Int J Earth Sci (Geol Rundsch) (2013) 102:545–570
DOI 10.1007/s00531-012-0802-3

ORIGINAL PAPER

# Palaeoecology of well-preserved coral communities in a siliciclastic environment from the Late Pleistocene (MIS 7), Kish Island, Persian Gulf (Iran): the development of low-relief reef frameworks (biostromes) in increasingly restricted environments

**Zahra Karimi Mossadegh · Justin Parker · Eberhard Gischler · Wolfgang Oschmann · David Blakeway · Anton Eisenhauer**

Received: 3 June 2011 / Accepted: 16 June 2012 / Published online: 24 July 2012


**Abstract** Major changes in community structure and depositional relief of high-latitude coral communities in the southern Persian Gulf between marine isotope stage (MIS) 7 and the present day suggest that the area has become increasingly restricted. Corals and bivalves from outcrops on Kish Island, Iran, were identified in order to interpret the Late Pleistocene palaeoenvironmental setting. U/Th disequilibrium dating was used to constrain the ages of the stratigraphic units. During MIS 7, two coral-bearing sequences were deposited on what is now Kish Island. The lower sequence is dated as MIS 7.5 and changes laterally from an assemblage dominated by *Cyphastrea* sp. and *Platygyra daedalea* in the west to one characterized by branching *Montipora* in the east. By contrast, the upper sequence, dated as MIS 7.1, transitions from an assemblage dominated by platy *Montipora* in the west to a diverse assemblage of *Platygyra* and other faviids in the east. The assemblages of both sequences are within a marl matrix and bounded by thin lithified mollusc-rich layers. Corals and bivalves indicate that the sequences were deposited on gentle slopes in sheltered environments less than 20 m deep. The MIS 7 deposits may be classified as coral carpets or biostromes that developed a low-relief framework. During MIS 5, coral communities were no longer framework building and are now limited to an *Acropora*-rich layer of coral rubble that covers large parts of the island, and two small incipient reefs with sparse faviids. Similarities between the MIS 5 and modern nearshore coral communities suggest that the environmental conditions during MIS 5 were comparable to those of today. The late Pleistocene coral carpets and non-framework coral communities of the southern Persian Gulf may serve as models for coral biostromes in the fossil record, which formed under restricted environmental conditions such as elevated terrigenous input, high turbidity, and strong seasonal changes in temperature and/or salinity.

**Keywords** Late Pleistocene · Persian Gulf · Coral reef · Biostrome · Bivalves · Marine isotope stage 7

**Electronic supplementary material** The online version of this article (doi:10.1007/s00531-012-0802-3) contains supplementary material, which is available to authorized users.

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## Introduction

Coral reefs and reef frameworks are characterized by depositional relief that modifies environmental conditions so that sediment is accumulated by means of trapping,

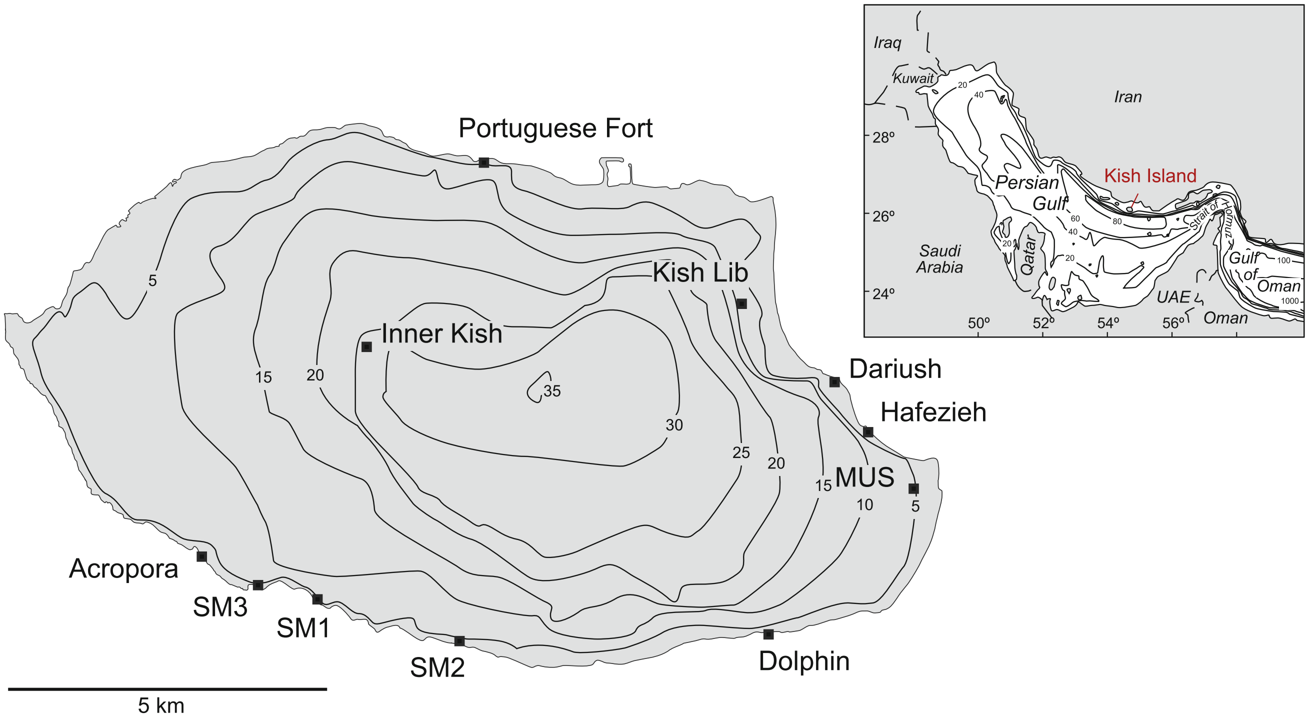


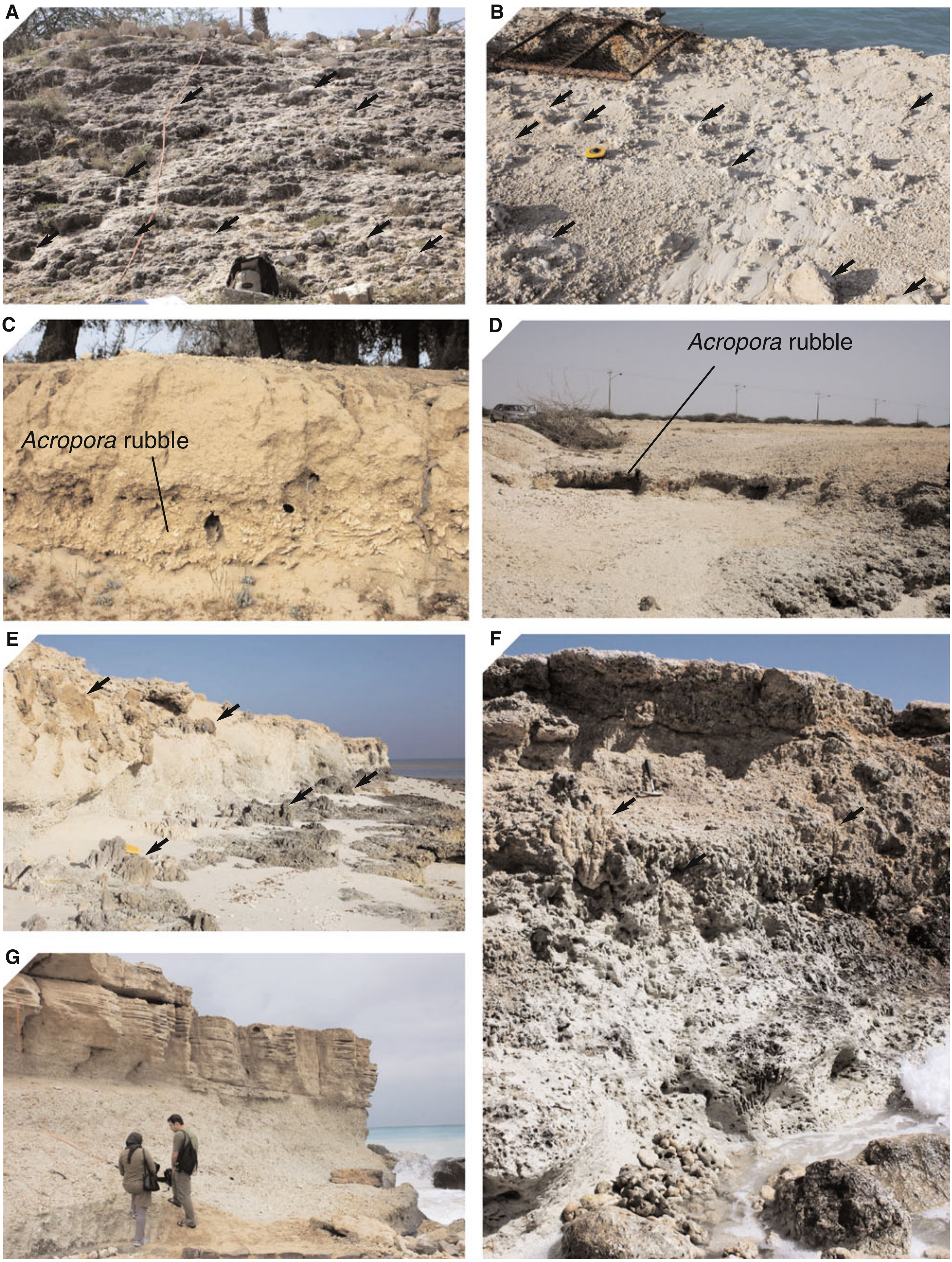

**Fig. 1** Topographic Map of Kish Island showing the sample localities and measured sections. *Inset* map shows location of Kish Island in the Persian Gulf

binding and stabilization (Ginsburg and Lowenstam 1958). Cumings (1932) noted that reefs with comparably low relief are widespread in the fossil record. He therefore differentiated between bioherms, that is, framework reefs with relief and biostromes lacking vertical elevation and usually having no true framework. However, Kershaw (1994) suggested to use biostrome as simple description of outline shape as many examples of biostromes do have a framework with clusters of in situ reef organisms. Based on studies of modern nearshore reefs in the Red Sea, Riegl and Piller (1997, 2000) coined the term coral carpet for low-relief Holocene coral frameworks developing on shallow shelves and lacking clear zonation. According to these authors, coral carpets eventually form biostromes.

Forms and shapes of many coral reefs in the Persian Gulf are characterized by a strong lateral and a low vertical component thereby resembling biostromes. These reefs are exposed to some of the most extreme conditions experienced by corals anywhere in the world (Shinn 1976; Coles and Fadlallah 1991; Riegl 2002, 2003). Although coral communities are of low diversity, they are resilient to major seasonal changes in temperature (Coles and Fadlallah 1991; Sheppard et al. 2000; Sheppard and Loughland 2002; Gischler et al. 2005) and are also tolerant of high salinity, high turbidity, high sedimentation and pollution (Coles and Fadlallah 1991; Sheppard and Sheppard 1991; Fatemi and Shokri 2001; Sheppard et al. 2010; Riegl 1999). They are best developed close to the Strait of Hormuz where they are exposed to normal salinity influx from the Gulf of Oman but are also found in coastal areas and islands as far north as Kuwait (Rezai et al. 2004; Gischler et al. 2005). The modern of Kish Island in the southern Persian Gulf is an example of such reefs (Fatemi and Shokri 2001; Riegl 2003; Wilson et al. 2002).

Kish Island was also significant for coral growth during the Late Pleistocene (Preusser et al. 2003; Pirazzoli et al. 2004). These studies indicated that coral communities developed during MIS 5 (100–150 ky) and MIS 7 (190–240 ky) interglacial intervals and were uplifted by

**Fig. 2** Photographs of localities described. *Arrows* in figures point to corals. **a** The reef at Dariush Hotel showing an antecedent slope with sparse corals; bag in foreground is about 30 cm high. **b** The reef at the Portuguese Fort showing a flattened surface with scattered coral heads; the tape measure is about 15 cm in diameter. **c** An example of the coral rubble that covered much of Kish Island; in this example, it occurs beneath a soil horizon at the Inner Kish locality; the lens cap is 5 cm in diameter. **d** An outcrop of the same coral rubble horizon as it appears in coastal outcrops, this example is from the KR10 site; the car in the background gives an indication of *scale*. **e** Sea cliffs along the southern coast of Kish Island; at the site studied by Pirazzoli et al. (2004), typical of studied sections SM1, SM2 and SM3. Most of the *reddish* to *dark* patches in the cliff face are corals in life position. The cliff is about 4–5 m high in the foreground. **f** The sea cliff at the Dolphin locality on the south east coast showing the more scattered coral occurrence; the hammer is about 30 cm long **g** The sea cliff at the Hafezieh locality on the eastern side of the island, note the cross-bedded sandstone overlying a marl with few coral heads; the people in the photographs are about 1.6 m tall ▶


A
B
C
Acropora rubble
D
Acropora rubble
E
F
G

tectonic displacement to their present position (1–30 m above MSL). Previous work on these sequences examined uplift rates and assessed the usefulness of ESR (Electron Spin Resonance) dating in studies where diagenesis can effect age determinations (Preusser et al. 2003; Pirazzoli et al. 2004). The Late Pleistocene reefs are well preserved and provide a resource for examining changes in Persian Gulf coral communities over this interval. They also provide a window into the environmental setting of a high-latitude coral assemblages deposited during MIS 5 and MIS 7. Outcrops of MIS 7 reefs are by far not as common as the abundant coastal terraces built by MIS 5 reefs (Johnson and Libbey 1997). This is the first study to examine community structure of the Kish Island fossil reefs and determine the long-term stability of high-latitude reefs in a stressed environment. These low-relief reefs offer the opportunity to study the development of coral carpets, that is, biostromes that are so common in the fossil record.

## Settings

### Geomorphology and climate

The Persian Gulf is an elongated (1,000 km long, 200–300 km wide), shallow (up to 100 m), restricted basin bounded to the south and west by the Arabian platform and to the north and east by the tectonically active Zagros Mountains (Purser 1973). The region experiences hot arid conditions throughout most of the year, with air temperatures between 10° minimum in winter and up to 50° maximum in summer. Precipitation is less than 8 cm per year (Sugden 1963). Circulation is anti-estuarine with low-salinity (~ 36 ‰), nutrient-rich water entering through the Straits of Hormuz, and flowing counter-clockwise along the Iranian and ultimately Arabian coastlines (Brewer and Dyrssen 1985; Kampf and Sadrinasab 2006). High levels of evaporation raise the salinity to >40 ‰, forming dense high salinity, low alkalinity, water in the shallow north-western gulf that flows down-slope into deeper parts of the basin, and out towards the Indian Ocean (Brewer and Dyrssen 1985). Water residence times are estimated at about 2.5–4 years (Alosairi et al. 2011). The annual range of sea surface temperature is up to 11–36 °C in the shallow northern and western parts of the Gulf, decreasing to 23–31 °C towards the deeper areas to the southeast, nearer the Indian Ocean (Coles and Fadlallah 1991, Sheppard et al. 2010). Once or twice a year dry Shamal winds have significant effects including the deposition of dust, cooling of surface waters, enhanced turbidity, and increasing wave intensity (Sirocko and Sarnthein 1989; Sheppard et al. 2010). Surface waters are phosphate rich, but nitrogenous nutrients appear to be a limiting factor for trophic influences. The outflow of the Tigris, Euphrates and Karun rivers in the north provides an intense, but low volume of fresh, alkaline water (Brewer and Dyrssen 1985).

Kish Island (26° 32′ 2″ N 53° 58′ 2″ E) is a low dome (8 km wide, 15 km long and 32 m high) off the Iranian coast of the southern Persian Gulf (Fig. 1). The island, consisting largely of Neogene rocks, is part of an anticlinal structure aligned parallel to the axis of the Zagros Mountains and separated from the mainland to the north by a stretch of water about 18 km wide and less than 40 m deep.

### Late Pleistocene sea-level effects on the Persian Gulf

It has been widely demonstrated that sea-level fluctuations of over 100 m occurred between Late Pleistocene glacial

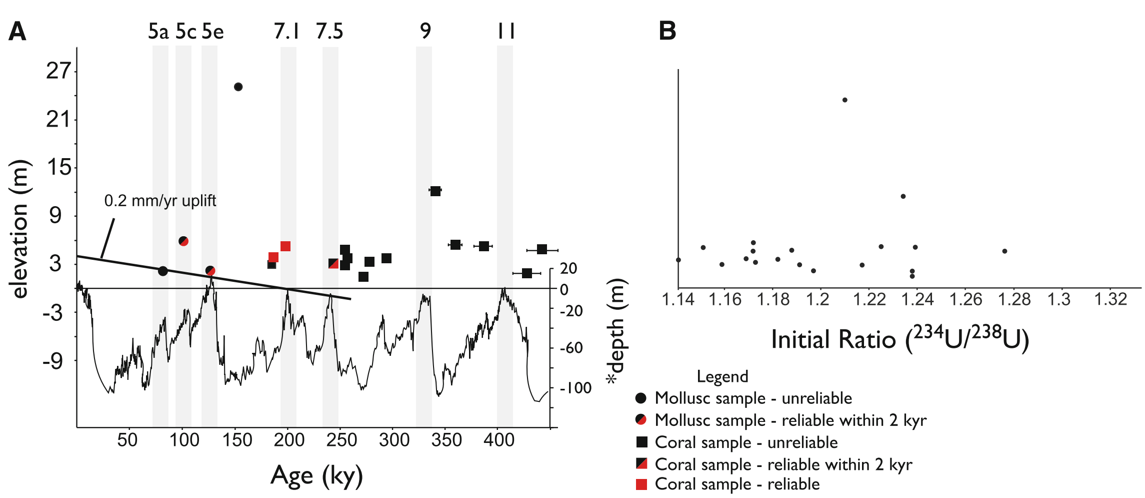



**Fig. 3** U/Th age dating of coral and mollusc samples. **a** Radiometric ages of samples relative to elevation, together with the sea-level curve for the past 450 ky from Rohling et al. (2009), and the predicted uplift rate from Pirazzoli et al. (2004). **b** Initial ratio of $U^{238}/U^{234}$. Measurements and additional data are provided in Table 1

and interglacial intervals (Rohling et al. 2009; Imbrie et al. 1984). Thus, as most of the Persian Gulf is less than 80 m deep, during glacial intervals, the basin floor became a subaerial valley, and the marine biota perished (Lambeck 1996). By contrast, sea-level peaks during interglacial intervals created favourable conditions for high-latitude coral reef development (Plaziat et al. 2008; Rohling et al. 2009). Pirazzoli et al. (2004) suggested that Kish Island was connected to the mainland when global sea level was 40 m below the present level. However, the Island provides an opportunity to study the extinction and re-establishment of high-latitude coral communities over geological time-frames.

## Holocene to modern coral reefs of the Persian Gulf

At the end of the Last Glacial Maximum, about 18,000 years ago, the Persian Gulf began to flood, but it was not until almost 6,000 years ago that sea level reached its present position (Rohling et al. 2009) and corals could recolonise the Persian Gulf. Present coral reef distribution is very patchy, and with low diversity (about 50–60 species; Sheppard and Sheppard 1991; Vogt 1996). The extremes of temperature and salinity are believed to be the main restrictions on coral growth and diversity. Coral cover rapidly declines below 10-m water depth and only near the Strait of Hormuz do corals form reef-building communities. Only three main coral types are common: branching *Acropora*, massive *Porites* and the brain coral *Platygyra*. Bleaching events in 1998 and 2004 killed much of the living coral around Kish Island and in other parts of the gulf (Fatemi and Shokri 2001; Rezai et al. 2004). Mortality was highest amongst branching *Acropora* and lowest amongst massive corals (Rezai et al. 2004). *Porites*, *Favia*, *Favites*, *Platygyra*, *Goniopora* and juvenile *Acropora* can be found on present reefs around Kish Island.

Pirazzoli et al. (2004) commented on the lack of a Holocene raised beach and shallow marine deposits on the island whereas these features were common on Qeshm Island to the south and also suggested that erosion during the last glacial interval had removed deposits, including MIS 5 corals overlying the MIS 7 reefs.

## Methods

The data were collected during field trips in October 2009 and February–March 2010. We surveyed accessible parts of the island, documenting, photographing, and sampling sites where fossil coral reefs outcropped (Fig. 1), and measuring sections of the main localities. Three sections along the southern coast were studied in detail, and in each of these, we determined the lateral and vertical relationships of the corals. Samples of corals, bivalves and adjacent sediment were collected at 50-cm vertical intervals in the measured sections. Positions of sites were determined using differential GPS (Magellan Mobilemapper 6). Elevations were measured from sea level and corrected to MSL for tides in the coastal localities. Inland, elevation data were obtained using differential GPS and checked against topographic maps, the error of the units at survey markers was ±1.5 m. Present coral reefs at Kish Island were examined by diving off of the south-eastern coast of the island where coral cover is highest.

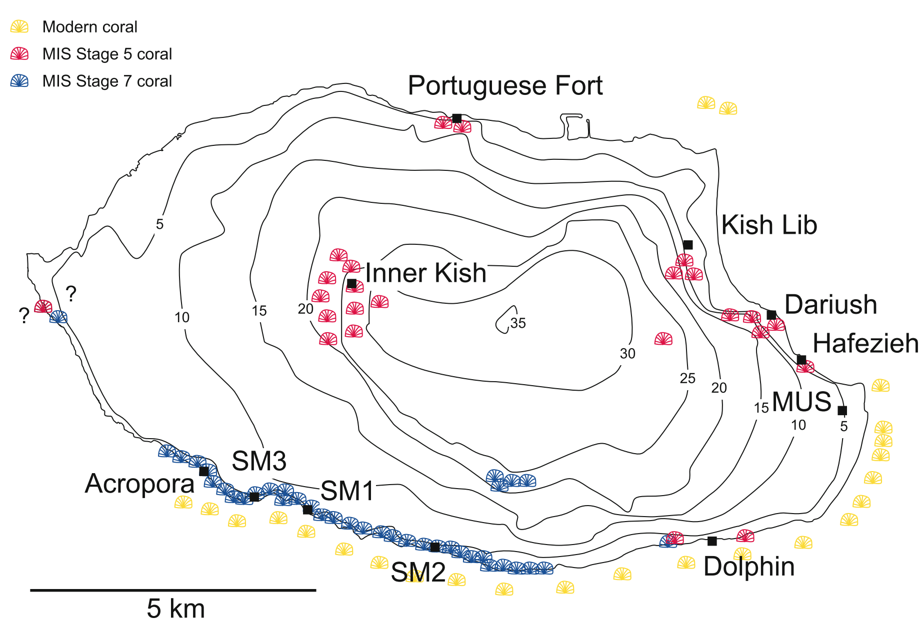



**Fig. 4** Topographic map of Kish Island showing the locations of MIS 5 and MIS 7 reef outcrops together with the distribution of modern corals

**Table 1** Results of U//Th age dating. An activity ratio of 0.6 ± 0.2 was used for the correction of detrital $Th^{230}$ and $Th^{230}/Th^{232}$

| Sample no. | Stratigraphic unit | Sample type | Aragonite (%) | MIS | Age (ky) | $^{238}U$ (ppm) | $^{232}Th$ (ppm) | $^{230}Th$ (ppt) |
|---|---|---|---|---|---|---|---|---|
| K11-01 | Upper bivalve layer | Tridacna | 99.6 | 5a | 80.9 ± 0.5 | 1.041 ± 0.001 | 2.581 ± 0.015 | 10.936 ± 0.021 |
| MUS01-01 | Upper bivalve layer | Tridacna | 99.6 | 5c* | 100.3 ± 0.8 | 0.661 ± 0.001 | 6.645 ± 0.020 | 7.564 ± 0.012 |
| K11-02 | Upper bivalve layer | Tridacna | 94.7 | 5e* | 126.1 ± 0.6 | 2.805 ± 0.002 | 38.952 ± 0.050 | 37.077 ± 0.037 |
| Kish Inner 01 | Inner Kish Coral Rubble | Acropora | 93.0 | 5 | 154.0 ± 0.8 | 3.440 ± 0.002 | 27.300 ± 0.027 | 50.176 ± 0.057 |
| SM3G-03 | KR10 Coral Rubble | Acropora | 91.1 | 7 | 185.5 ± 1.4 | 3.049 ± 0.002 | 248.937 ± 0.290 | 47.797 ± 0.051 |
| LM-Haf | Coral Marl | Favites | 91.6 | 7* | 186.0 ± 1.2 | 2.132 ± 0.001 | 128.079 ± 0.133 | 32.276 ± 0.040 |
| SM1-08b | Coral Marl | Platygyra | 99.0 | 7*** | 197.7 ± 1.1 | 2.791 ± 0.001 | 7.119 ± 0.012 | 42.850 ± 0.035 |
| K03 | Coral Marl | Cyphastrea | 99.7 | 7*** | 243.7 ± 3.5 | 2.517 ± 0.002 | 0.435 ± 0.012 | 41.037 ± 0.068 |
| Dolph02 | Coral Marl | Favites | 98.9 | 7 | 254.1 ± 2.8 | 2.688 ± 0.002 | 7.428 ± 0.019 | 45.702 ± 0.075 |
| SM1-07b | Coral Marl | Cyphastrea | 99.4 | 7 | 254.7 ± 2.2 | 2.810 ± 0.001 | 2.252 ± 0.011 | 46.592 ± 0.048 |
| SM1G-cc | Coral Marl | Platygyra | 91.4 | 7 | 255.7 ± 2.1 | 2.484 ± 0.001 | 41.263 ± 0.025 | 41.709 ± 0.038 |
| SM3-06 | Coral Marl | Cyphastrea | 96.4 | 7 | 256.2 ± 2.9 | 2.546 ± 0.001 | 4.232 ± 0.013 | 42.193 ± 0.061 |
| K11-03 | Coral Marl | Acropora | 97.7 | 7 | 272.1 ± 3.5 | 3.831 ± 0.003 | 42.08 ± 0.097 | 66.695 ± 0.099 |
| SM1-04 | Coral Marl | Cyphastrea | 98.2 | 7 | 278.2 ± 3.7 | 2.552 ± 0.002 | 0.954 ± 0.013 | 43.010 ± 0.059 |
| SM2-03b | Coral Marl | Branching type | 95.7 | 7 | 293.4 ± 3.4 | 3.089 ± 0.001 | 3.950 ± 0.010 | 52.717 ± 0.069 |
| DSH | Coral Marl | Montipora | 91.2 | n/a | 340.2 ± 5.8 | 2.204 ± 0.001 | 76.889 ± 0.052 | 39.351 ± 0.039 |
| SM2G-01 | Coral Marl | Favia | 90.2 | n/a | 359.3 ± 6.5 | 2.244 ± 0.001 | 6.577 ± 0.015 | 39.770 ± 0.050 |
| SM1-08 | Coral Marl | Montipora | 97.4 | n/a | 386.1 ± 8.6 | 3.059 ± 0.002 | 4.132 ± 0.012 | 54.627 ± 0.042 |
| Dolph01 | Coral Marl | Favites | 96.4 | n/a | 428 ± 13 | 2.679 ± 0.001 | 61.63 ± 0.084 | 49.250 ± 0.075 |
| SM1-07 | Coral Marl | Montipora | 94.5 | n/a | 442 ± 15 | 3.252 ± 0.002 | 12.317 ± 0.019 | 58.816 ± 0.090 |
| SM1-03 | Coral Marl | Cyphastrea | 94.1 | n/a | n.d. | 3.070 ± 0.002 | 10.553 ± 0.016 | 63.894 ± 0.085 |
| SM1-05 | Coral Marl | Montipora | 95.3 | n/a | n.d. | 2.893 ± 0.002 | 27.868 ± 0.018 | 56.501 ± 0.052 |
| SM1-06 | Coral Marl | Montipora | 95.3 | n/a | n.d. | 3.211 ± 0.001 | 38.202 ± 0.045 | 71.173 ± 0.089 |
| SM1-09 | Coral Marl | Montipora | 99.0 | n/a | n.d. | 3.125 ± 0.001 | 6.212 ± 0.015 | 60.641 ± 0.086 |
| SM1-10 | Coral Marl | Branching type | 89.3 | n/a | n.d. | 3.345 ± 0.002 | 47.100 ± 0.036 | 64.950 ± 0.065 |
| SM2-07 | Coral Marl | Gastropod | 94.2 | n/a | n.d. | 2.479 ± 0.001 | 57.946 ± 0.071 | 61.183 ± 0.088 |

**Table 1** continued

| Sample no. | $^{230}Th/^{232}Th$(dpm/dpm) | $^{238}U/^{232}Th$ (dpm/dpm) | $^{230}Th/^{238}U$ (dpm/dpm) | $^{230}Th/^{238}U$ | $^{234}U/^{238}U$ | $(^{234}U/^{238}U)_{initial}$ |
|---|---|---|---|---|---|---|
| K11-01 | 791 ± 5 | 1249 ± 8 | 0.634 ± 0.001 | 0.633 ± 0.002 | 1.189 ± 0.002 | 1.238 ± 0.002 |
| MUS01-01 | 212.5 ± 0.7 | 308 ± 1 | 0.691 ± 0.001 | 0.689 ± 0.002 | 1.129 ± 0.002 | 1.172 ± 0.002 |
| K11-02 | 177.7 ± 0.3 | 222.9 ± 0.3 | 0.797 ± 0.001 | 0.795 ± 0.001 | 1.138 ± 0.001 | 1.197 ± 0.001 |
| Kish Inner 01 | 343.1 ± 0.5 | 390.1 ± 0.4 | 0.880 ± 0.001 | 0.878 ± 0.001 | 1.136 ± 0.001 | 1.210 ± 0.001 |
| SM3G-03 | 35.8 ± 0.1 | 37.9 ± 0.1 | 0.946 ± 0.001 | 0.93 ± 0.002 | 1.113 ± 0.001 | 1.191 ± 0.001 |
| LM-Haf | 47.1 ± 0.1 | 51.5 ± 0.1 | 0.913 ± 0.001 | 0.902 ± 0.001 | 1.084 ± 0.001 | 1.141 ± 0.001 |
| SM1-08b | 1124 ± 2 | 1214 ± 2 | 0.926 ± 0.001 | 0.925 ± 0.001 | 1.086 ± 0.001 | 1.151 ± 0.001 |
| K03 | 17596 ± 479 | 17896 ± 487 | 0.983 ± 0.002 | 0.983 ± 0.002 | 1.080 ± 0.001 | 1.159 ± 0.001 |
| Dolph02 | | 1120 ± 3 | 1.025 ± 0.002 | 1.025 ± 0.002 | 1.106 ± 0.001 | 1.217 ± 0.001 |
| SM1-07b | 3862 ± 20 | 3862 ± 19 | 1.000 ± 0.001 | 1.000 ± 0.001 | 1.084 ± 0.001 | 1.172 ± 0.001 |
| SM1G-cc | 188.7 ± 0.2 | 186.4 ± 0.2 | 1.013 ± 0.001 | 1.009 ± 0.001 | 1.091 ± 0.001 | 1.188 ± 0.001 |
| SM3-06 | 1861 ± 7 | 1862 ± 6 | 1.000 ± 0.002 | 0.999 ± 0.002 | 1.082 ± 0.001 | 1.169 ± 0.001 |
| K11-03 | 295.9 ± 0.8 | 281.8 ± 0.7 | 1.050 ± 0.002 | 1.048 ± 0.002 | 1.110 ± 0.001 | 1.238 ± 0.001 |
| SM1-04 | 8417 ± 112 | 8282 ± 110 | 1.016 ± 0.002 | 1.016 ± 0.002 | 1.079 ± 0.001 | 1.173 ± 0.001 |
| SM2-03b | 2492 ± 7 | 2421 ± 6 | 1.029 ± 0.001 | 1.029 ± 0.002 | 1.080 ± 0.001 | 1.182 ± 0.001 |
| DSH | 95.6 ± 0.1 | 88.7 ± 0.1 | 1.077 ± 0.001 | 1.007 ± 0.002 | 1.090 ± 0.001 | 1.234 ± 0.001 |
| SM2G-01 | 1129 ± 3 | 1056 ± 2 | 1.069 ± 0.001 | 1.069 ± 0.002 | 1.081 ± 0.001 | 1.225 ± 0.001 |
| SM1-08 | 2468 ± 8 | 2291 ± 7 | 1.077 ± 0.001 | 1.077 ± 0.002 | 1.080 ± 0.001 | 1.239 ± 0.001 |
| Dolph01 | 149.2 ± 0.3 | 134.6 ± 0.2 | 1.109 ± 0.002 | 1.104 ± 0.002 | 1.092 ± 0.001 | 1.308 ± 0.001 |
| SM1-07 | 892 ± 2 | 817 ± 1 | 1.091 ± 0.002 | 1.090 ± 0.002 | 1.079 ± 0.001 | 1.276 ± 0.001 |
| SM1-03 | 1130 ± 2 | 9014 ± 2 | 1.255 ± 0.002 | 1.255 ± 0.002 | 1.075 ± 0.001 | n.d. |
| SM1-05 | 378.5 ± 0.4 | 321.4 ± 0.3 | 1.178 ± 0.001 | 1.176 ± 0.002 | 1.075 ± 0.001 | n.d. |
| SM1-06 | 347.8 ± 0.6 | 260.2 ± 0.3 | 1.337 ± 0.002 | 1.335 ± 0.002 | 1.077 ± 0.001 | n.d. |
| SM1-09 | 1823 ± 5 | 1558 ± 4 | 1.170 ± 0.002 | 1.170 ± 0.002 | 1.084 ± 0.001 | n.d. |
| SM1-10 | 257.5 ± 0.3 | 219.8 ± 0.2 | 1.171 ± 0.001 | 1.168 ± 0.002 | 1.083 ± 0.001 | n.d. |
| SM2-07 | 197.1 ± 0.4 | 132.4 ± 0.2 | 1.489 ± 0.002 | 1.484 ± 0.003 | 1.235 ± 0.001 | n.d. |

Details of the method can be found in Fietzke et al. (2005). *** indicates reliable samples. * indicates moderately reliable samples within 2 ky. All other samples are unreliable

Fifty coral and 60 bivalve samples were collected for identification and interpretation of palaeoenvironmental settings (see Appendix 1 in ESM for systematics). Thin sections were prepared of 42 of the corals to aid identification. These, and additional specimens photographed in the field, were identified to the lowest taxonomic level possible.

Fifty-six coral and mollusc samples were analysed by XRD to determine the percentage of aragonite and their suitability for dating. Twenty-two coral and four mollusc samples with greater than 90 % aragonite were dated by MC-ICP-MS, using the method described by Fietzke et al. (2005).

Determination of U- and Th-isotope ratios followed a multi-static, multi-ion-counting (MIC) ICP-MS approach (Fietzke et al. 2005). For isotope dilution measurements, a combined $^{233}U/^{236}U/^{229}Th$-spike was used, with stock solutions calibrated for concentration using NIST-SRM 3164 (U) and NIST-SRM 3159 (Th) and, as a combi-spike, calibrated against the CRM-145 uranium standard solution

**Table 2** Common corals from the Pleistocene of Kish Island, see Figs. 6 and 7 for illustrations

| Stratigraphic unit | Species | Habit |
|---|---|---|
| Inner Kish Rubble | *Acropora* sp. | Branched |
| | Faviidae spp. | Massive |
| Daruish & Portuguese Fort reefs | *Platygyra daedalea* | Massive, meandroid |
| | *Favia* spp. | Massive, placoid |
| | *Favites* spp. | Massive, cerioid |
| Coral Marl | *Cyphastrea* sp. 1 | Massive, cerioid |
| | *Platygyra daedalea* | Massive, meandroid |
| | *Favia* spp. | Massive, placoid |
| | *Favites* spp. | Massive, cerioid |
| | *Goniastrea* spp. | Massive, cerioid |
| | *Leptastrea* spp. | Massive, cerioid |
| | *Montipora* sp. 1 | Platy, cerioid |
| | *Montipora* sp. 2 | Branched, cerioid |
| | *Porites* spp. | Massive, cerioid |

For systematic positions, please refer to Appendix 1 in ESM

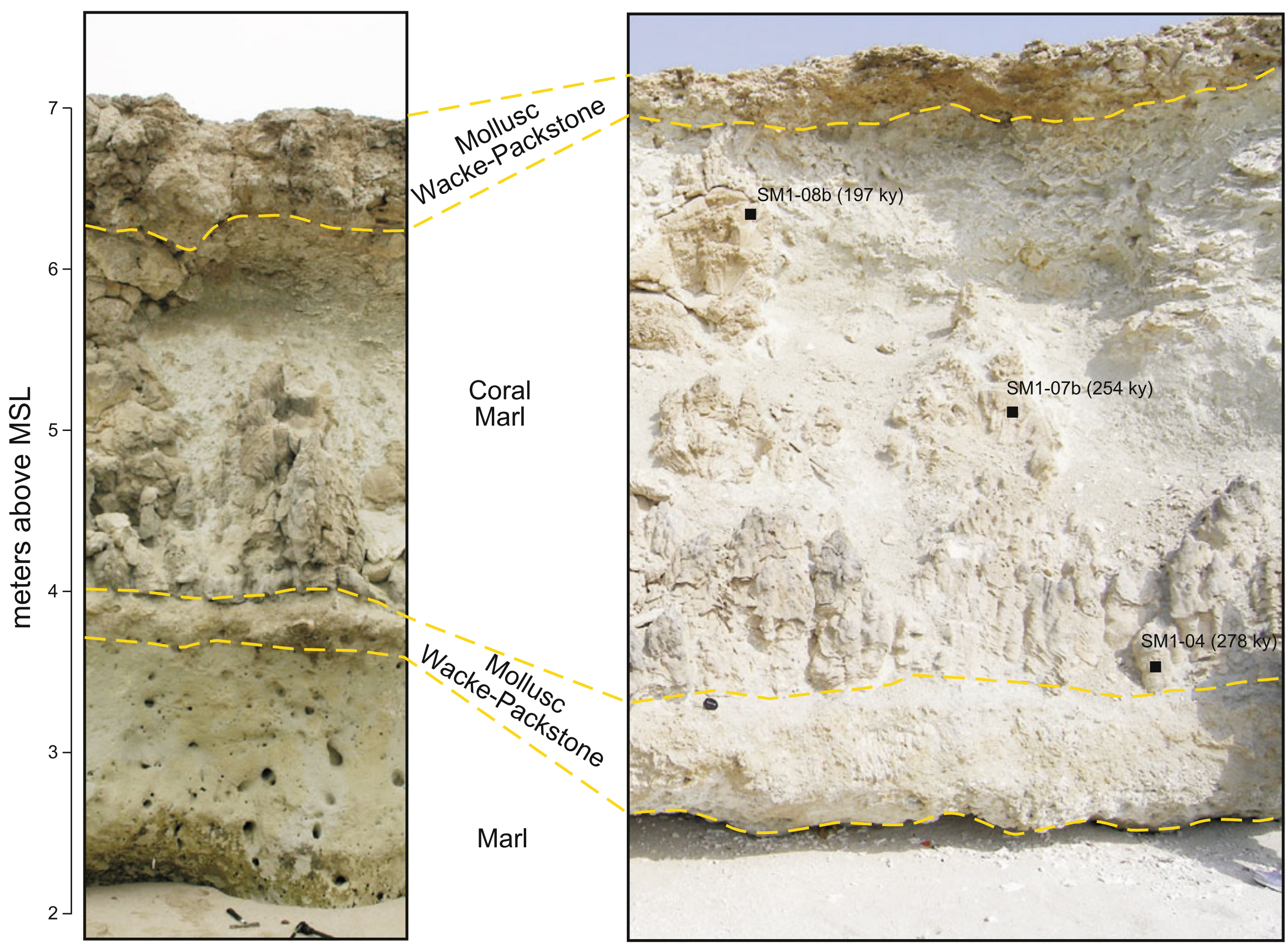



**Fig. 5** Stratigraphic section through SM1, showing the relationship between the coral marl layer and other facies. Also shown are the positions of samples with reliable age dates

(also known as NBL-112A) for U-isotope compositions, and against a secular equilibrium standard (HU-1, uranium ore solution) for the precise determination of $^{230}Th/^{234}U$ activity ratios. Whole procedure blank values of this sample set were measured to be around 2 pg for Th and between 4 and 8 pg for U. Both values are in the typical range of this method and the laboratory.

Isotopic screening for potential U and Th loss or gain is based on several standard criteria: the calculated $^{234}U/^{238}U$ activity ratio should lie within the range of modern corals and sea water, between 1.147 ± 0.002 and 1.150 ± 0.001, the $^{238}U$ concentration should reflect modern coral species values of between 2.0 and 3.5 ppm. Note, that higher U concentrations may also be possible as a function of cooler seawater temperatures. The $^{232}Th$ should be <2 ppb, and the abundance of calcite must be below XRD detection limits (<1 % calcite). For samples that meet the $^{238}U$ and $^{232}Th$ concentration ranges, and lack detectable calcite, the reliability of coral ages is based on the $^{234}U/^{238}U$ activity ratio criterion: ages with the same $^{234}U/^{238}U$ activity ratio as pristine modern coral and sea water (1.147–1.150) are considered 'strictly' reliable to within the analytical uncertainty (assuming marine $^{234}U/^{238}U$ has remained constant in time), whereas ages with values exceeding 1.149 ± 0.010 are considered accurate to ±2 kyr; ages that exceed 1.149 ± 0.010 are considered 'unreliable' although their ages may not necessarily be wrong.

### Study sites

The study sites on Kish Island were selected after a preliminary reconnaissance to identify the principal outcrops (Fig. 1). The Dariush Hotel site is a sloping reef platform 5–15 m above MSL east of the hotel (Fig. 2a), with some additional outcrops in the hotel grounds. The Portuguese Fort site is a small flat outcrop with scattered widely spaced corals on the northern coast of the island (Fig. 2b). The inner Kish site is collection of smaller outcrops near the airport at >20-m elevation (Fig. 2e). The sites consist of unconsolidated coral rubble that is being excavated for concrete manufacture and the uppermost layer of some coastal outcrops. Detailed study sites, SM1, SM2 and SM3, are accessible areas of sea cliff on the southern coast near the Seamaster Dive Centre (Fig. 2e). The cliffs are between 0.5 and 8 m high and are highest near the middle of the southern coast. The KR10 site is a low terrace, 2.5 m above MSL, west of the SM sites, near the end of the coral outcrop (Fig. 2d). The Dolphin site is a small sea cliff 0–2 m high east of the SM sites (Fig. 2f). The Hafezieh site is narrow cliff face on the east coast of the island, adjacent the Shiraz University of Medical Sciences (Fig. 2g). The MUS site refers to samples collected from an excavation in the south-eastern part of the island that is now inaccessible due to the construction of buildings.

## Results and discussion

### New U/Th dates from Kish Island

Twenty-two coral samples and four mollusc samples were dated (Fig. 3, Table 1) in order to evaluate the ages published by Pirazzoli et al. (2004), largely based on ESR, and to constrain the age of some undated stratigraphic units and a complete section with more reliable U-series dates.

Only two samples, a *Favites* and a *Platygyra,* are considered 'reliable' and gave calculated initial $^{238}U/^{234}U$ ratios of between 1.14 and 1.15, indicating deposition during MIS 7.1 (186 and 198 ky, respectively; Fig. 3). Nine other dates with calculated initial ratios of <1.20 give dates within the ranges for MIS 5 (100–126 ky) and MIS 7 (185–293 ky). All other dates, of *Montipora* samples in particular, either give unreliable ages or could not be dated (Table 1).

Our reliable dates cluster into three general periods, indicating that coral growth occurred during MIS 5, MIS 7.1 and MIS 7.5 (Fig. 3). Between these intervals, Kish Island and the surrounding area were emergent and there was no marine deposition (Pirazzoli et al. 2004).

### Marine isotope stage 5 deposits—observations

High-latitude coral reef growth during MIS 5 is well known from the Red Sea (Plaziat et al. 2008 and references within), Western Australia (Zhu et al. 1993; Stirling et al. 1995; Eisenhauer et al. 1996; Greenstein and Pandolfi 2008), Florida (Multer et al. 2002) and Japan (Nakamori 1986; Nakamori et al. 1995). Conditions during this interval allowed many scleractinians to occupy higher latitudes than at present, possibly due to higher-than-present sea levels producing larger shelf areas and slightly higher temperatures (e.g. Gischler et al. 2009). The first record of MIS 5 corals from the Persian Gulf was reported by Pirazzoli et al. (2004), who dated parallochthonous corals from Kish Island, including the Dariush Hotel site, at 100–150 ky (Pirazzoli et al. 2004). However, the focus of that research was on uplift rates, and only limited palaeoenvironmental data were provided.

Our study confirms the presence of MIS 5 deposits on Kish Island (Figs. 3, 4; Table 1). The samples dated as MIS 5 are from the coral rubble that caps much of the central part of the island and from some coastal outcrops to the south (Fig. 4). An additional site at a relict Portuguese port on the north coast of the island (Fig. 4), with similar community and preservation to that of the Dariush Hotel locality, is possibly also MIS 5 in age.

Two stratigraphic units are identified as having an MIS 5 age. The first is a sandy mollusc-bearing wackestone to packstone (upper bivalve layer in Fig. 5) that unconformably overlies the coral marl layer of MIS 7 age in southern outcrops and a mollusc-rich skeletal mudstone to wackestone to the east. In northern and eastern outcrops, this unit is characterized by many small massive corals in life position (visible in the Portuguese Fort and Dariush Hotel localities). On the reef terrace at Dariush Hotel, small domal faviids, including *Platygyra*, *Favia*, *Favites* and *Goniastrea,* are dominant (Table 2; Figs. 6, 7, 8). However, these corals are widely spaced; they do not form a growth framework and do not show any obvious ecological zonation. The second unit comprises coral rubble, dominated by *Acropora*, but including fragments of faviids. This unit caps much of the island, including outcrops to the south (Fig. 2) where it overlies the coral marl at the Dolphin site (2 to 2.5-m elevation; Fig. 2). Bivalves from the upper bivalve layer and reef units at Daruish Hotel and Inner Kish localities comprise six families, six genera and five species, including *Hyotissa hyotis*, *Codakia tigerina*, *Lithophaga cumingiana*, *Chlamys* cf. *C. ruschenbergerii*, *Pinctada margarifera* and *Tridacna* sp. (Tables 3, 4; Figs. 8, 9). One species, *L. cummingiana,* is a boring form. Bivalves from the first unit at the Dariush Hotel comprise three families, and three genera, *Saccostrea* sp., *Pinctada* sp. and *Marcia* sp., but only one identified species *Saccostrea cucullata* (Tables 3, 4). The coral rubble (Inner Kish locality) has a bivalve fauna represented by six families, six genera and six species including: *Barbatia* cf. *B. foliata*, *Trachycardium lacunosum*, *Chama pacifica*, *Codakia interrupta*, *Codakia tigerina*, *Mactra* sp., *Tellina palatam* and *Tellina scobinata* (Tables 3, 4).

## Marine isotope stage 5 deposits—interpretations

The modern coral accumulations of Kish Island form no framework, and by comparison, there appears to have been no significant coral framework development during MIS 5 either. The coral accumulations consisted of thin hardgrounds colonised by small faviid colonies. The depth of deposition of the different coral-bearing facies varied, with the Inner Kish coral rubble probably deposited above fair-weather wave base in a proximal back-reef environment. The bivalves support deposition in a shallow (<20-m water depth) in a littoral, sublittoral or lagoon environment. Most are infaunal species typical of soft substrates associated with coral reefs. Pirazzoli et al. (2004) concluded, from their uplift model, that these reefs were deposited in water less than 10 m deep. The deposits at Dariush Hotel and the Portuguese Port include only sporadic dome-like coral heads that resemble the communities on drowned limestone platforms in the modern Persian Gulf (authors' unpublished data). These platforms are limited to depths of 8–12 m due to turbidity, and the coral accumulations dated as MIS 5 are believed to have been deposited in no more than 20-m water depth. The few bivalves collected from the Dariush site reflect variable substrates that allowed both burrowing and byssal attachment or cementation on hard surfaces.

**Fig. 6** Common Pleistocene corals from Kish Island. **a**, **b** *Acropora* ▶ sp. **a** Coral rubble with numerous branches, Inner Kish 01. **b** *Thin-section* transverse to the axis of a branch from the Inner Kish site (Inner Kish 01). **c**–**e**. *Montipora* sp. 1 (platy habit), **c** Platy habit *Montipora*, site SM1. **d** Magnified view of plates in **c**, showing the dense skeleton. **e** *Thin-section* transverse to the axis of corallites, SM1 site (SM1-06). **f**–**h** *Montipora* sp. 2 (branching habit). **f** Branching *Montipora* at site SM2. **g** Magnified cross-section of branches in **f**. **h** *Thin section* transverse to the axis of a branch, from site SM2 (SM2-03b)

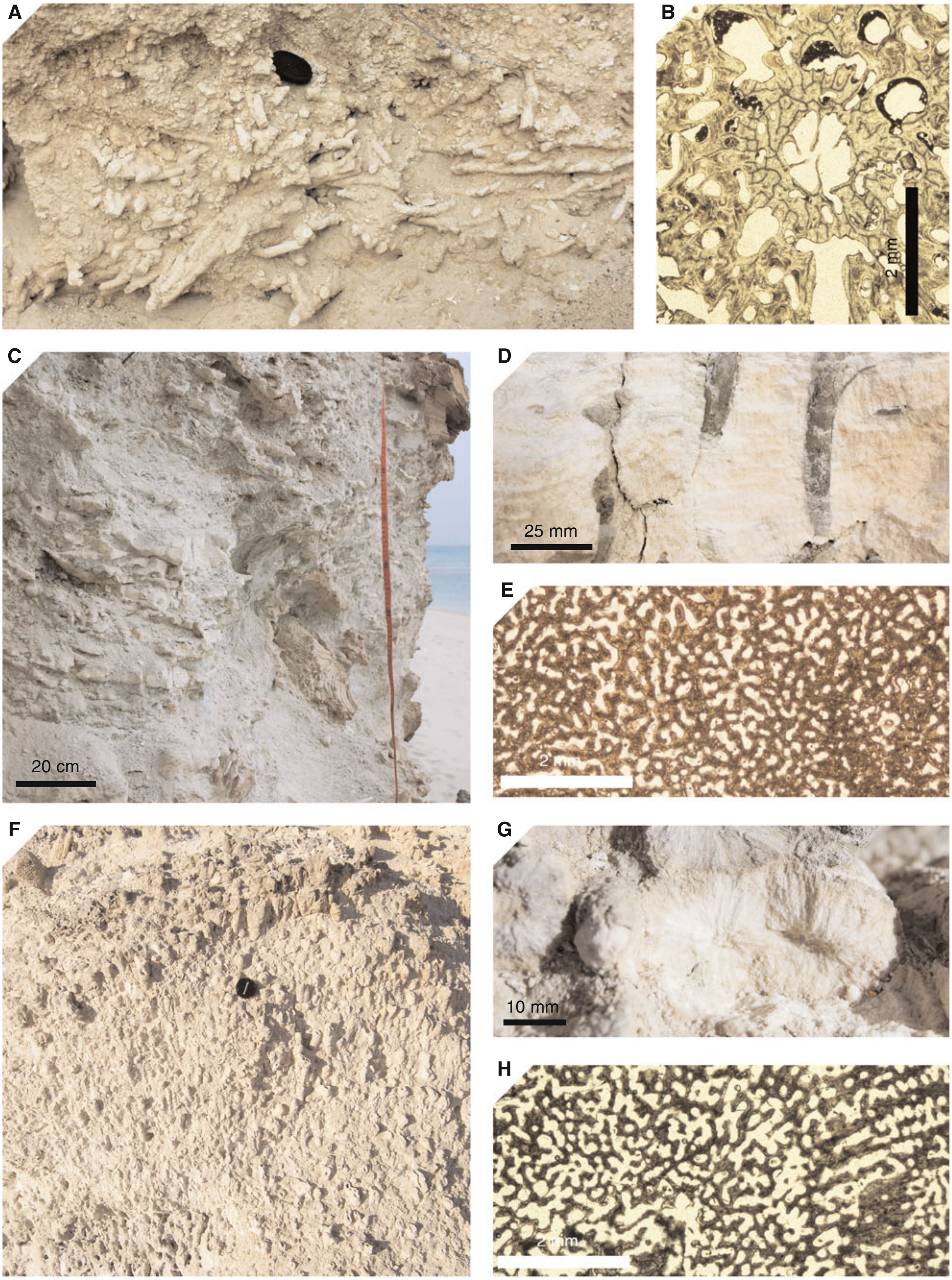
The upper bivalve layer contains an abundant bivalve fauna deposited in an intertidal to shallow subtidal environment (<20-m water depth). Although there is no dominant substrate preference indicated, most are epifaunal, and either byssally attached or cemented, that is, forms typically associated with coral-rich and/or reefal habitats.

Most of the turbidity around Kish Island is not anthropogenic, comprising fine-grained sediment transported by wind and algal blooms (Ghazban 2007; Samimi-Namin et al. 2010), and it is likely that the oceanographic setting during MIS 5 was similar.

## Marine isotope stage 7 deposits—observations

Records for the MIS 7 interglacial interval indicate that sea levels were lower than those of either MIS 9, MIS 5, or the present (Rohling et al. 2009; Imbrie et al. 1984). Accounts of coral reefs from this interval are limited but include reports from the Bahamas (Kindler et al. 2007), the Red Sea (Plaziat et al. 2008; Strasser et al. 1992), the Huon Peninsula (Chappell 1974) and the South Pacific (Camoin et al. 2001). Reef development during MIS 7 is not well known, as deposits are commonly covered by those of MIS 5 and by Holocene reef growth, or have been eroded during the penultimate glaciation. On Kish Island, the combination of favourable tectonic setting and burial processes has left MIS 7 deposits exceptionally well preserved and accessible.

Two age dates with initial isotope ratios close to those of seawater were obtained in this study, confirming an MIS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H
2 mm

7.1 age for one of the coral communities (Fig. 3). One sample (SM1-08) is a *Platygyra* from near the top of the section at SM1 (~5-m elevation), and the other (Hafezieh Lower Marl), a *Favites* from the eastern side of the island, near the top of the outcropping sandy marl (~4-m elevation). All other reliable dates with an initial ratio of less than 1.2 indicate a probable age of MIS 7.5. These samples are all stratigraphically lower in the section than the MIS 7.1 samples.

The coral marl unit dated as MIS 7 consists of large corals in life position embedded in a greenish, fine-grained, locally bioturbated sandy marl (Fig. 5). The unit is coherent, 1–5.5 m thick and outcrops in sea cliffs along the southern side of the island. It is gently folded with maximum exposure near the middle of the south coast, where it extends from 1.5 to 6 m above MSL. Outcrops of the topmost preserved parts of the unit occur up to 1.4 km inland (Fig. 4). In sections SM1, SM2 and SM3, the sequence consists of homogenous marl (>10 m in the subsurface), overlain by a thin mollusc-rich wackestone/packstone with sandy lenses (<0.5 m), the coral marl unit (1–4 m thick) and, finally, a thin mollusc-rich wackestone/packstone, with local coral debris, that is interpreted as MIS 5 (<1 m)(Fig. 5).

Eight coral genera have been identified including *Acropora*, *Cyphastrea*, *Favia*, *Favites,* *Goniastrea*, *Montipora* (platy and branching forms), *Platygyra* and *Porites* (Table 1; Figs. 6, 7, 8). Of these, *Cyphastrea*, *Platygyra* and variants of *Montipora* are dominant. *Cyphastrea* typically has a laminar-encrusting habit with protruding columns, and *Platygyra* is mostly a large columnar form with overgrowth margins. Growth bands counted in several specimens of *Platygyra* show that the corals were long-lived (100–300 years). Coralline algae encrusts coral skeletons throughout the section. Bioerosion of coral skeletons is uncommon within the section, but corals at the top of the section are intensely bioeroded by *Lithophaga* and boring sponges.

Coral assemblages show lateral variation and vertical succession. In western areas, as at section SM3, there is an indurated coral marl layer (~1 m thick) dominated by *Cyphastrea* sp. and *Platygyra daedalea* (Fig. 10). The top of this coral is truncated by an erosion surface overlain by the MIS 5 upper bivalve layer. Eight-hundred metres to the east, at section SM1, the base of the coral marl (here poorly lithified and about 3.5 m thick) comprises a similar *Cyphastrea*—*Platygyra*-dominated assemblage but midway to the top of the unit there is a change in the community to a *Montipora* sp. 1-dominated assemblage, still with *Platygyra daedalea* (Fig. 11a), but with fewer *Cyphastrea*.sp. Throughout the section, there are scattered small

**Fig. 7** Common Pleistocene corals from Kish Island. **a**, **b** *Porites* ▶ spp. **a** *Porites* colony near KR10 site. **b** *Porites* colony from the Dolphin site. **c** *Goniastrea* sp. from the top of the SM1 site. **d** *Leptastrea* sp., Photograph from site SM3. **e**, **f** *Favia* sp. From SM2 site (SM2G-01B). **e** *Favia* from SM2. **f** Thin section across the axes of the corallites. **g**, **h** *Favites* sp. From the SM2 site (SM2G-01). **g** *Favites* colony. **h** Thin-section across axes of corallites

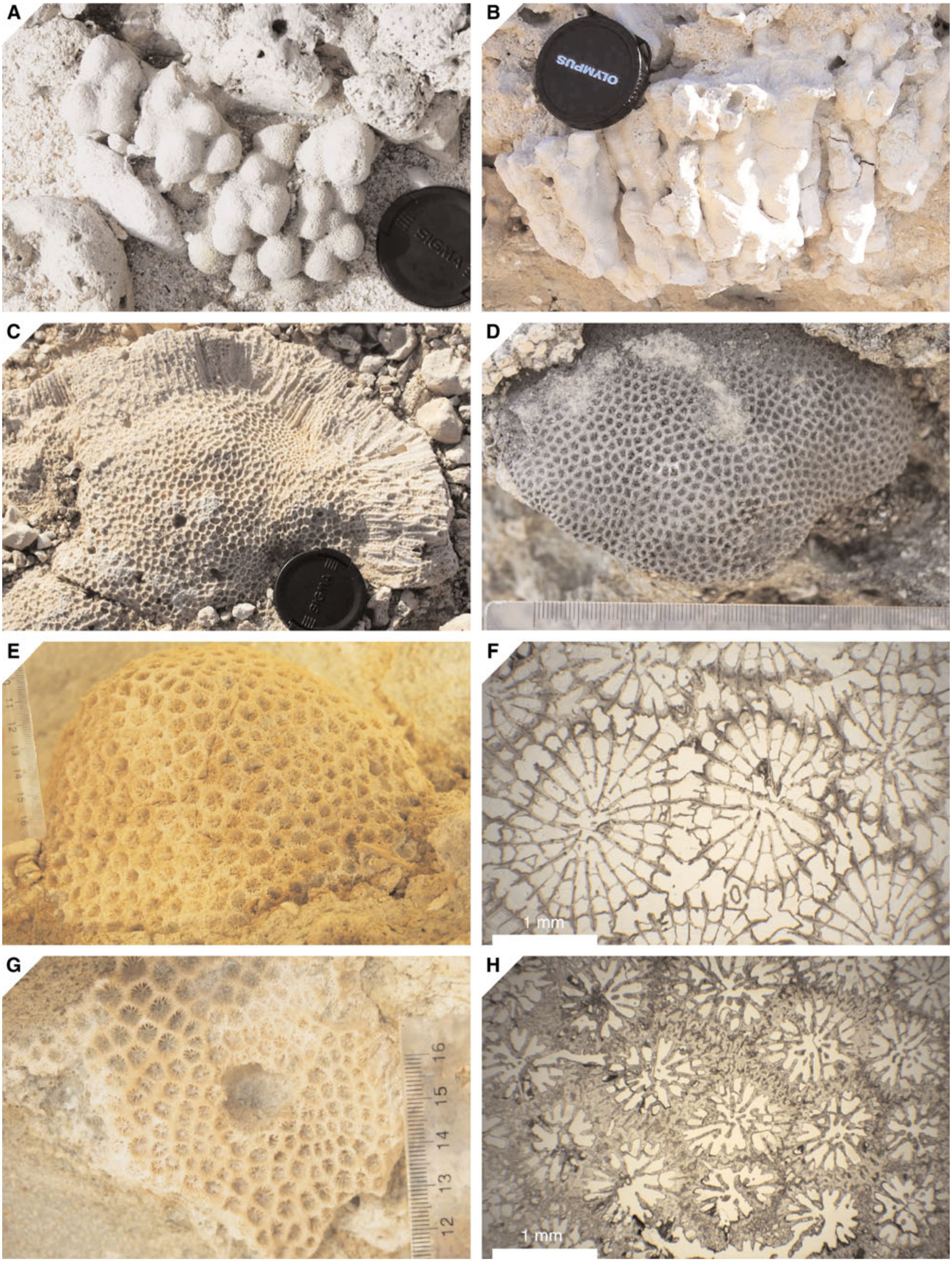
colonies of other faviids. At site SM2 a further 2 km to the east, the base of the section and the coral marl are dominated by large (up to 2 m diameter) branching colonies of *Montipora* sp. 2. The succession here is over 3 m thick (the base is not exposed) and the coral assemblage changes up-section to a more diverse association of *Platygyra daedalea*, *Cyphastrea* sp. and small colonies of various *Favites*, *Favia* and *Goniastrea* species (Fig. 11b). Branching *Montipora* sp. 2 are still present in outcrops up to 6 km to the east of SM2.

Bivalves are rare in the coral marl but are more diverse than those in other layers. Eight families, seven genera and six species have been identified, including *Trachycardium* cf. *T. rugosum*, *Codakia tigerina*, *Lithophaga cumingiana*, *Alectryonella plicatula*, *Ostrea* sp., *Chlamys* cf. *C. ruschenbergerii*, *Placuna* sp., *Solecurtus* sp., *Gafrarium* cf. *G. divaricatum*. The Solecurtidae are only found in samples from this layer. Boring *Lithophaga* sp. becomes very abundant in *Montipora* and *Cyphastrea* skeletons at the tops of the sections.

Two marl layers below the coral marl contain no corals but are characterized by abundant bivalves (Fig. 5). In the lower unit, eight families are present, including eight genera and five identified species: *Laevicardium* cf. *L. papyraceum*, *Chama* sp., *Hyotissa hyotis*, *Mactra* cf. *M. chatina*, *Alectryonella plicatula*, *Ostrea* sp., *Annochlamys* sp., Psammobiidae indet. sp, *Lioconcha omata* (Tables 3, 4; Figs. 8, 9). The unit is mostly lithified, and the shells of most aragonitic molluscs are completely dissolved. Of the identifiable forms, only two families are common, including two genera and three identified species: Pectinidae, *Pinctada radiata* and *Pteria* sp. (Tables 3, 4; Fig. 8).

## Marine isotope stage 7 non-fatal coral disturbance

Many of the corals in the MIS 7 deposits show evidence of disturbance, marked by the death of some colonies and recolonisation by other species (Fig. 12b–e). There are also examples of partial necrosis of colonies and recolonisation by the same species (Fig. 12d). In the latter instances, there may be sediment, other species of coral, coralline algae or more typically a combination of these embedded within the colony, separating stages of coral growth (Fig. 12e–g). A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similar feature is observed in living corals in the Persian Gulf, with the tops of colonies covered by fine-grained marl and filamentous algae (Fig. 12a).

## Reefs or coral carpets: nature of the Kish Island Pleistocene coral communities

The concept of a reef has different interpretations depending on whether it is being analysed by a biologist or a geologist (e.g. Riegl and Piller 1997, 2000). During the different phases of MIS 7, the living corals colonised a lithified substrate and grew up to a maximum of 3–4 m above the sea floor. From a biological point of view, these coral communities certainly developed reef structures. Even the MIS 5 scattered coral communities on an antecedent reef topography would be considered coral reefs by a biologist. From a geological perspective, however, the MIS 5 communities are certainly not biohermal and did not form framework. Many aspects of the older MIS 7 reef sequences fit well into the coral-carpet–biostrome model (Kershaw 1994; Riegl and Piller 1997, 2000). They have a broad lateral extent (up to 2 km wide and >7 km long), lack a clear vertical succession and are characterized by a low topographic relief (<4 m above the seafloor). The only features typical of bioherms within the coral frameworks that developed during MIS 7 include a lateral zonation from shallower to deeper communities. However, lateral zonation in the reef sequences does not exhibit typical coral reef geomorphological characteristics, including fore-reef, reef-crest and back-reef zones. Compared to the coral-carpet frameworks of Riegl and Piller (1997) defined in the northern Red Sea, the *Cyphastrea-Platygyra* communities (Fig. 11a) appear similar to their *Porites*-carpet and the *Montipora* sp. 2 community (Fig. 11b) to the *Stylophora*-carpet (thicket) community, but with much larger colonies (up to 2 m diameter). The *Montipora* sp. 1 community (Fig. 11b) also exhibited morphologies similar to a *Stylophora*-carpet, but it did not form thickets. In the easternmost outcrops, coral communities did not build frameworks, just as those dated as MIS 5 and that inhabit modern reefs of Kish Island. The turbid and eutrophic depositional setting of the coral communities during MIS 7 probably repeatedly constrained vertical growth and inhibited development of typical bioherm characteristics.

## Marine Isotope Stage 7 deposits—interpretations

There were no coral reefs in the area that is now Kish Island prior to MIS 7. Older units consist of fine-grained marly sediments with abundant bivalves at intervals. Marl deposition was the dominant sedimentary process in the Persian Gulf during the Late Pleistocene and Holocene marine intervals (Stoffers and Ross 1979; Ghazban 2007). Present-day marls are formed by the deposition of fine-grained wind-blown sediment (Ghazban 2007), and autochthonous carbonate production (including both biogenic and inorganic precipitation of aragonite). Similar processes were probably responsible for deposition of the Late Pleistocene marl. The age of the older (pre-MIS 7) marl is not known, but due to its stratigraphic position, the modern bivalve and foraminiferal communities (Mossadegh et al. 2012) and sea-level history for the gulf, we interpret it to have formed during one of the preceding interglacial intervals. The bivalves in this unit include both epifaunal and infaunal taxa that typically inhabit shallow marine environments (<20-m water depth). The lack of coral faunas prior to MIS 7 may reflect the lack of a suitable substrate, rather than unfavourable oceanographic conditions (Purkis et al. 2011). Overlying the marl is an indurated unit with abundant bivalves, the lower bivalve layer, which forms the substrate upon which the corals of the coral marl layer began to grow. All bivalves in this layer are epifaunal, byssally attached, and are species commonly associated with coral habitats and/or coral reefs.

During MIS 7, two short-lived, prolific coral-bearing sequences (MIS 7.5 and 7.1) formed in turbid waters on the coastline of the south-eastern Persian Gulf. Although corals and coral reefs are considered to be not typically associated with turbid water and marl deposition, many examples are reported in the literature (Sanders and Baron-Szabo 2005 and references within). For example, some reefs from the northern Great Barrier Reef started growing in a muddy environment (Johnson and Risk 1987), and coral patch reefs are common on the siliciclastic-influenced coast of the southern Belize Barrier Reef, where they have to cope with turbid waters (Purdy and Gischler 2003; Purdy et al. 2003). Four corals are common in the MIS 7 marl sequences of Kish Island, *Platygyra daedalea*, *Cyphastrea* sp., *Montipora* sp. 1 and *Montipora* sp. 2, and all four are recorded in present-day turbid-water environments. *Platygyra* and *Cyphastrea* are found in both MIS 7 sequences, and colonies are commonly inter-grown and overlapping. Where *Montipora* is dominant it forms largely

**Fig. 8** Common Pleistocene corals from Kish Island. **a**, **b** *Platygyra daedalea* from the SM1 site. **a** Large *Platygyra* showing elongate growth style. **b** Magnified view of corallites. **c–f** *Cyphastrea microthalma* from site SM1. **c** Magnified view of cross-section of broken specimen. **d** Photograph of large *Cyphastrea* near the base of section at SM1. **e** Magnified view of specimen showing the corallites. **f** Thin-section across axes of corallites (SMG04)

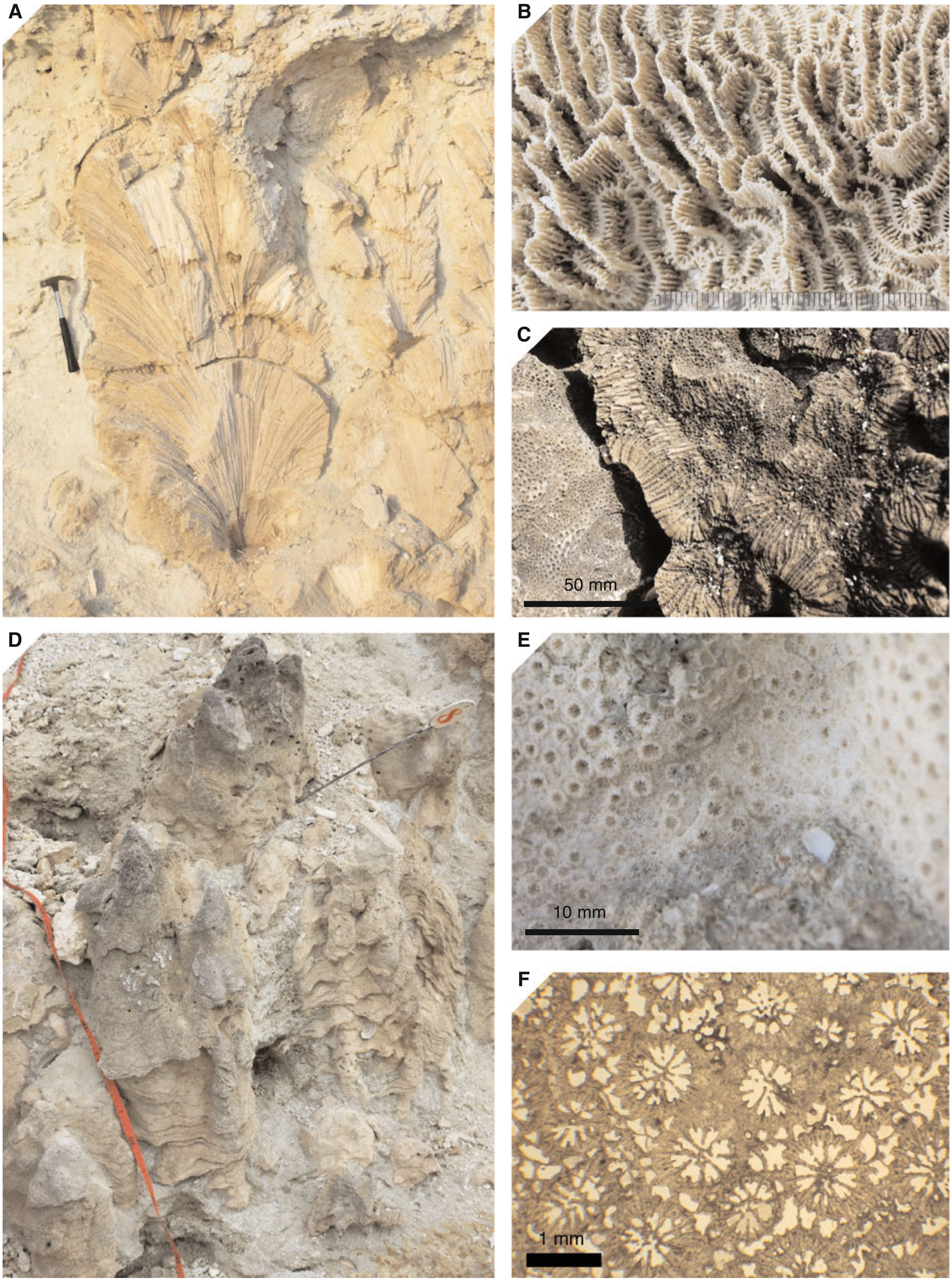
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**Table 3** Life mode and feeding habits of bivalves from the Pleistocene of Kish Island

| Mode of feeding | Epifaunal | | | Infaunal | | Boring |
|---|---|---|---|---|---|---|
| | Byssally attached | Cemented | Unattached | Burrowing—shallow | Burrowing—deep | |
| Detritus feeding | | | | | *Tellina scobinata* | |
| | | | | | *Tellina palatam* | |
| Suspension filter-feeding | *Scapharca* sp. | *Tridacna* sp. | *Glycymeris pectunculus* | *Gafrarium* cf. *G. divaricatum* | *Solecurtus* sp. | *Lithophaga cumingiana* |
| | *Barbatia* cf. *B. foliata* | *Chama* sp. | *Placuna* sp. | *Lioconcha ornata* | *Mactra* cf. *M. chatina* | |
| | *Annachlamys* sp. | *Chama pacifica* | | *Marcia sp.* | *Mactra* sp. | |
| | *Chlamys* cf. *C. ruschenbergerii* | *Hyotissa hyotis* | | Psammobiidae indet. sp. | | |
| | *Pinctada* sp. | *Ostrea* sp. | | *Trachycardium* cf. *T. rugosum* | | |
| | *Pinctada radiata* | *Saccostrea cucculata* | | *Trachycardium lacunosum* | | |
| | *Pinctada margaritifera* | *Alectryonella plicatula* | | *Laevicardium* cf. *L. papyraceum* | | |
| | *Pteria* sp. | | | *Codakia interrupta* | | |
| | | | | *Codakia tigerina* | | |

See Figs. 8 and 9 for illustrations. For systematic positions, please refer to Appendix 1 in ESM

monospecific communities. It is not entirely clear as to why *Montipora* sp. 2 (a branching form) is restricted to the lower (MIS 7.5) sequence and *Montipora* sp. 1 (a platy form) is confined to the upper (MIS 7.1) sequence.

Of the prominent coral taxa, *Platygyra* is the only one considered to have good active-rejection mechanisms for sediment removal and is common in many present-day turbid-water reefs (e.g. McClanahan and Obura 1997; Browne et al. 2010). By contrast, *Montipora* has poor rejection mechanisms but is nevertheless highly tolerant of turbidity and sedimentation and, with *Porites,* is the dominant taxon in many turbid-water habitats (James and Macintyre 1985; Potts et al. 1985; Tudhope and Scoffin 1994). Although *Porites* is the dominant coral taxon in the Persian Gulf today, only a few small colonies were found in the MIS 7 deposits. *Montipora,* on the other hand, a prominent coral during MIS 7, is not found in the modern Persian Gulf (Rezai et al. 2004; Fatemi and Shokri 2001) and was not found amongst MIS 5 corals in the area. Whereas both taxa inhabited turbid waters in the Persian Gulf during MIS 7, only *Porites* is present today, and turbidity and sedimentation alone cannot explain the discrepancy. A more detailed comparison of modern habitats dominated by *Porites* or *Montipora* is needed to fully understand the environmental controls that inhibit or promote selection.

The morphology of the MIS 7 corals on Kish Island, but particularly the columnar form and overgrowth margins of the large *Platygyra daedalea,* reflect sedimentation in a turbid-water environment (Sanders and Baron-Szabo 2005). The co-occurrence of corals and marls, although unusual, is not unprecedented, and it is likely that deposition occurred in two phases: (1) during the growth of the coral, but with sedimentation rates low enough to avoid mortality, demonstrated by the incursions of marl during minor disturbance events; and (2) once corals were deceased, indicated by the occurrence of marl in dense *Lithophaga* borings and deepening suggested by Mossadegh et al. (2012). For these phases to occur in sequence, the depositional environment was probably balanced near the border between conditions favourable for coral growth, and those promoting marl deposition.

It is not possible to constrain the depositional depth of the MIS 7 coral marl unit directly from the occurrences of corals and bivalves. Pirazzoli et al. (2004) noted that the corals are dominantly deep-water taxa and suggested that because the reefs are presently 2–6 m above sea level, an assumed uplift rate of 0.2 mm/year would imply formation at 25–35-m water depth. Mossadegh et al. (2012) suggested depositional depths of between 5 and 30 m for the two successions and that corals were

**Table 4** Substrate and environment of modern representatives of the bivalve taxa from the Pleistocene of Kish Island. See Figs. 8 and 9 for illustrations. Data from Poutiers (1995), Hosseinzadeh et al. (2001) and Hauser et al. (2007)

| Family | Species | Substrate | Environment | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | Intertidal | Littoral | Sublittoral | SHELF | Comments | Depth (m) | Coral reef association |
| Arcidae | *Scapharca* sp. | Sand and mud | | X | X | | | Max depth of 20 m | |
| | *Barbatia* cf. *B. foliata* | Sand and mud | | X | X | | Bays and coastal lagoons | Max depth of 20 m | |
| Glycymerididae | *Glycymeris pectunculus* | Sand and mud | | | X | | | From 5 to 50 m | |
| Mytilidae | *Lithophaga cumingiana* | various hard substrates | | X | X | | | To a depth of 66 m | X |
| Pteriidae | *Pinctada* sp. | Rock, sand or mud | | X | X | X | | From low tide to 150 m | X |
| | *Pinctada radiata* | Rock, sand or mud | | X | X | X | | From low tide to 150 m | X |
| | *Pinctada margaritifera* | Rock, sand or mud | | X | X | | | To a depth of 20 m | |
| | *Pteria* sp. | Hard rocky | | X | X | | | From low tide to 35 m | X |
| Ostreidae | *Alectryonella plicatula* | various hard substrates | X | X | | | | To a depth of 5 m | |
| | *Saccostrea cuccullata* | various hard substrates | X | X | | | Shallow marine, estuarine and mangrove areas | To a depth of 5 m | |
| | *Ostrea* sp. | Hard rocky | | X | | | Estuarine | From 0 to 71 m | |
| Gryphaeidae | *Hyotissa hyotis* | Hard rocky | X | X | | | | From 5 to 50 m | X |
| Pectinidae | *indet*. sp. | Rock, sand or mud | | X | | | | Low Tide to 100 m | X |
| | *Chlamys* cf. *C. ruschenbergerii* | Rock, sand or mud | | X | X | | | From 1 to 50 m | X |
| | *Annachlamys* sp. | Sand | | X | X | X | | From shallow water to a depth of 125 m | |
| Placunidae | *Placuna* sp. | Sand and mud | | X | X | X | Protected lagoons, bays and mangrove areas or near estuaries | From low tide levels to a depth of about 100 m. | |
| Lucinidae | *Codakia tigerina* | Sand and mud | | X | X | | | To a depth of 20 m | X |
| | *Codakia interrupta* | Sand | | X | X | | | To a depth of 15 m | X |
| Chamidae | *Chama pacifica* | Hard rocky | | X | X | | | to a depth of 30 m | X |
| | *Chama* sp. | Hard rocky | X | X | | | Shore | | X |

**Table 4** continued

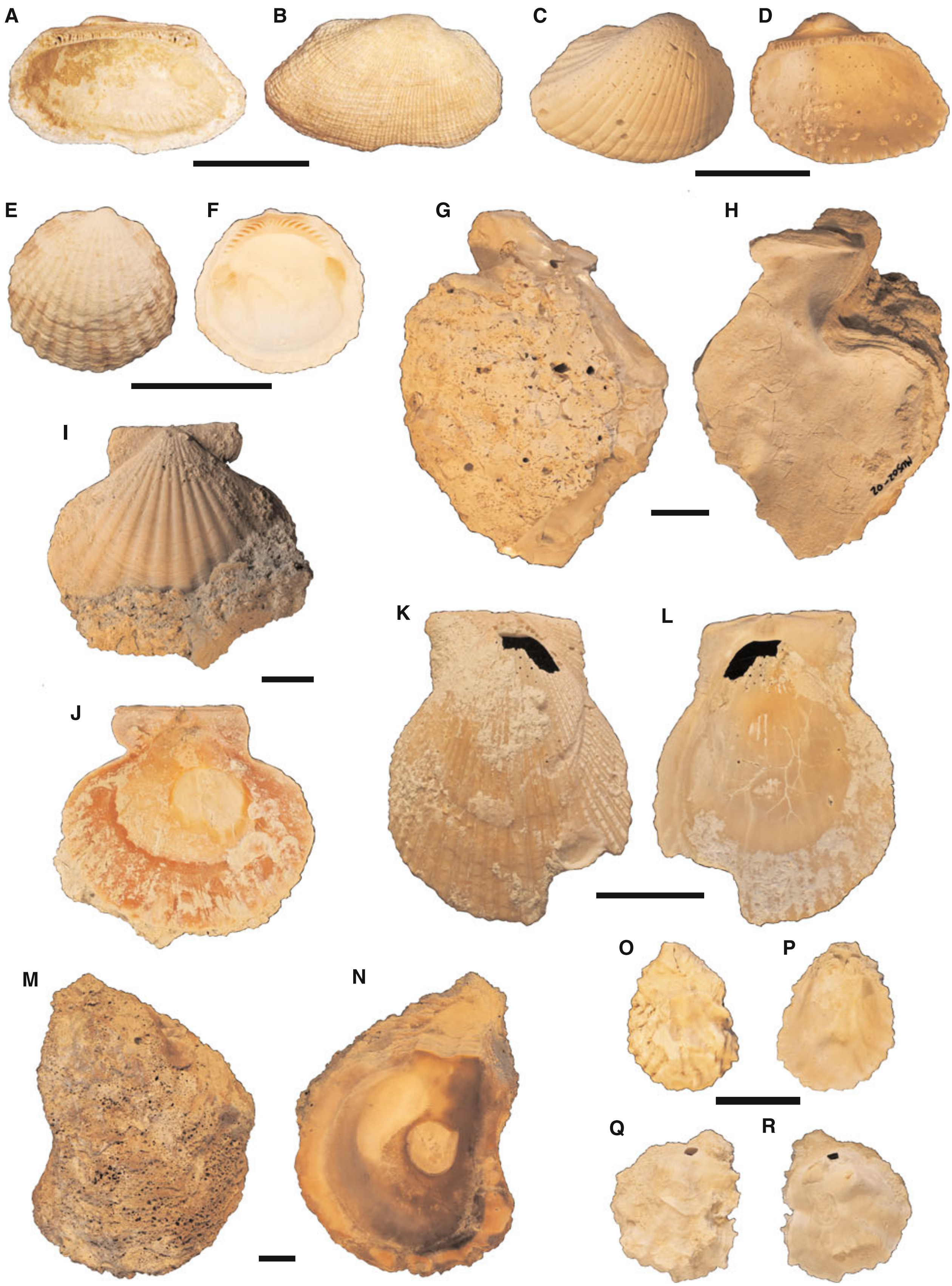
| Family | Species | Substrate | Environment | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | Intertidal | Littoral | Sublittoral | SHELF | Comments | Depth (m) | Coral reef association |
| Cardiidae | *Trachycardium lacunosum* | Sand and mud | X | X | | | | To a depth of 20 m | X |
| | *Trachycardium* cf. *T. rugosum* | Sand and mud | X | X | | | | To a depth of 20 m | X |
| | *Laevicardium* cf. *L. papyraceum* | Sand and mud | X | X | | | | To a depth of 20 m | X |
| Tridacnidae | *Tridacna* sp. | Sand | X | X | | | shallow water, reef flats | From 2 to 20 m | X |
| Mactridae | *Mactra* cf. *M. chatina* | Sand and mud | | X | X | | | From low tide to20 to 60 m | |
| | *Mactra* sp. | Sand and mud | | X | X | | | From low tide to20 to 60 m | |
| Tellinidae | *Tellina palatam* | Coarse sand | | X | X | | Lagoons of coral reefs | To a depth of 20 m | |
| | *Tellina scobinata* | Coarse sand and gravel | | X | X | | | To a depth of 20 m | |
| Psammobiidae | indet. sp. | Sand and mud | x | x | x | | Estuarine | To a depth of 20 m | |
| Solecurtidae | *Solecurtus* sp. | Sand | | X | X | | | To a depth of 20 m | |
| Veneridae | *Lioconcha ornata* | Sand | | X | | | | To a depth of 20 m | X |
| | *Marcia* sp. | Sand and mud | X | X | | | Protected coastal areas and near estuaries | To a depth of 20 m | X |
| | *Gafrarium* cf. *G. divaricatum* | Sand and mud | X | X | X | | | To a depth of 20 m | X |

For systematic positions, please refer to Appendix 1 in ESM

deceased during periods of deeper water. Present-day corals around Kish and Qeshm Islands are rare below 10–12 m water depth, restricted by both the high turbidity and the lack of suitable substrate (Purkis et al. 2011; Riegl 2003). The coral assemblages in the MIS 7.5 and 7.1 units both include shallow and deep-water forms that probably grew in a sheltered environment. *Montipora* is known to occur in turbid-water carbonate shore zones and lagoons (Sanders and Baron-Szabo 2005). In the MIS 7.5 sequence, the large branching *Montipora* sp. 2 colonies in life position, with little evidence of breakage, suggest a sheltered environment, probably near or below fair-weather wave base. The bivalves from the sediment surrounding the coral also imply a shallow, sheltered environment (<20-m water depth). Most are shallow infaunal species although some are epifaunal. Corals at the top of this layer are intensively bored by *Lithophaga cummingiana* and may reflect an intertidal environment that formed after the demise of the corals.

The lateral changes in both sequences suggest that corals grew on a gentle slope that deepened to the southeast (Fig. 13). In the lower, MIS 7.5, sequence, there is a

**Fig. 9** Photographs of selected bivalves. **a**, **b** *Barbatia* cf. *B. foliata*. ▶ (Inner Kish 01e), right valve from Inner Kish site (MIS 5). **c**, **d** *Scapharca* sp. (SM3G01a), right valve from SM3G01 (Holocene). **e**, **f** *Glycymeris pectunculus* (SM3G01-c), left valve from SM3G01 (Holocene). **g**, **h** *Pinctada margaritifera* (MUS02-02), left valve from MUS site (MIS 5). **i**, **j** *Annachlamys* sp. (SM1 west beach marl **b**), right valve from SM1 (MIS 7). **k**, **l** *Chlamys* cf. *C. ruschenbergerii* (Hafezieh lower marl **c**), left valve from Hafezieh (MIS 7). **m**, **n** *Hyotissa hyotis* (Kish lib 06), right valve from Kish Lib 06 (MIS 7). **o**, **p** *Alectryonella plicatula* (SM3-02), left valve from SM3 (MIS 7). **q**, **r** *Saccostrea cucullata* (DAR04), left valve from Dariush (MIS 7)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change from robust dome-like *Platygyra* and organ-pipe *Cyphastrea* in the west to branching corals in the east, which is interpreted as a transition to lower energy conditions and deeper water. A similar lateral change is seen in the MIS 7.1 sequence, with coral rubble in the west, passing laterally into a platy *Montipora* sp. 1 assemblage and a deeper and more diverse faviid assemblage towards the east. In outcrops on the eastern side of the island, corals are rare and dispersed throughout the marl. One of these from the Hafezieh locality was dated as MIS 7.1.

Many of the *Cyphastrea*, *Platygyra* and *Montipora* in the basal part of the coral marl were long-lived and grew to reach large sizes, with some colonies up to two metres high. For corals to achieve these sizes, the conditions during their formation would have had to have been stable for hundreds of years. Some of the colonies show partial necrosis and microatoll forms, as described by Stoddart and Scoffin (1979). These corals grew in a subtidal environment, however, and sediment deposited on top of the colonies is believed responsible for the microatoll morphology observed. Examples of this process were observed in modern corals of the Persian Gulf and have been reported from Holocene corals (Hendy et al. 2003). There are also many examples of coral mortality and recovery with changes in species composition, but no change in overall community structure. Such changes may be related to 15–20 year climatically induced disturbances like those that affect present-day corals of the Persian Gulf (Riegl 1999, 2003; and hiatuses observed in *Porites* by Gischler et al. 2005). Mortality is also believed to reflect periods of extreme water temperatures and high sedimentation rates, as suggested by Riegl (1999). It seems that during MIS 7, natural climatic fluctuations played a significant role in the mortality observed in the fossil corals.

## Late Pleistocene (MIS 7, 5) changes in reef communities

There are significant differences in the coral communities of Kish Island between MIS 7, MIS 5 and the Holocene. During MIS 7, corals formed substantial growth frameworks that are not observed in MIS 5 deposits and do not occur at the same latitude at the present day (Rezai et al. 2004; Fatemi and Shokri 2001). The closest parallels in the Persian Gulf today are found close to the Straits of Hormuz, for example, on Hengum, Larak and Qeshm Islands and on the eastern coast of the United Arab Emirates and Oman (Salm 1993). However, large corals (*Porites lutea*) have been recorded from pinnacle reefs offshore of Kuwait, at the northern limit of the gulf (Gischler et al. 2005).

**Fig. 10** Photographs of selected bivalves. **a**, **b** *Codakia interrupta* (Inner Kish 1-I), left valve from Inner Kish (MIS 5). **c–f** *Codakia tigerina* (Inner Kish 1-a) complete shell from Inner Kish site (MIS 5). **c**, **d** Right valve. **e**, **f** Left valve. **g**, **h** *Chama* cf. *C. pacifica* (Inner Kish 1-c), right valve from Inner Kish site (MIS 5). **I** *Laevicardium* cf. L. *papyraceum*, (Lower part city lib3b). Right valve from KishLib03 (MIS 7). **j** *Trachycardium* cf. *T. rugosum* (SM3G3) right valve from SM3G (MIS 7). **k**, **l** *Tridacna* sp. (K11-1) left valve from K11 (MIS 5). **m**, **n** *Mactra* cf. *M. achatina* (Lower part city lib 3a), right valve from KishLib03 (MIS 7). **o–r** *Tellina palatam* (Inner Kish 1-f), complete shell from Inner Kish site (MIS 5). **o**, **p** Left valve. **q**, **r** right valve. **s**, **t** *Tellina scobinata* (Inner Kish 1-b), left valve from Inner Kish site (MIS 5) **u–w** *Solecurtus* sp. (Hafezieh lower marl), right valve from Hafezieh (MIS 7). **x**, **y** *Lioconcha ornata* (Lower part city lib 3c), right valve from KishLib03 (MIS 7)

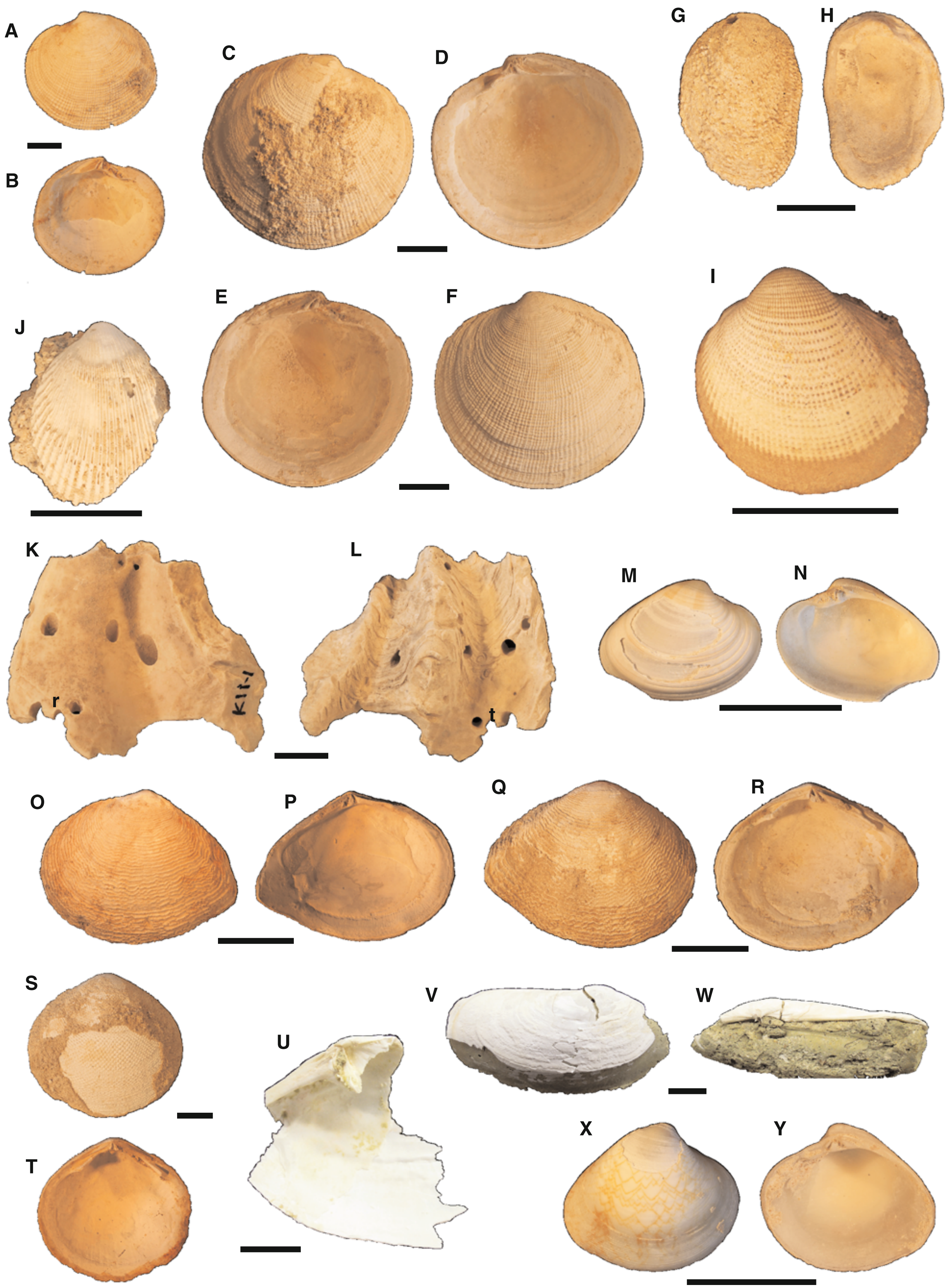
The dominant taxa of the coral communities of both MIS 7.5 and MIS 7.1, *Cyphastrea* sp., *Platygyra* sp., *Montipora* sp. 1 and *Montipora* sp. 2, are no longer dominant in either MIS 5 deposits or any modern coral reefs. In shallower MIS 5 deposits, there is evidence from rubble that *Acropora* was abundant and dominated the community, but in the deeper deposits at Daruish Hotel, there are no dominant reef-building taxa. *Acropora* was formerly abundant around Kish Island, but following the bleaching events in 1998 and 2004, the genus has been reduced to rubble in shallow marine and beach deposits, with few juveniles. Of the living corals in Kish Island *Porites* is dominant (Fatemi and Shokri 2001) and whilst small faviids are common, they are widely dispersed.

*Montipora* has been reported as 'absent' from the present Persian Gulf (Riegl 2003), and it was not found in the deposits dated as MIS 5 reef from Kish Island. The dominance of this form in both MIS 7 sequences underlines important differences between the environmental conditions prevailing during those times and today.

Riegl (1995, 2003) noted that the volume and grain-size of sediment within a system can have an important effect on the types of coral able to inhabit an environment, and in particular, the sensitivity of *Acropora* to environments with high sediment suspension. This observation provides a possible explanation for the paucity of this genus in the MIS 7 deposits that are predominantly marls.

## Conclusions

- Corals growing around what is nowadays Kish Island during MIS 7 were long-lived, and framework-forming coral carpets or biostromes, but during both MIS 5, and the Holocene corals in the same area were short-lived and unable to form reefs with depositional relief. One explanation is that the influence of Indian Ocean water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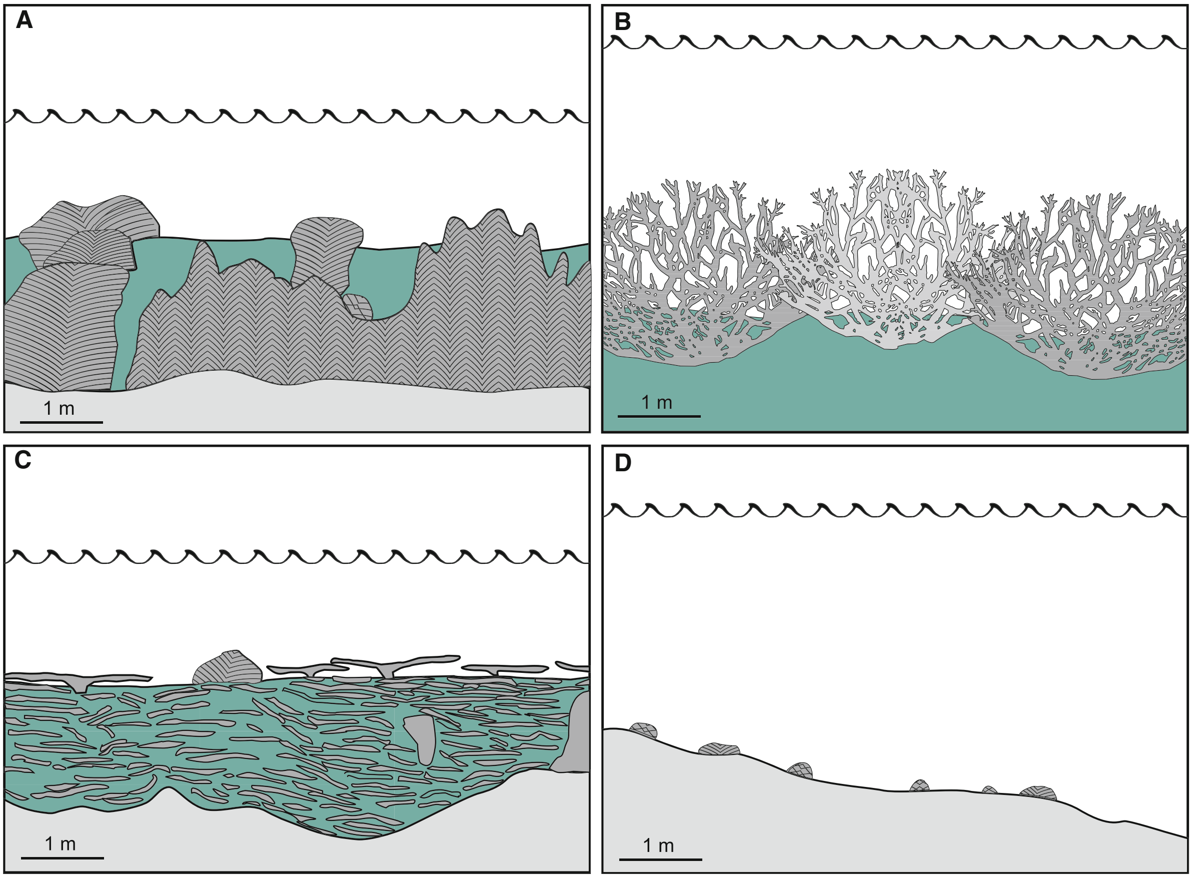
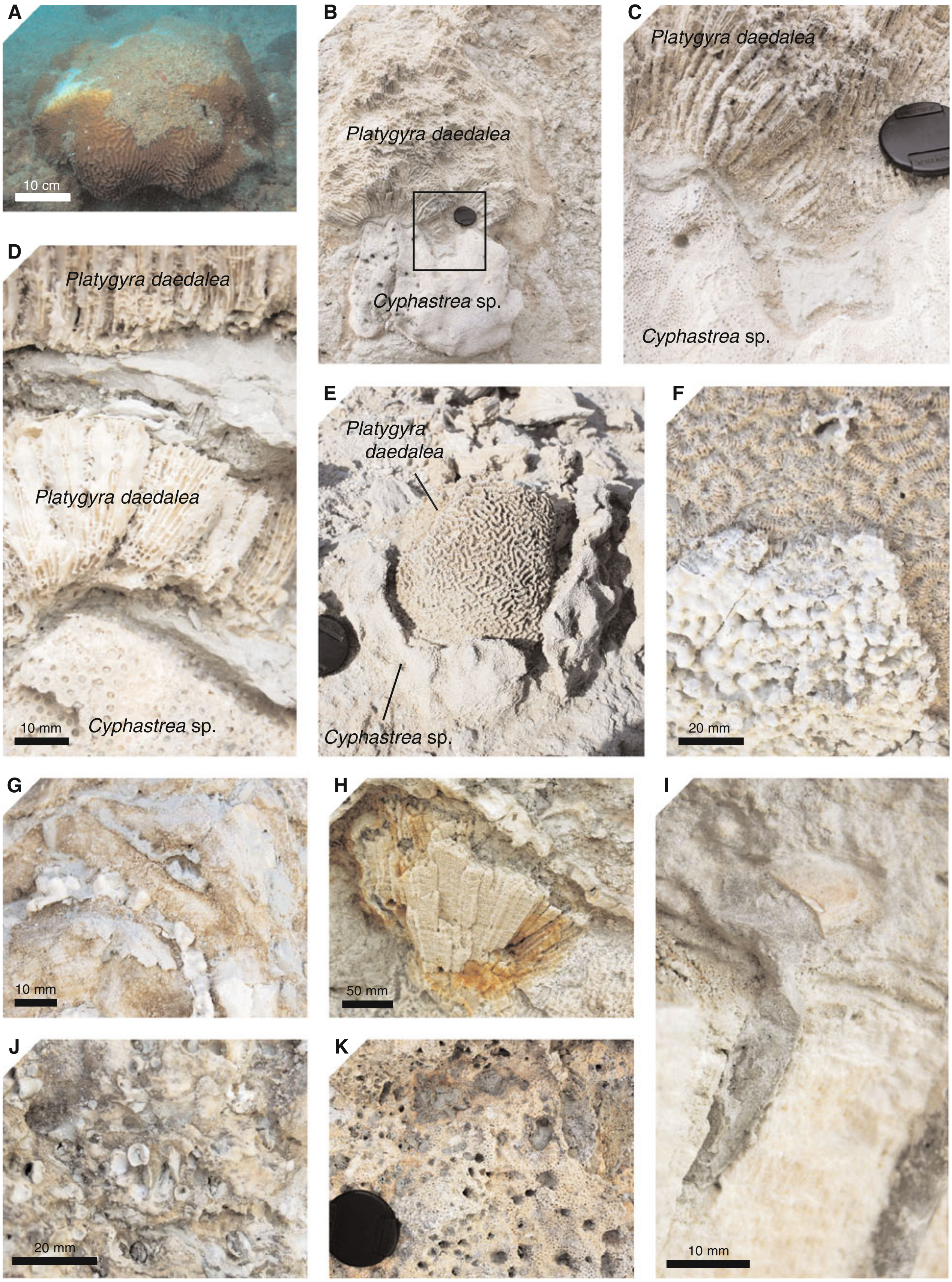



**Fig. 11** **a** Schematic figure showing the *Cyphastrea-Platygyra* community from section SM1 and dated as MIS 7.5. **b** Schematic figure showing the *Montipora* sp. 2 (branching habit) community from section SM2, which was seaward of the community shown in **a**. **c** Schematic figure showing the *Montipora* sp. 1 (platy habit) community from section SM1 and dated as MIS 7.1. **d** Schematic figure showing the scattered favid community on an antecedent reef slope from the Dariush and Portuguese Fort sites, typical of the coral communities dated as MIS 5. *Blue*: interstitial sediment

may have extended further into the Persian Gulf during MIS 7, in part as a result of a deeper gulf at the time. During the late Quaternary, the gulf has been shallowing and becoming more restricted due to tectonic processes. Environmental conditions during MIS 5 were probably very similar to those of the Holocene.

- The corals of MIS 5 and MIS 7 probably grew at a shallower depth (<20 m) than suggested by Pirazzoli et al. (2004). Consequently, the uplift rate during the Late Pleistocene was significantly lower as reconstructed before, thus affecting sea-level reconstructions.
- Periodically during MIS 7 partial necrosis or mortality of the corals caused only few changes in the community structure. An extinction event at the end of MIS 7.5 is marked by a major change in community structure that is probably related to persistent environmental and geomorphological changes. A second extinction event at the end of MIS 7.1 is characterized by a facies change due to the draining of the Persian Gulf, leading into the MIS 6 glacial interval.

**Fig. 12** Disturbance events. **a** *Platygyra daedalea* from 8-m water depth (dive computer measurement) in the present Persian Gulf (Hengam Island). Note that whilst the sides of the coral are living the top has died off and is covered in muddy sediment and filamentous algae. **b** *Cyphastrea* sp. from the MIS 7.1 reef that died and acted as the substrate for growth of *Platygyra daedalea*, from the MIS 7.1 succession at SM2. **c** Enlarged view of the contact between the corals in B, showing the layer of marl between. **d** Magnified view of two disturbance events from the MIS 7.1 succession at SM1. The first is the die-off of *Cyphastrea* sp. and overgrowth by *Platygyra daedalea*, the second is the partial necrosis of the *Platygyra daedalea* that has regrown over the marl intercalation that covered the coral. **e** The MIS 7.1 succession at SM2 showing a *Platygyra daedalea* that has died off and acted as a substrate for the growth of *Cyphastrea* sp.; the marl between the corals has been eroded. **f** Enlarged view of coralline algal encrustation on *Platygyra daedalea*, from the MIS 7.1 succession at SM2. **g** Enlarged view of *Monitpora* sp. 1 plates with coralline algal crust and marl between plates, from the MIS 7.5 succession at SM1. **h** Iron-staining in *Platygyra daedalea* at SM1, indicating subaerial exposure of the MIS 7.1 succession. **i** Magnified view of *Lithophaga* boring with the shell preserved, near the top of SM1. The lens cap in B-D and J is 50 mm in diameter. **j** Enlarged view of dense *Lithophaga* borings in *Montipora* sp. 1 at the top of the MIS 7.1 succession at outcrop section SM1. **k** Enlarged view of dense *Lithophaga* borings in *Cyphastrea* at the top of the MIS 7.5 succession at an outcrop section near SM3 ▶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Platygyra daedalea
10 mm
Cyphastrea sp.
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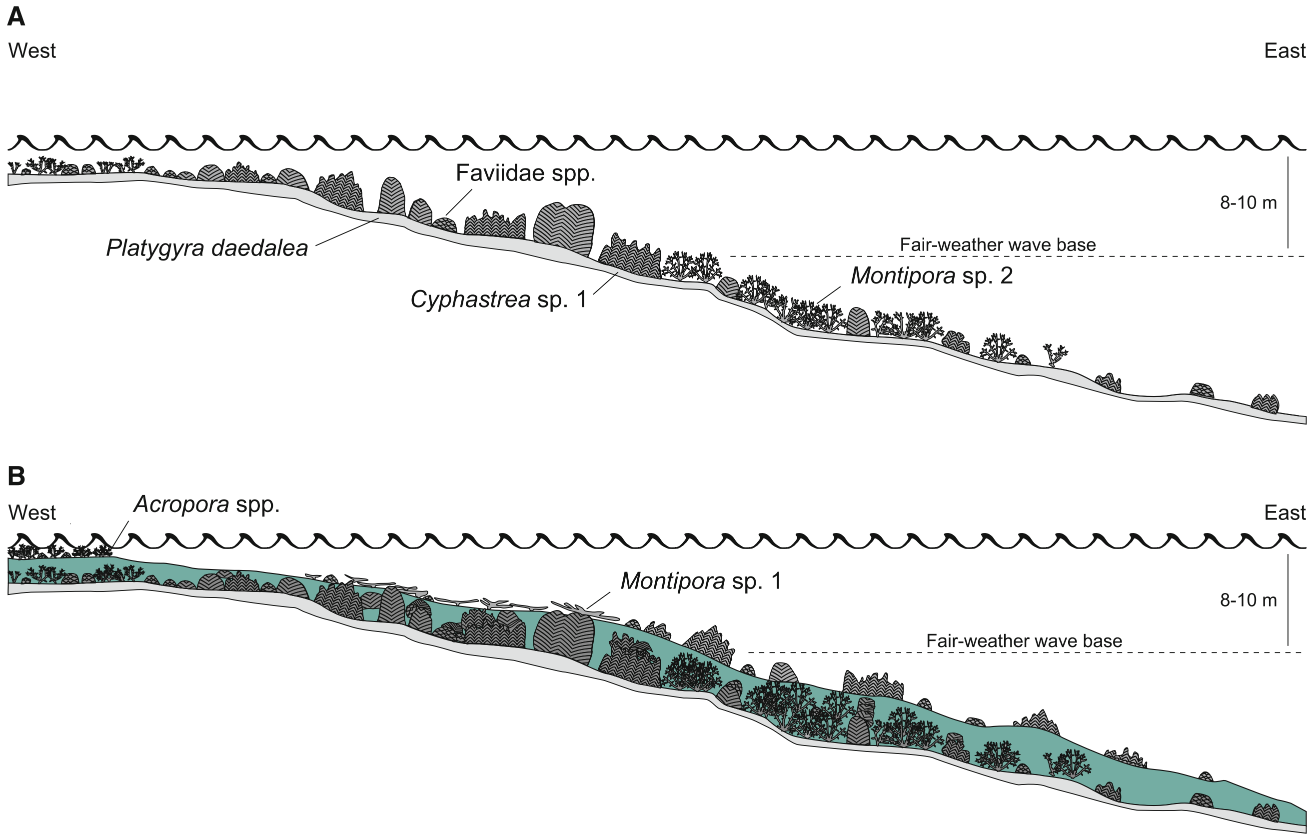


**Fig. 13 a** Vertically exaggerated schematic section linking the outcrops along the southern coastline of Kish Island during MIS 7.5 showing the lateral variation in coral faunas. **b** Vertically exaggerated schematic section between outcrops along the southern coastline of Kish Island at MIS 7.1, showing the lateral variation in coral faunas. Blue: interstitial sediment

**Acknowledgments** This study was funded under project A3.1 of the Biodiversity and Climate Research Centre (LOEWE), Frankfurt Germany. Advice and suggestions of Dr Hamid Rezai from the Iranian National Centre for Oceanography (INCO), whose help made this study possible, are greatly appreciated. Assistance in the field was provided by Mustafa Khoeniy, Kaveh Samimi and Ali Mirshahidi. Mr Khoeniy is especially acknowledged for helping with the necessary authorities and general advice about Kish Island. Ms Mohammadi and Mr Shirani of the Kish Island Authority are thanked for providing data and information about Kish Island. Export permits were issued by INCO, and permission to conduct the field-work on Kish Island was provided by the Kish Island Authority. Thin sections were prepared by Anja Isaak and Eckehard Gottwald. Rainer Petschick made the XRD analyses. We are grateful to Dan Bosence, Colin Braithwaite and Elias Samankassou, whose detailed comments and suggestions greatly improved the manuscript.

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