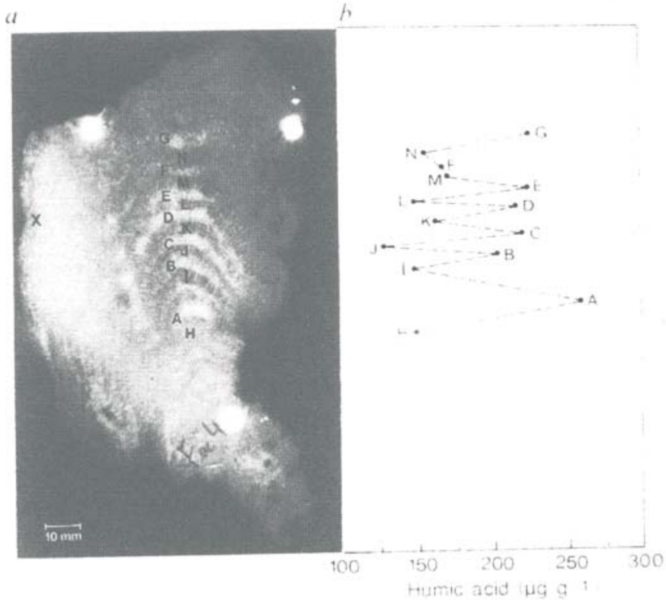

FIG. 2 *a*, Alternation of fluorescent (light) and non-fluorescent (dark) bands in fossil *Porites* (Fos4) under ultraviolet light. The fluorescent bands are superimposed on the low-density sub-bands. *b*, Humic acid concentrations from fluorescent (A–G) and non-fluorescent (H–N) bands. Samples for HPLC were taken from the centre of each band. The labelling in *b* corresponds to that in *a* indicating the specific band from which each sample was taken. The points X and Y represent the horizontal transect in which the sub-samples for humic acid analysis were taken (see text).

TABLE 1 Summary of relevant characteristics of modern and fossil Red Sea corals

	Modern	Fossils	
	Coral S21	Coral Fos4	Coral 1389
Location	Eilat	The Garden, Marsa el-At	Wadi Mureikha, northern bank
Longtitude	34°56′34″	34°21′00″	34°23′18″
Latitude	29°31′29″	27°54′34″	27°57′00″
Morphological terrace	Modern	Middle	Lower
Analyses			
Fluoresence	Absent	Present	Present
Phosphorescence	Absent	Present	Absent
Rhombs of low-Mg calcite*	Absent	Present	Absent
Humic acid† ($\mu g\ g^{-1}$) in fluorescent bands (mean ± s.d.)		220 ± 29 ($n = 7$)	284 ± 32 ($n = 3$)
Humic acid ($\mu g\ g^{-1}$) in adjacent non-fluorescent bands (mean ± s.d.)	10.2 ± 7.4‡ ($n = 3$)	153 ± 11 ($n = 7$)	226 ± 13 ($n = 3$)
Per cent aragonite§ (mean ± s.d.)	100 ± 0 ($n = 4$)	85.5 ± 7.5 ($n = 4$)	90.0 ± 2 ($n = 3$)
Sr‖($\mu g\ g^{-1}$)	7,800	6,570	6,930

* Samples were run on an Etec autoscan scanning electron microscope fitted with a Link 290 energy dispersive system.

† High-performance liquid chromatography (HPLC) was according to ref. 13. Water for chemical analysis was purified by a Millipore system (Bedford, Massachusetts) and then doubly distilled from potassium permanganate. Powdered coral skeletal matter (~20 mg) was weighed into a 4-ml glass vial and after the addition of 500 μl water, 75 μl concentrated hydrochloric acid (Aristar grade; BDH, UK) was added slowly with gentle shaking to effect solution. The sample was adjusted to pH ~6 with ~40 μl sodium hydroxide solution (10 M; Aristar grade, BDH, UK) and the final volume adjusted to 800 μl with water. Fifty microlitres of sample was injected into the system.

‡ Mean of three randomly selected areas, because no fluorescent bands exist.

§ Using X-ray diffractometry on a Rigaku D-max CN 2155D5 powder diffractometer with monochromatic Cu Kα radiation.

‖ Strontium was analysed by dissolving ~50 mg coral skeletal matter in a minimal amount of concentrated hydrochloric acid and adjusting the final volume to 10 ml with water. Samples were directly aspirated into a SpectraScan V direct-current plasma emission spectrometer (Beckman, California).

exclude any argument that the fluorescent compounds might have been introduced into the fossil corals during diagenesis.

Finally, we investigated the possibility of post-growth humic acid intrusion into the fossil corals by testing whether there had been inward migration of humic acid, in which case the humic acid concentration would be expected to be highest in the outer portions of the coral, with a decreasing inward gradient. Eight sub-samples of skeletal material along a horizontal transect in the middle of Fos4 were analysed for humic acid. Values were 159, 101, 106, 160, 210, 116, 107 and 143 $\mu g\ g^{-1}$ and represent the order in which the sub-samples were taken; the first and last indicated the two external portions of the coral (X and Y in Fig. 2). As these results show, there is no gradient in humic acid concentration along the transect. Furthermore, the dissolved humic acid concentration in soils is normally lower than in the coral skeletons. The concentration gradient between the coral head and surrounding soil would preclude humic acid intrusion (M.S., K. G. Boto and P. J. Isdale, manuscript in preparation). The absence of a humic acid gradient in the coral is consistent with this observation. Therefore, we propose that there are two independent phenomena: (1) fluorescent bands exist as a function of periodic events during the life of the corals, irrespective of later events; and (2) phosphorescence is attributable to events after the death of the corals, probably as a consequence of deposition of low-Mg calcite in the coral voids.

We attribute the increased concentrations of the terrestrially derived humic compounds in the fossil coral samples to the late Quaternary runoffs. The terrestrially derived fluorescence overlies a faint blue background fluorescence throughout the coral, probably as a result of the incorporation of marine humic acid[6] and terrestrial residuals of the wet season humics (M.S., K. G. Boto and P. J. Isdale, manuscript in preparation). This explains the relatively high humic acid concentrations characterizing the non-fluorescent bands of the fossil corals (Table 1). Both the Sinai fossil corals and modern inshore Great Barrier Reef corals contain similar concentrations of humic acid in the non-fluorescent regions, but these concentrations are an order of magnitude greater than the humic acid concentrations in modern Sinai corals. Assuming that sea water contains at least some terrestrial humic acid even after periods of little or no terrestrial runoff, then the runoff in the Sinai during the late Quaternary was more like present-day runoff in the Great Barrier Reef than present-day runoff in the Sinai.

Finally, comparison of skeletal density bands (as shown by X-rays) and photographs of fluorescing fossils under ultraviolet light show that the fluorescent bands correspond to the low-density portions of the skeleton. Analysis of modern *Porites* corals from the living reef of the Gulf of Eilat showed that wide low-density bands were deposited during summer, and narrow high-density bands during winter[3]. The fossil corals have a similar density-banding pattern (wide low-density and narrow high-density bands). Assuming unchanged seasonal deposition of bands, the fluorescent bands in the fossil corals therefore correspond to summer events.

Our findings indicate that during the time of reef growth and high-stand sea levels, a wet climate, possibly with a summer rainfall regime, probably prevailed in the Sinai, in contrast to the present extremely dry conditions (with rare precipitation during winter). Most of the palaeoclimate evidence known for Israel and the Sinai regions extends to the periods of the Holocene and the last Glacial. The existence of a series of palaeosols in the present-day desert region of southern Israel (the northern Negev Desert) indicates that there were wetter climates corresponding to the global warmer periods of the last Glacial[16–17]. Pollen spectra and the isotopic composition of fossil groundwater[18-19] suggest that during the late Wurmian and mid Holocene, Israel experienced at least some summer rains. Other evidence for wetter conditions in the Negev Desert of Israel in the mid Holocene is indicated by a palaeodiet study of fossil land snails[20]. Study of lake deposits extend our palaeoclimate knowledge of the region to the interglacial intervals of the isotope stages 5 and 7 (ref. 21), suggesting that during these warmer global episodes the arid southern region of Israel (Arava Rift Valley) was considerably wetter than it is now. Palaeoclimate oscillations, ranging from tropical humid to warm arid climates, in regions such as central Africa, the Ethiopian Plateau and eastern Sahara, were recorded from deposition of heavy minerals in the Nile delta during periods of the last Glacial and the mid Holocene[22].

Several studies discuss monsoonal appearance in response to orbital insolation. Marine sapropels, deposited in the eastern Mediterranean sea as a result of heavy discharge from the Nile River, indicate that African monsoons were always at their heaviest during all the interglacials in the past 464 kyr as an immediate response to orbital variations of insolation[23]. Climatic characteristics of the interglacial intervals, as detected from a 150-kyr oxygen-isotope pollen record from the Arabian Sea, describe the intensification of the summer southwest monsoonal flow[24-25]. Finally, climate models[26-27] have been used to explain the monsoonal variability over the past 150 kyr. These models reveal that, under interglacial conditions, increased Northern Hemisphere solar radiation produced a larger land–ocean pressure gradient, strong winds and great precipitation over southern Asia and North Africa.

Our interpretation of summer rainfall in the Sinai desert, during the late Quaternary periods of high-sea-level interglacial intervals (1) supports climate evidence and models that show the linkage between monsoonal flow, interglacial intervals and orbital insolation; (2) provides possible evidence of northward extension of the monsoonal belt over the Sinai region and (3) extends the knowledge of the climate conditions prevailing in the Sinai more extensively than periods of the last Glacial. Analysis of fluorescent bands in fossil corals provides a new and promising method for palaeoclimate reconstruction. □

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