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2060-41

Advanced School on Non-linear Dynamics and Earthquake Prediction

28 September - 10 October, 2009

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doi: 10.1111/j.1365-3121.2004.00541.x

Large earthquakes kill coral reefs at the north-west Gulf of Aqaba

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ABSTRACT

Down-faulting at the north-west margins of the Gulf of Aqaba is inferred to have triggered a catastrophic sedimentary event at 2.3 ka that killed the Elat fringing coral reef. Whereas segments of the Holocene reef were perfectly fossilized and preserved beneath a veneer of siliciclastic sediments, other segments were abraded, settled by nomads, and later re-submerged under 4 m of water. Repeated damage triggered by down-throwing earthquakes degenerate the fringing reefs of the north-west end of the gulf. Conversely, on the north-eastern and southern parts of the gulf, where earthquakes uplift the margins, modern reefs are thriving, attached to uplifted fossil reef terraces. Therefore, coastal subsidence moderates the development of fringing coral reefs during the late Holocene sea-level stand still.

Terra Nova, 16, 133–138, 2004

Introduction

Coral reef terraces often record palaeoseismic events at tectonically active coastal regions (Chappell, 1974; Lajoie, 1986; Edwards *et al.*, 1988; Ota and Chappell, 1999). This paper examines the effects of Holocene earthquakes on coral reefs along the north-western coast of the Gulf of Aqaba (GOA). This evaluation was achieved by U-series and radiocarbon dating of corals from displaced reefs and by documentation of the changes in the coastline after displacement events. The GOA (Fig. 1) comprises several pull-apart basins that were formed by left-lateral movement along the southern part of the Dead Sea Transform (Ben-Avraham *et al.*, 1979; Garfunkel, 1981; Ben-Avraham, 1985). In addition to the dominant left-lateral motion, the topography of the GOA reflects a significant amount of vertical motion that produced this morphotectonic depression. The gulf is currently the locus of extensive seismic activity (GII, 1996; Salamon *et al.*, 1996; Pinar and Turkelli, 1997). The last large earthquake ($M_W = 7.1$) occurred on 22 November 1995, off the town of Nueiba (Fig. 1) at the central part of the GOA (Shamir, 1996; Dziewonski *et al.*, 1997; Baer *et al.*, 1999; Klinger *et al.*, 2000b). The Nueiba earthquake caused significant damage along the GOA from Elat and Aqaba in the north to Nueiba and Dahab in the south (Al-Tarazi, 2000). Various rockfalls, liquefactions and slip features were also reported along the coast (Wust *et al.*, 1997; Klinger *et al.*, 1999). Of particular interest is a slow rising wave that reached dozens of metres inland in the central Sinai coast following the main shock.

Several historical earthquakes were documented in the region, damaging the ancient Byzantine town of Ayla and settlements in the southern Arava Valley (Ambraseys *et al.*, 1994; Klinger *et al.*, 2000a). Palaeoseismic trenches dug in alluvial fans in the southern Arava valley documented localized east-side-down displacement on western marginal faults (Enzel *et al.*, 1996; Amit *et al.*, 1999, 2002).

Where the marginal faults reach the GOA, coral reefs that were growing during the late Pleistocene – Holocene periods provide a potential recorder of seismic events in the gulf. Late Pleistocene reef terraces are uplifted along the southern coasts of the Sinai Peninsula (Gvirtzman *et al.*, 1992; El-Asmar, 1997) and on the north-eastern side of the GOA, near the city of Aqaba (Al-Rifaiy and Cherif, 1988), indicating a long-term tectonic pattern of marginal uplift in these regions. By contrast, along the north-western part of the GOA, Pleistocene reefs including the last Interglacial reef are not exposed, and the long-term pattern seems to be one of subsidence. In contrast to the different positions of the last Interglacial reefs, Holocene reefs along the entire gulf are located just above the present shoreline (< 1 m). This configuration is unlikely to reflect the long-term tectonic movements along the GOA because the north-western margins are subsiding. Rather, the elevation of *in-situ* Holocene reefs probably records changes in sea-level. The GOA sea-level curve is that of a high stand at 6.5–4.5 ka, subsequently decaying to present-day elevation. Deviations from this regional sea-level pattern reflect local tectonic displacement (cf. Lajoie, 1986).

Here we report the finding of a fossil late Holocene reef buried beneath the surface of the Interuniversity Marine Laboratory of Elat. The buried reef (termed here MLR = marine laboratory reef) is perfectly preserved beneath a 4-m-thick sequence of siliciclastic sediments. The MLR platform is 0.6 m lower in elevation than that of the modern reef, indicating that its burial was associated with localized subsidence, probably related to a down-faulting event. Offshore, north of the MLR, a fossil late Holocene reef is submerged 4 m underwater. On top of the submerged reef (SR) platform an ancient dwelling site was discovered. The SR provides another indication of a late Holocene down-faulting event.

The destruction and burial of the marine laboratory reef (MLR)

The buried reef is covered by cross-bedded siliciclastic beach sediments comprising clasts of rocks from the nearby crystalline hills, with minor

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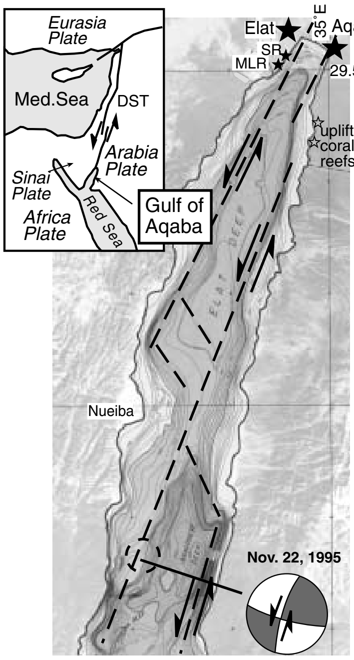

Fig. 1 Location of the Gulf of Aqaba at the southern end of the Dead Sea Transform (inset). Bathymetric chart of the Gulf of Aqaba (Hall and Ben-Avraham, 1978) showing the location and solution of the sinistral 1995 earthquake east of the town Nuweiba, and the locations of the nature reserve reef of Elat where a fossil Holocene reef (SR) overlain by an archaeological site is submerged 4 m under water, and the Marine Laboratory of Elat where a buried Holocene reef (MLR) was discovered.

Cretaceous carbonates and cherts, and modern marine fragments. Large cobbles are common next to the buried reef at the lower part of the ~4-m-thick section, and are rare towards the top that is indistinguishable from sediments of the active beaches in the vicinity. The clastic sequence contains a beachrock layer, < 1 m thick, that was indurated at the intertidal elevation (Shaked *et al.*, 2002).

The perfect preservation of corals from the upper living surface of the buried reef (to the finest skeletal texture, seldom observed in fossil reefs) is suggestive of very fast burial of the reef, while corals were still alive. We interpret the sediments of the marine laboratory shore to have been deposited during catastrophic event(s) that killed the reef instantaneously, while preserving the tiny delicate parts of the corals (Fig. 2). The question is: what caused this catastrophic event? Is it related to enhanced runoff and sediment supply from land, or was it induced by earthquakes in the gulf? To address these questions we drilled 12 m into the buried reef and excavated a wide pit that allowed us to study its structure, composition and chronology in detail.

A large variety of corals were collected from the MLR. Corals selected for dating include a variety of species (*Porites*, *Favia*, *Lobophilia*, *Gyrosmilia*) recovered from the main reef structure (Table 1). These are composed of 100% aragonite showing pristine textures, with only minute amounts of secondary aragonite cement precipitated in coral pores.

Two fragments from the top and the bottom of a large *Favia* (KC-43 and KC-44, respectively) yielded near identical ^{230}Th–^{234}U ages of 4910 ± 50 years and 4990 ± 50 years, with similar initial $\delta^{234}U_i$ values (178 ± 3‰ and 186 ± 3‰) (where $\delta^{234}U_i = \{\{[(^{234}U/^{238}U)\ \text{measured}]/[(^{234}U/^{238}U)\ \text{secular variation}]\}-1\}1000$). A beautifully flat-topped *Porites* (KC-Y) that is inferred to have grown to sea-level (Fig. 2) was radiocarbon dated to 4685 ± 125 cal years BP. Another coral (KC-42) recovered from a hole drilled into the buried reef yielded an age of 6750 ± 100 years, with a $\delta^{234}U_i$ value of 171 ± 3‰. This coral was brought from 11–12 m deep and does not represent a reef platform. The pristine texture and mineralogy of these corals suggest that no significant diagenetic alteration affected the corals except for minor cementation. Nevertheless, the initial $\delta^{234}U_i$ values are significantly higher than those of present GOA seawater and living corals ($\delta^{234}U_i$ = 144 ± 4‰) (Lazar *et al.*, 2004). The elevated $\delta^{234}U_i$ values of corals from this group are perhaps caused by the presence of minor aragonite cement that was precipitated in coral pores from a high $\delta^{234}U_i$ mixture of seawater and brackish groundwater that leached the nearby granitic basement (Cohen *et al.*, 2000; Lazar *et al.*, 2004). The identical ^{230}Th–^{234}U ages in the different coral fragments attest to their validity. The 4.9 ka age of these buried corals is consistent with ages determined for an emerged reef terrace near the town of Elat. Two corals from the emerged reef south of Elat yielded ^{230}Th–^{234}U ages of 5380 ± 50 years and 4960 ± 50 years with identical $\delta^{234}U_i$ of 140 ± 3‰. These corals (TYS and AA-1, respectively) were collected from the outer edge of the emerged reef at the elevation of the present sea-level and were never exposed to groundwater, hence the original $\delta^{234}U_i$ value. A similar radiocarbon age was previously determined for this emerged reef (Friedman, 1965).

A second group of corals recovered from the pit yielded younger ages that cluster at about 2.3 ka. ^{230}Th–^{234}U ages of pristine *Favites* (BRR-1) and *Lobophilia* (BRR-3) are 2370 ± 30 years and 2520 ± 30 years, with $\delta^{234}U_i$ of 143 ± 3‰ and 151 ± 3‰, respectively. Radiocarbon ages of two other corals from the buried reef (BRR-109 and BRR-106.2) are 2120 ± 190 and 2505 ± 195 cal year BP, consistent with the U-series ages.

The two age groups of corals from the buried reef may represent two stages in the development of the reef: the older corals grew when Holocene sea-level was at its maximum (Fig. 3), whereas the second age group represents a younger reef platform established following slight sea-level drop to present elevation.

The MLR platform is presently 0.6 m lower than the modern reef platform at Elat, although sea-level at the GOA apparently stabilized at its present elevation shortly after the mid-Holocene maximum (Fig. 3). Thus, it appears that the MLR was down-faulted 0.6 m sometime later than 2.3 ka. Subsequently, large quantities of beach sediments were transported to the site and buried the reef.

Submerge reef (SR) and archaeological site

Underlying the modern nature reserve reef of Elat (NRR) ~1 km north of the MLR, we found another fossil Holocene reef (Fig. 2). The fossil reef platform, covered by a thin veneer (< 10 cm) of loose carbonate sand, is now submerged 4 m underwater. Beneath the sandy cover we found typical reef rock with scattered coral heads in growth position. The SR platform seems to have undergone some abrasion and cavity filling by reef debris to form a flat surface, but judging from the diameter of small

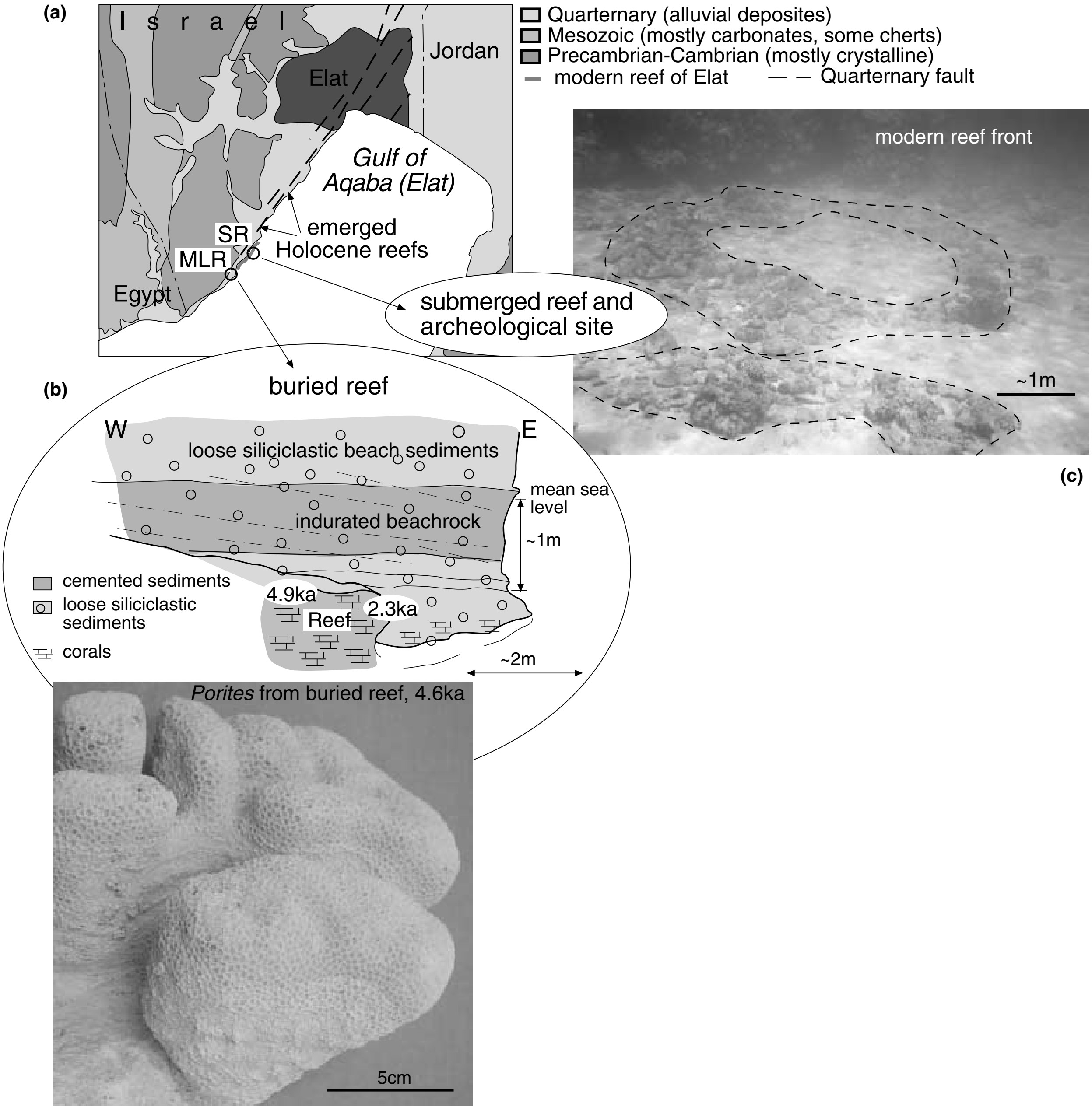

Fig. 2 (a) Simplified geological map of the north-western end of the Gulf of Aqaba (modified from Garfunkel *et al.*, 2000) showing the location of the buried marine laboratory reef (MLR) and the submerged reef (SR). (b) Cross-section of the excavated pit where the buried MLR was studied, and photograph of a 4.6 ka *Porites* sp. coral from the buried reef. (c) Photograph of the archaeological site on top of the submerged reef. Note the modern Elat nature reserve reef in the background, partly overgrowing the site.

coral heads abrasion has not exceeded several centimetres.

An ancient dwelling site was discovered on top of the SR platform, built after its exposure and abrasion. This primitive site consists of several adjacent circular walls, a heap of stones that might be a burial place and small installations such as rounded hearths. The basic layout consists of a ~4–5-m-diameter room and adjacent ~15-m-diameter circular courtyard that was apparently used to keep livestock (Fig. 2). Similar sites became common in the region at 6–5 ka (Avner *et al.*, 1994; Avner, 1998) and were used by nomads of the region until recent times. The sparse archaeological remains spread over an area of ~500 m^2 in front of, and partly underlying, the modern reef imply a short period of occupation. We drilled five samples from the SR platform, using a hand-held pneumatic drill powered by compressed air. The sampled area spans ~30 m along the modern reef front. Four pristine corals from the SR were radiocarbon and U–Th dated to between 5.4 and 2.4 ka (samples NRR-1, 3, 3b, 4.2; Table 1).

Table 1 ^{230}Th–^{234}U and ^{14}C ages of corals from fossil reefs south of Elat

Sample	Location	Elevation (m)	Coral type	Age (years)	Error (years)	δ^{234}U initial	Error (1σ)	^{238}U (p.p.m.)	^{232}Th (p.p.m.)	[^{230}Th/^{238}U]	[^{234}U/^{238}U]
NRR-1	SR reef-platform	(–)4	*Favidae*	2430	30	150	3	2.96	0.018	0.0254	1.149
NRR-3	SR reef-platform	(–)4	*Favidae*	3500	50	155	3	2.62	0.026	0.0366	1.153
TYS	Emerged reef (south)	(+)1	*Leptastrea*	5380	50	140	3	2.63	0.001	0.0550	1.138
AA-1	Emerged reef (north)	(+)1	*Favites*	4960	50	140	3	2.69	0.001	0.0505	1.135
BRR-1	MLR, pit1	~(–)0–1	*Favites*	2370	30	143	3	2.41	0.001	0.0246	1.142
BRR-3	MLR, pit1	~(–)0–1	*Lobophilia*	2520	30	151	3	1.66	0.003	0.0264	1.150
KC-42	MLR, borehole	(–)9	–	6750	100	171	3	2.41	0.006	0.0703	1.167
KC-43	MLR, pit1	~(–)0–1	*Favia*	4910	50	178	3	3.55	0.004	0.0520	1.175
KC-44	MLR, pit1	~(–)0–1	*Favia*	4990	50	186	3	3.17	0.016	0.0531	1.184
				^{14}C age (years BP)	Error (years)	Calibrated age (cal years BP)	Error (1σ) (year)				
NRR-3b	SR reef-platform	(–)4	*Favidae*	4110	50	4150	160				
NRR-4.2	SR reef-platform	(–)4	*Favidae*	5170	90	5430	195				
BRR-109	MLR, pit2	(–)0.6	*Gyrosmilia*	2470	80	2120	190				
BRR-106.2	MLR, pit2	(–)0.6	*Lobophilia*	2755	80	2505	195				
KC-Y	MLR, pit1	~(–)0–1	*Porites*	4500	100	4685	125				

MLR, buried reef beneath the IUI marine laboratory, Elat; SR, submerged reef at the Elat marine nature reserve. (–) (+) Below and above sea-level, respectively. U and Th isotope abundances were analysed by TIMS at MPI für Chemie Mainz. Analytical procedures (U and Th extraction and mass spectrometry) follow Haase-Schramm *et al.* (2004). [^{234}U/^{238}U] are measured activity ratios. [^{234}U/^{238}U] activity = atomic (^{234}U/^{238}U)/(^{234}U/^{238}U) where (^{234}U/^{238}U) = $\lambda_{238}/\lambda_{234} = 2.835 \times 10^{-6}$ years^{-1} (Jaffey *et al.*, 1971; Lounsbury and Durham, 1971). δ^{234}U is the fractional deviation from the equilibrium value in per mill. The ^{230}Th/^{238}U is reported as the measured activity ratio, which is equal to the atomic ratio divided by $\lambda_{238}/\lambda_{230} = 1.687 \times 10^{-5}$ ($\lambda_{230} = 9.195 \times 10^{-6}$) (Jaffey *et al.*, 1971; Meadows *et al.*, 1980).

Calibrated ages (1σ) in calendar years have been obtained from the OxCal v3.5 code (Ramsey, 1995, 2001) that incorporates a 402 years ocean residence time (OxCal: http://www.rlaha.ox.ac.uk/orau).

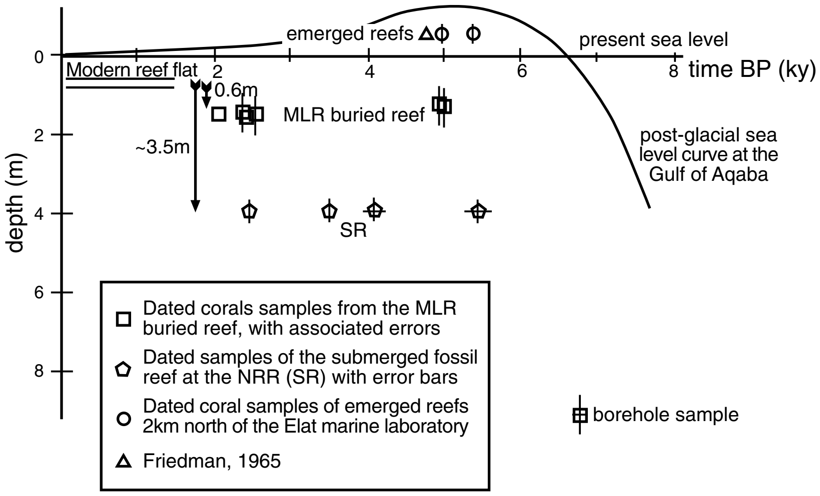

Fig. 3 Plot of coral ages vs. depth for the north-west Gulf of Aqaba. The sea-level curve is constrained by emerged corals south of Elat in addition to emerged Holocene reefs at southern Sinai (Gvirtzman *et al.*, 1992) and Aqaba (Al-Rifaiy and Cherif, 1988). Deviations from the regional sea-level pattern are considered the result of local displacements. The buried reef at the Marine Laboratory of Elat (MLR) was displaced 0.6 m at ~2.3 ka; 1 km to the north the Holocene reef was displaced by 3.5 m. Down-faulting brought about the death of these reefs.

The evolution of the SR and the overlying archaeological site is constrained by the fossil coral ages and the development of the modern reef. We suggest the following history:

1 A fringing reef developed following the postglacial sea-level rise, catching up with the sea surface at ~5 ka.
2 The SR reef platform expanded laterally over the next 3000 years until at least 2.4 ka. During this time sea-level dropped slightly, killing the top of the reef.
3 At 2.4 ka the SR was exposed and a dwelling site was established over the flat surface.
4 The SR and the overlying archaeological site then subsided to below sea-level. Drowning must have been extremely rapid because the crudely constructed site was not completely obliterated by waves. This is suggestive of a down-faulting event.
5 Corals resettled over the fossil SR and the modern Elat reef was established. Considering the time it takes to develop a 3.5-m-high reef with a flat 20-m-wide surface (Barnes and Lazar, 1993; Kennedy and Woodroffe, 2002), downward displacement was not later than ~2 ka. It is likely that a single event displaced the reef by 4 m to its present position.

This sequence of events at a site located between the emerged ~5.1 ka reef and the MLR strongly supports the occurrence of a large earthquake that down-faulted the north-western margin of the GOA some 2300 years before the present.

Demise of the Elat Holocene reefs

Catastrophic flash-floods, which are typical of this area, could account for the burial of the MLR, but there is no drainage outlet nearby that can supply the sediments. The nearest large outlets are those of west Taba ~2 km to the south and north Shelomo ~2 km the north (Fig. 2). Moreover, the lithic composition of the adjacent drainage systems is different from the sediments at the site. Sedimentary structures and marine bioclasts within the sediments that bury the reef indicate transportation and deposition by waves. In the absence of a fluvial source of flood sediments, the burial of the reef reflects sediment influx by sea waves.

Tsunami and seiche waves often accompany large earthquakes. Indeed, the 1995 Nueiba earthquake induced a wave that washed over the shores of the GOA and the 1999 Izmit earthquake caused extreme flooding along the Marmara Sea (Öztürk *et al.*, 2000). We suggest that a large earthquake ~2300 years ago caused the submergence of the SR with the archaeological site on top of it, and the displacement and initial burial of the MLR. The abundance of large cobbles at the lower part of the sediment section at the MLR supports this scenario. However, in the absence of vegetation on these arid coasts, other indications of tsunami deposits were not found.

Following the earthquake that buried the MLR, sediments transported by waves pushed the shoreline seaward by 100 m (Shaked *et al.*, 2002). A new state of coastal equilibrium was reached and a new reef started to grow along the shoreline. The beachrock layer that formed within the covering sediments is not faulted, indicating that later earthquakes did not affect the site.

Conclusions

The demise of the Elat reefs by an earthquake at ~2.3 ka illuminates a mechanism by which reefs along this stretch of the GOA coastline are episodically destroyed and rejuvenated. Such a pattern may explain the pronounced differences in biomass between the Elat reef and the nearby reefs of southern Sinai and Aqaba. The latter comprise wide well-developed structures, in contrast to the Elat reefs that are narrow and composed of linear arrays of knolls and patches. It appears that the tectonic pattern affects reef structure. Whereas down-faulting of the Elat coastline kills its fringing reefs, the reefs at the uplifting coasts of Sinai and Aqaba continue to grow seaward.

In many uplifting regions, Holocene coral reefs are well developed seaward of a stepped fossil reef sequence [e.g. the Huon Peninsula (Chappell, 1974; Ota and Chappell, 1999) and Tiran Island (Goldberg and Beyth, 1991)]. Reef growth at such locations was supported during the early Holocene by rising sea-level. At tectonically subsiding margins, by contrast, coral reefs had fewer survival chances as a result of drowning and burial. During the late Holocene when sea-level was virtually stable, vertical tectonic movements determined the fate of reefs. In subsiding regions tectonics are associated with drowning and rapid accumulation of sediments. Under such conditions, reefs at subsiding margins degenerate and eventually die.

Acknowledgements

We thank the Interuniversity Institute in Elat and the Nature and Parks Authority of Israel for assistance, and the Israel Ministry of Infrastructure for support of this research. We thank E. Boaretto of the Weizmann Institute of Science for radiocarbon age determinations, and C. Cohen, E. David, D. Tchernov and D. Zakai for assistance in the field. This manuscript benefited from helpful reviews by J. Neilson and M. Wilson.

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Received 21 October 2003; revised version accepted 8 March 2004

