Coral Reefs (2005) 24: 165–172
DOI 10.1007/s00338-004-0454-2

REPORT

**Yonathan Shaked · Boaz Lazar · Shmuel Marco**
**Mordechai Stein · Dan Tchernov · Amotz Agnon**

# Evolution of fringing reefs: space and time constraints from the Gulf of Aqaba

Received: 4 April 2003 / Accepted: 1 September 2004 / Published online: 11 November 2004


**Abstract** This study documents the pattern and rate of reef growth during the late Holocene as revealed by unique geological conditions at the subsiding NW Gulf of Aqaba. We discovered that the modern fringing reef near the city Elat grows on top of a fossil submerged mid-Holocene reef platform. Four coral cores from the fossil platform were dated using the radiocarbon and U-Th methods. The fossil corals range from $5.6 \pm 0.1$ to $2.4 \pm 0.03$ ka, constraining the initiation of the modern reef to 2,400 years ago at most. We documented the detailed morphology of the reef using aerial photographs and scuba diving. The survey shows that at its northern end, growth of the 2-km-long reef is inhibited by an active alluvial fan, and it is composed of isolated knolls that are just approaching the sea surface. Towards the south, the knolls are progressively larger and closer together, until they form a continuous reef platform. Along this north-to-south trend we follow the evolution of reef morphology, changes in coral distribution, and the development of a lagoon separated from the open sea. Based on these observations, we suggest a four-stage reef growth model: (a) the reef initiates as coral colonies, forms knolls, and begins to grow upward, limited by the sea surface. (b) Upon reaching the surface, the knolls spread laterally, preferentially parallel to the dominant wave direction assuming an elongated morphology. (c) Continued growth results in adjacent knolls eventually coalescing to form a continuous jagged reef. We interpret the spurs-and-grooves morphology that can be traced across the reef at Elat as remnants of the original trends of knolls. (d) While reef expansion continues, the original knoll trends may be obscured as a massive reef front takes shape. Considering reef growth rates and observations from the modern reef at Elat, this evolution scheme predicts an age range of $10^3$ years for corals on the reef platform. The range and distribution of radiometric ages we obtained from the fossil reef platform underlying the living Elat reef confirm this hypothesis.

**Keywords** Fringing reefs · Holocene · Down-faulting · Reef structure

Communicated by Geological Editor P.K. Swart

Y. Shaked · B. Lazar · M. Stein · A. Agnon
Institute of Earth Sciences, Hebrew University,
Jerusalem, 91904, Israel

S. Marco
Department of Geophysics and Planetary Sciences,
Tel Aviv University, Tel Aviv, 69978, Israel

M. Stein
Israel Geological Survey,
30 Malkeh Israel St., Jerusalem, 95501, Israel

*Present address*: Y. Shaked (✉) · D. Tchernov
Institute of Marine and Coastal Sciences,
Rutgers University, 71 Dudley Road,
New Brunswick, NJ 08901, USA
E-mail: shaked@marine.rutgers.edu
Tel.: +1-732-9326555
Fax: +1-732-9324083

## Introduction

Coral reefs are commonly used as geologic markers of various conditions and processes such as local paleo-oceanographic conditions, sea level changes, and vertical displacements along coasts (Braithwaite et al. 2000; Chappell 1974; Chappell et al. 1996; Eisenhauer et al. 1993; Enmar et al. 2000; Yamano et al. 2001; Zachariasen et al. 1999). The advantages of reefs for such purposes stem from their potential for accurate dating with the radiocarbon and uranium series techniques (Bard et al. 1990; Bloom et al. 1974; Burr et al. 1992; Chen et al. 1991; Edwards et al. 1987; Stein et al. 1993), and from the narrow range of living conditions suitable for their development. In order to use coral reefs as precise geological markers and to perceive what the ages attained from coral samples signify, we must understand how they grow and develop. Therefore, in this study we follow the morphology and growth pattern of a young reef after determining its initiation age by radiocarbon dating the underlying substrate. This substrate is a fossil reef downfaulted and submerged some 2,000 years ago (Shaked et al. 2004). Classification of coral reefs according to their morphology began with (Darwin 1842), and a review of the variety of fringing reef morphologies and their inferred growth histories is found in (Kennedy and Woodroffe 2002). Here we combine morphological observations from a living reef and ages of the underlying basement to deduce the stages of development of fringing coral reefs. The studied reef is in the northwestern Gulf of Aqaba (Fig. 1).

The unique properties of the growth study reported here are: (a) The timing of initial settlement of modern corals is well constrained, (b) reef growth is inhibited in one section, and has not reached the mature stage in which the initial features are obscured. We can therefore observe the various stages of reef evolution within a few hundred meters. The growth pattern of fringing reefs at the scale of the entire reef structure in three dimensions affects the significance of coral samples as geological recorders.

Most modern reefs began to develop following the rapid post-glacial sea level rise. About 7,000 years ago, the global sea level rise slowed (Fleming et al. 1998; Pirazzoli 1991) and reefs were able to catch up with the sea surface and begin to expand (Cabioch et al. 1999; Davies and Marshall 1980; Grigg 1998; Montaggioni 2000; Shinn et al. 1981). Subsequently, coral reef morphology is controlled by a combination of ''oceanic'' conditions and local geology and topography. These factors determine initial colonization, coral species, coral growth rates and zonation patterns, and may also limit the lateral expansion of an existing reef. The effects of these factors may be traced in the morphology and stratigraphy of reefs (Kennedy and Woodroffe 2002). Many fringing reefs display a morphology of spurs and grooves (sub-parallel linear features of promontories and gullies extending seaward at an angle to the reef trend, forming the ''buttress zone'' of the reef (Goreau 1959; Shinn et al. 1981)). Such reefs are hypothesized to evolve through several major stages that reflect on both vertical and planar development (Braithwaite et al. 2000; Kan et al. 1995; Kan et al. 1997). The formation and morphology of spurs and grooves is sometimes attributed to wave energy (Blanchon and Jones 1995), implying that physical erosion by waves affects the micro-topography (meter-scale) of reefs. Spurs and grooves may also be constructional features (Goreau 1959; Goreau and Goreau 1973; Shinn 1988). The spacing between spurs is in some cases attributed to wave energy, and in others it is thought to result from antecedent topography (Shinn et al. 1981). Wave action forces may also affect the accretion rates of reefs (Grigg 1998) and the population distribution of coral species (Blanchon and Jones 1995; Camoin et al. 1997; Grigg 1998). Therefore, morphologic zones within the reef are also characterized by species zonation (Goreau and Goreau 1973) and may indicate the factors and conditions that shape the spurs and grooves.

On tectonically active shorelines growth may also occasionally be interrupted by tectonic displacements. Commonly, the reef is either destroyed or continues to grow according to the new conditions. A unique combination of geological, morphological, and oceanographic conditions on the NW margin of the Gulf of Aqaba suggests a testable model for reef initiation and development.

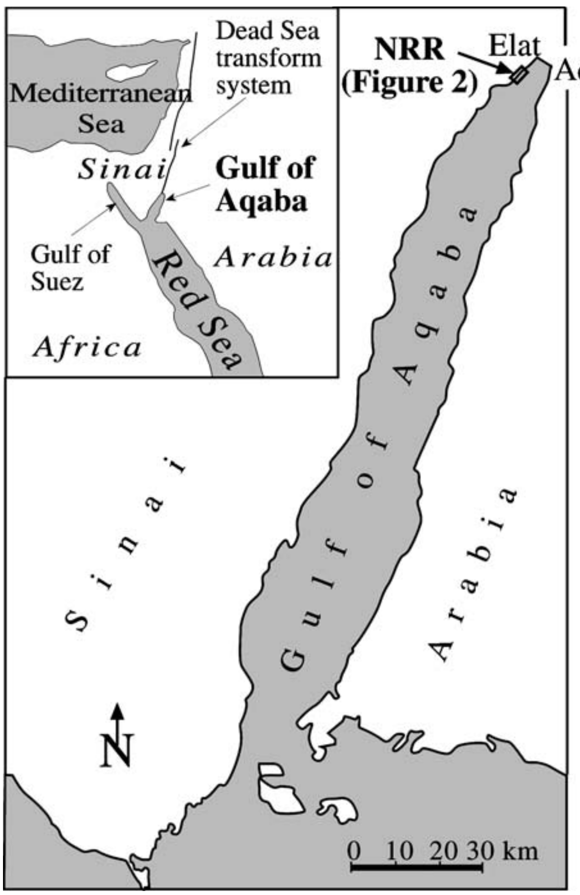


**Fig. 1** Location of the Gulf of Aqaba and the Elat NRR at its northwestern tip

## Setting and morphology of the Elat nature reserve reef (NRR)

Repeated tectonic movements have downfaulted the NW margin of the Gulf of Aqaba, often killing adjacent fringing reefs (Shaked et al. 2004). We discovered a Holocene reef south of Elat that was exposed and leveled by wave abrasion during the inter-seismic interval, prior to stress release by a large downfaulting earthquake (Tudhope et al. 2000; Zachariasen et al. 1999). The subsequent earthquake displaced the reef to 3–4 m below sea level, where it provides substrate for re-colonization and development of a modern reef. We are therefore given a glimpse of the ''adolescent'' stage in reef development and can constrain the age and growth rate of the modern fringing reef. This contemporary reef displays a morphology of spurs and grooves and helps to elucidate the origins of these morphologic features. Our investigation of the initiation and development of fringing reefs is based on observation of this key stage in the growth that is commonly not available for examination. We then test a four-stage growth and development model against morphologic observations from the modern reef and the age pattern of the submerged fossil Holocene reef beneath the modern one.

The coral reef at the Elat nature reserve beach is ~1 km long, with an average width of about 20 m (Fig. 2). The NRR extends parallel to the shoreline, separated from it by a lagoon less than 2.5 m deep and up to 50 m wide. The reef terminates at the shoreline to the north and the south, where fans of coarse silisiclastic gravel protrude into the sea (Shaked et al. 2002). We define three zones along the reef. In the central zone, the reef grows almost vertically from the underlying sub-horizontal carbonate shelf that is the displaced fossil reef. This shelf is ~4 m deep, and thinly covered by loose reef rubble and carbonate sand (less than 0.2 m thick). The shelf extends east at least 30 m past the modern reef front before the slope gets steeper (Fig. 3). Knolls of various sizes dot the shelf east of the reef. Towards its northern and southern ends, the shelf is less distinct. To the north, near the silisiclastic fan that limits the northern extension of the reef, a thicker blanket of sandy and coarse clastic sediments ( > 0.5 m) covers the shelf. Thus the reef in the northern zone grows over a sandy substrate that is only 2.7 m deep. To the south, it grows over a topography comprising three distinct steps at 4, 8, and 15 m. These seemingly reflect faulting of the gulf margin. Three distinct reefs with different morphologies are found in this southern zone: the shallower of these is the southward continuation of the reef, but the deeper two have no counterparts in the central and northern zones. In the three zones the shallow part of the NRR features a reef flat that is 0.6 m below mean sea level (tidal variations do not exceed 0.7 m (IOLR data, http://marine.ocean.org.il/Tideelat/callinke.htm)).

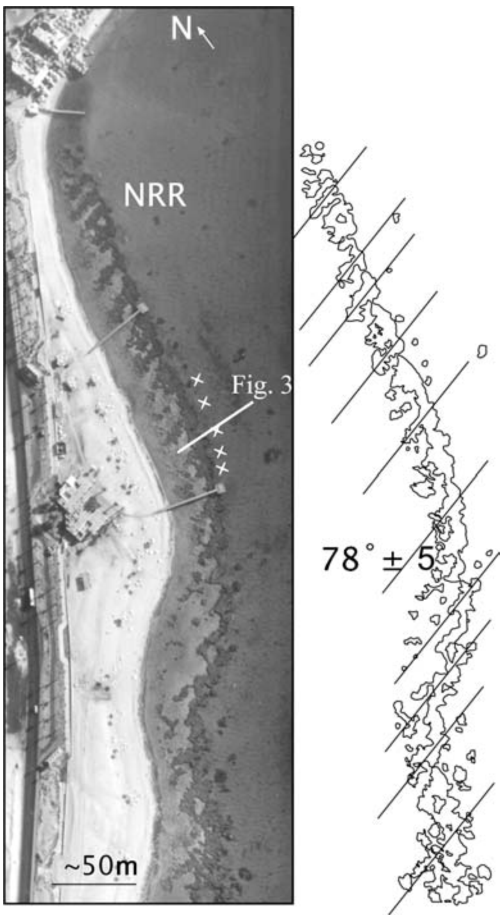


Fig. 2 The central and northern zones of the NRR fringing the shore south of Elat. Outline of the reef showing the parallel lines of spurs and grooves trending ~80°, at an angle of 55–60° to the trend of the reef structure. Notice that the spur-and-groove features are discernible on both leeward and windward sides of the reef. *White Xs* denote location of samples drilled for dating, *white line* is the location of the profile in Fig. 3

The NRR is best developed in the southern zone where it has apparently evolved from the deeper reefs. It is least developed in the northern zone. This may stem either from a difference in ecological–physiological conditioning of the reef or varying wave action along the shore. The modern reef flat is thinner towards the north, and is dissected by progressively wider channels. A parallel trend is observed in the reef mass; at its northern end the reef is patchy and composed of a linear array of isolated patches, whereas to the south it is massive and continuous, and supports a well-developed lagoon.

In plan view, the reef displays prominent "spurs and grooves" trending ~80° (Fig. 2). The spurs are linear coral patches that extend seaward a few meters, separated by channels with little or no coral growth. The outer reef crest with shallow spurs and grooves forms the buttress zone of the NRR (Loya and Slobodkin 1971). The linear trend of the spurs can be traced across the reef from windward to leeward into the lagoon. They are aligned parallel to the average wave direction at the NRR beach, and probably reflect preferred growth in that direction (Goreau 1959; Kan et al. 1997; Shinn et al. 1981). A similar relationship between the wave direction and the trend of spur structures is well known elsewhere and has previously been demonstrated for the reefs of this region (Sneh and Friedman 1980).

## Methods

Trends of the reef and spur-and-groove structures were derived from aerial photos after orientation correction using DGPS readings. Depth measurements were taken from a SUUNTO dive computer calibrated with a measuring tape. Absolute depth is ± 30 cm of the given numbers, but relative depths between locations are accurate. Coral species were counted along representa-

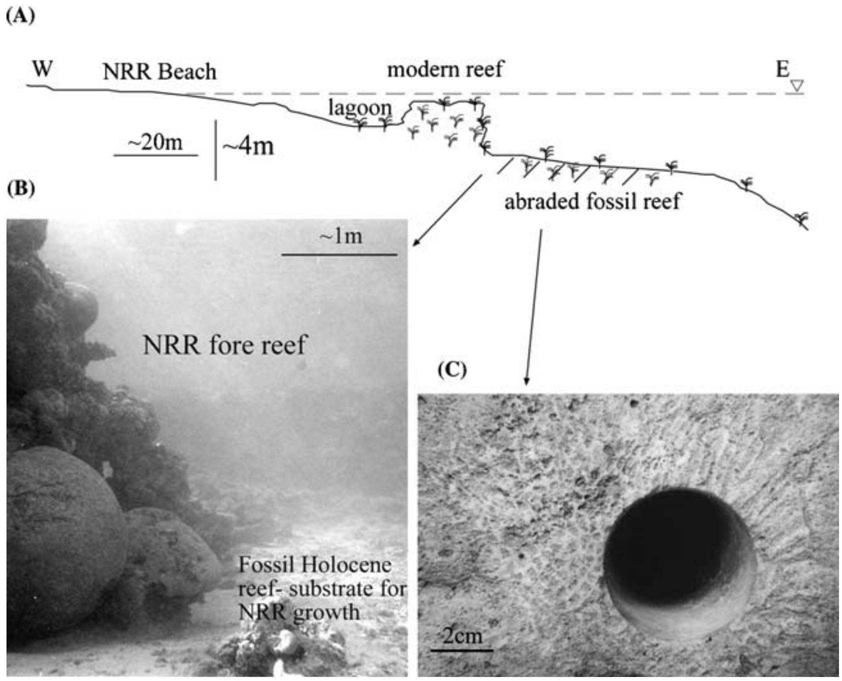


**Fig. 3** **a** Profile across the Elat NRR in the central zone (not to scale-note vertical exaggeration). For location, see Fig. 2. **b** The NRR grows almost vertically from a sub horizontal platform that is an abraded fossil Holocene reef. **c** Drill hole into a fossil coral head that is part of the platform underlying the NRR. The radiocarbon age of this fossil coral is 2.2 ka

tive transects of knolls and segments of the modern reef-front at the northern and central regions of the NRR. Sites for sampling the fossil reef-flat were selected after removing the clastic sediment cover from the fossil flat and identifying massive coral heads in growth position. Samples were obtained by drilling cores 5 cm in diameter using a diver-operated hand-held pneumatic drill. Samples for dating were examined with a reflected light microscope and a petrographic microscope to identify unaltered corals (Bar-Matthews et al. 1993). Mineral composition of the selected samples was determined with X-ray diffraction, and only unaltered samples comprising >98% aragonite were chosen. Samples were dated with the U-Th method and the AMS radiocarbon method (see table). In order to achieve a uniform timescale the radiocarbon ages were calibrated with the OxCal v3.5 program (Ramsey 1995, 2001) using the marine calibration curve of Stuiver et al. (1998) that incorporates a 402-year ocean residence time (OxCal: http://www.rlaha.ox.ac.uk/orau).

## Results

### Distribution of massive versus branching corals

Several small isolated knolls are found at the northern end of the NRR. These are composed primarily of massive corals (e.g. *Favia* sp., *Favites* sp., *Galaxea astreata*, *Lobophyllia corymbosa*). Branching corals (e.g. *Acropora echinata*, *Acropora formosa*, *Acropora gemmifera*, *Acroporamicroclados*, *Stylophora pistilata*, and *Pocillopora verrucosa*) are usually found in gaps between knolls that provide shelter from direct wave force. Where the reef is continuous, branching corals are only found below the reef edge, which is occupied by massive coral heads. Towards its southern end the reef flat is wider and the reef more massive. Branching corals are dominant on the reef platform and on deeper parts of the reef front. The NRR reef supports 97 scleractinian coral species of 40 genera and 13 families (Loya and Slobodkin 1971). The diversity and distribution of corals may reflect its response to occasional severe southern storms (occurring once or twice a decade). Rare strong waves may affect the population distribution of massive versus branching corals as anticipated by the intermediate disturbance theory (Aronson and Precht 1995; Bythell et al. 2000; Edmunds 2000; Lirman et al. 2001). The response to such waves is partly controlled by the spur-and-groove morphology.

### Ages and growth rates at the NRR

The central section of the NRR was examined by clearing the sand cover from the carbonate shelf at closely spaced intervals. Individual coral heads in growth position indicate that the shelf over which the NRR grows is an abraded fossil reef flat (Fig. 3). We drilled five sample cores (diameter 5 cm, length 10–25 cm) from this fossil reef flat, a few meters apart along the outer margin of the overlying NRR (Fig. 2). Four pristine corals were selected from the cores for radiocarbon and U-Th dating.

The ages of corals from the fossil reef range from 5.6 ka to 2.4 ka (Table 1) indicating that this reef flat was active for at least 3,000 years, until 2.4 ka. The abrasion surface indicates that the reef top was subsequently briefly exposed and abraded, perhaps as a result of stress accumulation prior to a stress-releasing earth-

Table 1 Ages of corals from the submerged platform

| Sample | Coral | Location | $^{14}C$ BP | Calibrated age[a] | Th-U |
|---|---|---|---|---|---|
| NRR-1 | Alveopora | NRR fossil flat, S1 | – | – | 2,432 ± 30 |
| NRR-3 | N/A | NRR fossil flat, S3 | – | – | 3,502 ± 50 |
| NRR-3a | N/A | NRR fossil flat, S3 | 4,228 ± 51 | 4,225 ± 125 | – |
| NRR-4.II | N/A | NRR fossil flat, S4 | 5,273 ± 69 | 5,595 ± 115 | – |

U-Th samples prepared and measured at the Max-Planck-Institut für Chemie in Mainz, Germany
Radiocarbon dating was preformed at the AMS laboratory of University of Arizona, United States. $^{14}C$ ages are reported in conventional radiocarbon years (present = 1,950) in accordance with international convention (Stuiver and Polach 1977).
[a]Calibrated $^{14}C$ ages (1$\sigma$) are given in calendar years before present

quake. Shortly after exposure, a devastating earthquake displaced the abraded surface to its present depth of 3–4 m. This scenario is supported by the existence of a fossil reef of similar age excavated beneath beach sediments about a kilometer to the south, and is also at a lower elevation than contemporary reefs in the region (Shaked et al. 2004). The clear-cut field relations between the fossil reef and the overlying modern reef indicate that the contemporary reef is younger than 2.4 ka. In the past 2,000 years, corals of the NRR recolonized the site, grew ~3.5 m vertically to catch up with the sea surface, and began to spread laterally.

The productivity and calcification rate of a representative section of the NRR reef flat was measured in-situ by (Barnes and Lazar 1993), who extrapolated a yearly calcification rate of 6.0 kg $CaCO_3$ $m^{-2}$ $year^{-1}$. To translate into meters per 1,000 years we assume a porosity of 50% for the reef, and a density of 2,300 kg $m^{-3}$ for $CaCO_3$. The growth potential of the reef is therefore estimated at ~5.2 m $ka^{-1}$. In other words, the reef can potentially grow vertically over 5 m in 1,000 years.

In the northern zone, the NRR is notably less developed than in the central and southern zones. At its northern end, the reef is composed of sporadic patches and knolls, some of which do not reach the sea surface to form a reef flat despite the shallower water depth (only 2.7 m). Grazing in this part of the NRR is not conspicuously high and it is somewhat protected from direct waves. We therefore assume that reef development is inhibited by reduced growth rates. Although productivity and growth rates were not quantitatively assessed in the northern zone, these are clearly less than the numbers quoted above.

Two factors possibly inhibit the development of the reef at its northern end: (a) a larger supply of sandy sediments from an adjacent alluvial fan. A sandy sea floor may inhibit initial coral settlement (here the carbonate shelf is buried by a 0.5-m thick sand layer), and suspended sand may reduce coral growth rate after settlement; (b) in this region reefs seem to grow preferentially towards the wave direction, presumably since waves provide well-oxygenated water rich in zooplankton. The alluvial fan, which protrudes into the sea north of the reef, partly shields it from direct waves driven from north to south by the dominant northerly winds. Therefore, although we assume the same "initiation" age of ~2 ka in the northern zone, reduced growth rates have kept the northern end of the NRR at a less mature stage in development.

## Discussion

### Reef growth model

A reef begins to grow when suitable conditions prevail, and will develop as long as they persist. The rate of sea level rise and the depth below present sea level where suitable substrates are available are major controls on the timing of reef initiation. There are several paths through which a fringing reef may evolve after initiation, according to circumstances (Kennedy and Woodroffe 2002). Here we consider a three-dimensional development model for fringing coral reefs initiated at a few meters depth, and test it against observed features in reefs (Fig. 4).

1. Coral reefs begin to grow as isolated coral colonies that settle at a depth and distance from shore that are dictated by availability of sunlight, nutrients, and suitable substrate in addition to local conditions such as sediment flux, temperature, wave energy, and slope gradient. The colonies act as "nucleation centers" and begin to grow and develop into coral knolls. Once established, coral knolls provide protection from mechanical erosion and sediment accumulation, and offer ecological advantage for continued growth. Upwards growth is preferred as long as accommodation space is available (Kennedy and Woodroffe 2002) supporting the development of established knolls. At this primary stage vertical growth is rapid as corals strive to approach the sea surface.
2. As the coral knoll approaches the sea surface vertical growth decreases and lateral growth dominates (Burke et al. 1998; Kan et al. 1995). The knoll grows most rapidly parallel to the wave direction forming an elongated structure (Kan et al. 1997) normal to the wave front (Sneh and Friedman 1980). At this stage the embryo reef is composed of elongated knolls aligned parallel to the wave direction.
3. As they grow bigger, adjacent knolls begin to coalesce forming the outline of a reef (Burke et al. 1998). An effective barrier of wave energy, the juvenile reef promotes deposition of suspended carbonate sand and

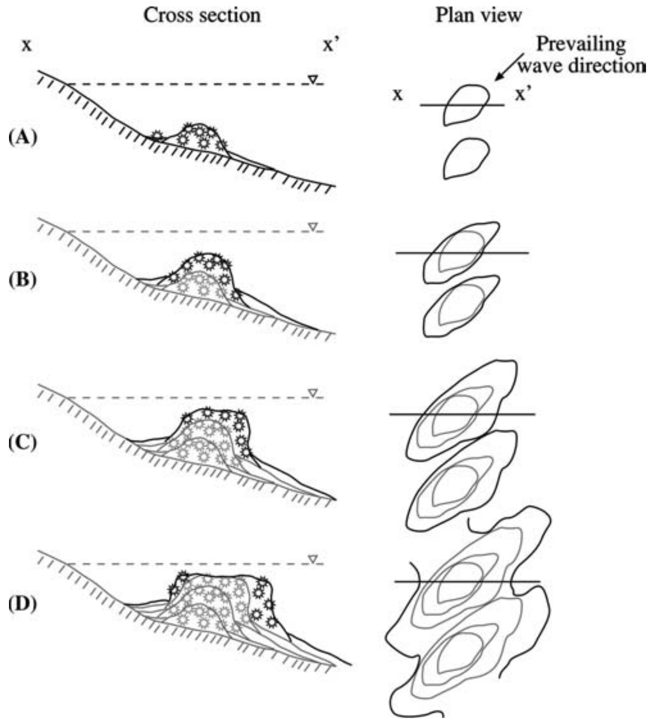


**Fig. 4** Illustration of reef growth model in cross section and plan view. **a** Settlement of coral colonies on the sea floor. Many such initial colonies are expected at optimal depth and where a suitable substrate is available. **b** Dominantly vertical growth towards the sea surface, lateral growth is limited and mainly parallel to the wave direction. **c** Coral patches approach the sea surface and as vertical accommodation space becomes limited, lateral growth begins to dominate. **d** Lateral growth of coral patches forms reef flats, and adjacent patches begin to coalesce creating a complex reef structure

terrigenous clasts, as well as bioclasts transported over the reef edge, in the placid waters of the forming lagoon. At this stage leeward bioclastic sediment accumulation accelerates (Hopley et al. 1983; Yamano et al. 2001), and the reef framework begins to consolidate. The outline of the reef begins to emerge, with wide gaps still common. The linear trend of the original knolls is still discernable on both margins of the reef.

4. As the reef matures and knolls coalesce the fore-reef becomes a massive framework where reef rubble is kept in-situ by early diagenetic encrustation and cementation (Perry 1999). Macroboring, dissolution, and sediment deposition in the back reef inhibit coral growth and preservation (Perry 1998, 1999) and the original knoll trends may be obscured. The fore reef, however, may still preserve these trends as spurs and grooves. The expanding reef may continue to absorb isolated knolls initiated seaward of the emerging reef trend, forming larger spurs. Grooves are preserved as channels funneling water and sediment in and out of the lagoon.

In this model, the spur-and-groove morphology of the reef is a constructional feature. It reflects initiation of the reef as dispersed coral-colonies that settled at optimum depth and grow to merge with each other and form the reef. In a mature reef the spur-and-groove features may be obscured as the reef propagates seaward and water depth becomes a major constraint on growth. Where wave energy is an important factor erosional spur-and-groove structures may be preserved, commonly deeper than the reef flat surface (Goreau and Goreau 1973).

## The NRR and the reef growth model

The initiation of the NRR at about 2 ka provides the time frame for development of fringing reefs of this type. Its morphology reflects the transitional stage from knolls and patches to a continuous structure, characteristic of a reef at development stage 3.

The growth rates of fringing reefs are commonly between 2 and 7 mm year$^{-1}$ (Kennedy and Woodroffe 2002) and references therein. Vertical accretion rates of Holocene reefs vary from less than 1 to 7 m kyear$^{-1}$ but are commonly 2–4 m kyear$^{-1}$ (e.g. Great Barrier Reef (Davies and Marshall 1980); Eastern Pacific (Cortès et al. 1994); Hawaii (Grigg 1998); southwestern Indian Ocean (Camoin et al. 1997)). The 'growth potential' measured at the NRR (Barnes and Lazar 1993) conforms to these reported rates. It is apparent that the NRR could have reached the sea surface not more than 1000 years ago, leaving a similar time for lateral expansion.

The growth rate of the NRR seems to increase from its northern end to the central zone, probably reflecting shoreline geometry and the dominant north-to-south wave direction. Along this path, the transition from the knolls and patches to the reef can be directly observed (Fig. 5), implying a transition from stage 2 to stage 3. Following the linear trends apparent on aerial photos, there are wide gaps between distinct knolls at the northern end of the reef (Fig. 5a). Somewhat to the south, knolls are partly amalgamated near the sea floor (Fig. 5b), and nearly coalesced knolls are present in the central zone (Fig. 5c, d). Where the reef is well developed (central and southern zones), the original trend of the patches is discernable as spurs and grooves.

The north-to-south transition from knolls to reef is also reflected in coral species distribution. Knolls at the northern end of the NRR comprise mainly massive corals. To the south branching corals appear, sheltering in grooves and growing on the protected reef flat and deeper reef front.

Reef morphology and reef growth patterns change as reefs evolve through the stages from initiation to maturity. In mature reefs sediment accumulation and erosion affecting coral settlement and growth patterns, commonly obscure the initial morphology. Thus the initial stages of reef development are inferred from drilling and dating samples out of reef crest, flat, and back reef (e.g. Braithwaite et al. 2000; Burke et al. 1998; Cortés et al. 1994; Davies and Marshall 1980; Kennedy and Woodroffe 2002; Woodroffe et al. 2000; Yamano et al. 2001). Local tectonic conditions preserved the

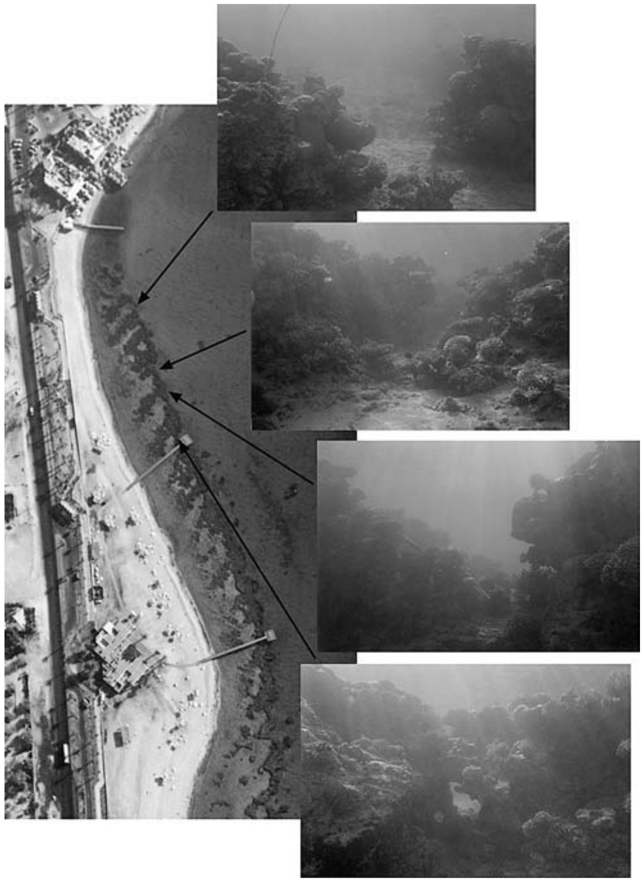

**Fig. 5** The northern zone of the NRR shows a transition from a linear array of knolls at the northern end to a composite reef with continuous reef flat. Progressive coalescence of knolls into reef can explain the observed variety of patterns along a north-to-south path

NRR in the transitional stage between youth and maturity. It thus provides living proof of the validity of a transitional reef growth model through coalescence of reef patches as previously suggested by (Burke et al. 1998; Cortés et al. 1994; Woodroffe et al. 2000).

## Geological implications

The growth pattern of fringing reefs implies that geological interpretations without multiple samples, and attention to the sampled reef morphology, may be erroneous. Morphological changes that occur as reefs evolve must also be considered. The 3,000-year interval represented in four coral samples within approximately 30 m on the fossil reef beneath the NRR, demonstrates these points well. Three issues should be considered when studying coral reefs for geological purposes:

1. The reef platform marks relative sea level with greatest precision. A coral sample without observation of its morphological location, or a reef that had not yet developed a reef platform provides only loose constraint on sea level. Other features, such as coral assemblages and secondary framework species and morphologies may assist sea level interpretation.
2. There is commonly a lag between stabilization of relative sea level and the development of a reef flat morphology. That is the time needed for the reef to catch up with the sea surface and for knolls to coalesce.
3. The reef platform is diachronous. It may span thousands of years, in which the oldest age signifies the beginning of reef flat development, and the youngest the latest time in which the reef lived. The age pattern of samples may be complex as knolls and patches grow laterally towards each other and coalesce.

## Conclusions

The NRR of Elat, at the NW Gulf of Aqaba, has been kept at an early stage of development by down-faulting of the margin that forces corals to re-colonize the site time and again. Thus, it provides an opportunity to observe a key stage in the evolution of coral reefs: the transitional stage in which knolls and reef patches begin to coalesce and form a continuous reef structure. This transition is reflected in the morphology of the reef, where spur-and-groove features are discernable on both seaward and leeward parts of the reef.

The proposed growth pattern of fringing reefs indicates that the reef platform is the preferred indicator of sea level, and that it represents a few thousand years rather than a point in time. This is the case for the fossil Holocene reef beneath the modern reef of Elat. The oldest age of a reef platform represents time of transition from 'catch-up mode' to growth according to prevailing sea level, and the youngest age is the latest time at which the reef was still living. Coral samples spanning this age range may form complex patterns within the reef platform.

**Acknowledgements** We wish to acknowledge the help and support provided by the Interuniversity Institute at Elat. We also thank D. Zakai, and the Israel Nature and Parks Authority for supporting the work at the Elat Nature Reserve beach. E. Boaretto of the Weizmann Institute of Science undertook radiocarbon dating. This research was funded by the Israel Ministry of National Infrastructures, and the Shapira Fund, Hebrew University. Careful reviews by C. Braithwaite and C. Perry greatly improved this manuscript.

## References

Aronson RB, Precht WF (1995) Landscape patterns of reef coral diversity—a test of the intermediate disturbance hypothesis. J Exp Mar Biol Ecol 192:1–14

Bard E, Hamelin B, Fairbanks RG (1990) U-Th ages obtained by mass spectrometry in corals from Barbados: sea level during the past 130,000 years. Nature 346:456–458

Bar-Matthews M, Wasserburg GJ, Chen JH (1993) Diagenesis of fossil coral skeletons: correlation between trace elements, textures, and 234U/238U. Geochim Cosmochim Acta 57:257–276

Barnes DJ, Lazar B (1993) Metabolic performance of a shallow reef patch near Eilat on the Red-Sea. J Exp Mar Biol Ecol 174:1–13
Blanchon P, Jones B (1995) Marine-planation terraces on the shelf around Grand Cayman—a result of stepped Holocene sea level rise. J Coastal Res 11:1–33
Bloom AL, Broecker WS, Chappell JMA, Matthews RK, Mesolella KJ (1974) Quaternary sea level fluctuations on a tectonic coast: new 230Th/234U dates from the Huon Peninsula, New Guinea. Quaternary Res 4:185–205
Braithwaite CJR, Montaggioni LF, Camoin GF, Dalmasso H, Dullo WC, Mangini A (2000) Origins and development of Holocene coral reefs: a revisited model based on reef boreholes in the Seychelles, Indian Ocean. Int J Earth Sci 89:431–445
Burke CD, McHenry TM, Bischoff WD, Mazzullo SJ (1998) Coral diversity and mode of growth of lateral expansion patch reefs at Mexico Rocks, northern Belize shelf, Central America. Carbonate Evaporite 13:32–42
Burr GS, Edwards RL, Donahue DJ, Druffel ERM, Taylor FW (1992) Mass spectrometric 14C and U-Th measurements in coral. Radiocarbon 34: 611–618
Bythell JC, Hillis-Starr ZM, Rogers CS (2000) Local variability but landscape stability in coral reef communities following repeated hurricane impacts. Mar Ecol-Prog Ser 204:93–100
Cabioch G, Correge T, Turpin L, Castellaro C, Recy J (1999) Development patterns of fringing and barrier reefs in New Caledonia (southwest Pacific). Oceanologica Acta 22:567–578
Camoin GF, Colonna M, Montaggioni LF, Casanova J, Faure G, Thomassin BA (1997) Holocene sea level changes and reef development in the southwestern Indian Ocean. Coral Reefs 16:247–259
Chappell J (1974) Geology of coral terraces, Huon Peninsula, New Guinea: a study of Quaternary tectonic movements and sea-level changes. Geol Soc Am Bull 85:553–570
Chappell J, Ota Y, Berryman K (1996) Late Quaternary coseismic uplift history of Huon Peninsula, Papua New Guinea. Quaternary Sci Rev 15:7–22
Chen JH, Curran HA, White B, Wasserburg GJ (1991) Precise chronology of the last interglacial period: 234U-230Th data from fossil coral reefs in the Bahamas. Geol Soc Am Bull 103:82–97
Cortés J, Macintyre IG, Glynn PW (1994) Holocene growth of an eastern Pacific fringing reef, Punta Isoltes, Costa Rica. Coral Reefs 13: 65–73
Darwin CR (1842) The structure and distribution of coral reefs. Smith, Elder and Co., London, p 214
Davies PJ, Marshall JF (1980) A model of epicontinental reef growth. Nature 287:37–38
Edmunds PJ (2000) Patterns in the distribution of juvenile corals and coral reef community structure in St. John, US Virgin Islands. Mar Ecol-Prog Ser 202:113–124
Edwards RL, Chen JH, Wasserburg GJ (1987) 238U-234U-230Th-232Th systematics and the precise measurement of time over the past 500,000 years. Earth Planet Sci Lett 81:175–192
Eisenhauer A, Wasserburg GJ, Chen JH, Bonani G, Collins LB, Zhu ZR, Wyrwoll KH (1993) Holocene sea-level determination relative to the Australian continent: U/Th (TIMS) and 14C (AMS) dating of coral cores from the Abrolhos Islands. Earth Planet Sci Lett 114:529–547
Enmar R, Stein M, Bar-Matthews M, Sass E, Katz A, Lazar B (2000) Diagenesis in live corals from the Gulf of Aqaba. I. The effect on paleo-oceanography tracers. Geochim Cosmochim Acta 64:3123–3132
Fleming K, Johnston P, Zwartz D, Yokoyama Y, Lambeck K, Chappell J (1998) Refining the eustatic sea-level curve since the Last Glacial Maximum using far- and intermediate-field sites. Earth Planet Sci Lett 163:327–342
Goreau TF (1959) The ecology of Jamaican coral reefs I. Species composition and zonation. Ecology 40:67–90
Goreau TF, Goreau NI (1973) The ecology of Jamaican coral reefs. II. Geomorphology, zonation, and sedimentary phases. J Mar Sci 23:399–464
Grigg RW (1998) Holocene coral reef accretion in Hawaii: a function of wave exposure and sea level history. Coral Reefs 17:263–272
Hopley D, Slocombe AM, Muir F, Grant C (1983) Nearshore fringing reefs in North Queensland. Coral Reefs 1:151–160
Kan H, Hori N, Nakashima Y, Ichikawa K (1995) The evolution of narrow reef flats at high-latitude in the Ryukyu Islands. Coral Reefs 14:123–130
Kan H, Hori N, Ichikawa K (1997) Formation of a coral reef-front spur. Coral Reefs 16:3–4
Kennedy DM, Woodroffe CD (2002) Fringing reef growth and morphology: a review. Earth-Sci Rev 57:255–277
Lirman D, Glynn PW, Baker AC, Morales GEL (2001) Combined effects of three sequential storms on the Huatulco coral reef tract, Mexico. Bull Mar Sci 69:267–278
Loya Y, Slobodkin LB (1971) The coral reefs of Eilat (Gulf of Eilat, Red Sea). Symp Zool Soc Lond 28:117–139
Montaggioni L (2000) Postglacial reef growth. Comptes Rendus De L Academie Des Sciences Serie II Fascicule A-Sciences De La Terre Et Des Planetes 331:319–330
Perry CT (1998) Macroborers within coral framework at Discovery Bay, north Jamaica: species distribution and abundance, and effects on coral preservation. Coral Reefs 17:277–287
Perry CT (1999) Reef framework preservation in four contrasting modern reef environments, Discovery Bay, Jamaica. J Coastal Res 15:796–812
Pirazzoli PA (1991) World atlas of Holocene sea-level changes. Elsevier, Amsterdam, p 299
Ramsey CB (1995) Radiocarbon calibration and analysis of stratigraphy: the OxCal program. Radiocarbon 37:425–430
Ramsey CB (2001) Development of the radiocarbon program OxCal. Radiocarbon 43:381–389
Shaked Y, Marco S, Lazar B, Stein M, Cohen C, Sass E, Agnon A (2002) Late Holocene shorelines at the Gulf of Elat: migrating shorelines despite tectonic and sea level stability. EGS Stephan Mueller special publication series 2, pp 105–111
Shaked Y, Agnon A, Lazar B, Marco S, Avner U, Stein M (2004) Large earthquakes kill coral reefs at the north-west Gulf of Aqaba. Terra Nova 16:133–138
Shinn EA (1988) The geology of the Florida Keys. Oceanus 31:46–53
Shinn EA, Hudson JH, Robbin DM, Lidz B (1981) Spurs and grooves revisited: construction versus erosion Looe Key reef, Florida. In: Proceedings of the 4th International Coral Reef Symposium, vol 1. Manila, pp 475–483
Sneh A, Friedman GM (1980) Spur-and-groove patterns on the reefs of the northern gulfs of the Red Sea. J Sediment Petrol 50:981–986
Stein M, Wasserburg GJ, Aharon P, Chen JH, Zhu ZR, Bloom A, Chappell J (1993) TIMS U-series dating and stable isotopes of the last interglacial event in Papua New Guinea. Geochim Cosmochim Acta 57:2541–2554
Stuiver M, Polach HA (1977) Discussion; reporting of c-14 data. Radiocarbon 19:355–363
Stuiver M, Reimer PJ, Bard E, Beck JW, Burr GS, Hughen KA, Kromer B, McCormac G, Van-Der-Plicht J, Spurk M (1998) INTCAL98 radiocarbon age calibration, 24,000-0 cal BP. Radiocarbon 40:1041–1083
Tudhope AW, Buddemeier RW, Chilcott CP, Berryman KR, Fautin DG, Jebb M, Lipps JH, Pearce RG, Scoffin TP, Shimmield GB (2000) Alternating seismic uplift and subsidence in the late Holocene at Madang, Papua New Guinea: evidence from raised reefs. J Geophys Res 105:13797–13807
Woodroffe CD, Kennedy DM, Hopley D, Rasmussen CE, Smithers SG (2000) Holocene reef growth in Torres Strait. Mar Geol 170:331–346
Yamano H, Kayanne H, Yonekura N (2001) Anatomy of a modern coral reef flat: a recorder of storms and uplift in the late Holocene. J Sediment Res 71:295–304
Zachariasen J, Seih K, Taylor FW, Edwards RL, Hantoro WS (1999) Submergence and uplift associated with the giant 1833 Sumatran subduction earthquake: evidence from coral microatolls. J Geophys Res 104:895–919