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Coral growth and reef growth: a brief review

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Abstract The growth potential of modern zooxanthellate corals from the major reef provinces is reviewed with respect to Holocene reef growth. Both coral growth and reef growth is enhanced globally at the beginning of the Holocene and is maintained regionally in the Caribbean Sea up to the present in contrast to reefs of the Indo-Pacific Ocean. This regional difference is mainly caused by the siphoning effect of the tropical Atlantic, which is characterised still by a rising sea level in contrast to global ocean. Hence, Indo-Pacific reefs exhibit a well-cemented reef crest and reef roof barren of living corals. The evaluation of reef growth rates throughout the Phanerozoic shows reduced growth rates of more than one order of magnitude in comparison to their modern counterparts. This is a result of compaction and diagenesis but also strongly biased by uncertainties in absolute dating. Point counting of individual framebuilders with known growth rate may result in more comparative figures for growth rates of fossil reefs with respect to modern ones.

Keywords Coral growth · Reef growth · Holocene · Phanerozoic · Caribbean Sea · Indo-Pacific Ocean

Introduction

Ever since the discovery of large and even giant hydrocarbon accumulations in carbonates ancient reefs and carbonate platforms have been studied extensively by sedimentologists all over the world. After detailed studies of modern and ancient facies patterns and their relationship, the geometry of carbonate build-ups and reefs became the prime target of research. The invention of small-scaled drilling gears pioneered the investigations in modern reefs to better

understand their growth in time and space. Since then the quantification of sedimentary processes and their numerical modelling became an important part of this research field. Although some very useful data compilations exist (Enos 1991; Bosscher 1992; Bosscher and Schlager 1993), a comparative study of coral growth and shallow-water reef growth is still lacking. Even though the discovery of modern deep-water coral reefs and reef mounds impacted considerably on our understanding of coral and reef growth, this review will not really touch on this burning issue of carbonate sedimentology, as all available data so far are of regional importance and a global perspective still remains very vague. The role of different carbonate factories was recently described in a comprehensive study by Schlager (2003) and well elucidated by Mutti and Hallock (2003) with respect to nutrient and temperature gradients. Recently, Vecsei (2004) published a new estimate of global reefal carbonate production.

Carbonate production by benthic organisms is an essential process in the global budget of CO_3^{2-} and CO_2 . Shallow-water reefs, apart of the still unknown contribution of deep-water coral reefs, are the major constituents in this process. During Earth history, several frame-building organisms took part in the formation of reefs and in the production of shallow-water carbonates (Wood 1999; Flügel and Kiessling 2002). Today, this shallow-water-carbonate production in the tropical region is mainly formed by zooxanthellate scleractinian corals (Schlager 2003), whereas in the boreal and even polar regions mainly azooxanthellate corals, bryozoans, coralline algae, and other calcifying benthic organisms are the main producers (Henrich et al. 1995; Freiwald et al. 1997).

Corals live in a clear and warm tropical shallow-water environment. There, they form fringing reefs of different dimensions, atoll islands, and even giant barrier reefs such as the Australian Great Barrier Reef (Davies et al. 1985), or the Belize margin (Purdy and Gischler 2003). Vertical reef growth is limited by space for accommodation, which in turn is controlled by sea level. Carbonate production of scleractinian corals and their associated reef biota tend to fill the available space of accommodation as a result of

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varying sea level. Reef biota will always maintain their growth rates in order to keep-up with sea-level rise. Although coral growth is several orders of magnitude higher than any observed sea-level change, a rapidly rising sea level—as seen in the geological record—may cause reef growth to give up in combination with other limiting factors like nutrient input and reduced amount of carbonate formation resulting in the paradox of drowned reefs (Schlager 1981, 2003). On the other hand, coral growth may catch up with a rising sea level, if the amplitude of sea-level rise outpaces coral growth only for a short period (Neumann and Macintyre 1985). However, if sea level falls coral reefs will become emerged and the living reef is forced to step-down with the sea level and migrate oceanwards. Therefore, sea level has a major control on coral reef growth (Sarg 1988; Vecsei 2004). Like coral reefs, carbonate platforms are affected by sea-level changes in a similar pattern (Schlager 1981, 2003).

The growth potential of reefs and carbonate platforms depend on the maximum growth rate of the frame-building organisms. Another important measure of growth potential is the volume of sediment an entire carbonate platform can produce (Vecsei 2004). The growth rates of Holocene reefs can be measured relatively accurately, however, the growth potential of ancient reefs and carbonate platforms is more difficult to access due to the lack of exact dating and the diagenetic overprint of distinct time lines (Mutti and Hallock 2003).

This paper presents some data on the growth rates of modern corals in relation to modern reefs and will discuss some data on ancient reefs and ancient carbonate platforms. Many of the referenced papers date back in time, however, this review touches on the original data.

Coral growth

Coral growth depends on various exogenic and endogenic factors (Buddemeier and Kinzie 1976). Water depth and geographical location are factors most easy to determine. The relation of the growth of scleractinian corals to water depth has long been recognized (Vaughan 1919). However, depth is a mixed environmental variable, including mainly the effects of light, water movement, and resuspension of sediments and organic matter. Light is assumed to be the primary environmental factor controlling growth and carbonate production of zooxanthellate corals. Light-enhanced calcification is responsible for most of the skeletal growth and carbonate production of reef-building corals (Goreau 1959; Chalker et al. 1985; Mutti and Hallock 2003).

In laboratory experiments, the dependency of coral growth on both insolation and temperature was observed for the genera *Porites*, *Pocillopora*, *Montipora*, *Cyphastrea* and *Pavona* (Houck et al. 1977). Some of these genera had sharp growth optima at specific temperatures (*Porites*, *Pocillopora*), while for example *Montipora* had a poorly defined maximum. Response to decreasing insolation is

also different. The growth of *Porites* and *Pocillopora* decreased with decreasing light intensity, while *Montipora* even shows enhanced growth (Houck et al. 1977).

Decrease in growth rates with increasing water depth is generally caused by the decrease of illumination and was first reported for the Caribbean corals *Montastrea annularis* (Baker and Weber 1975; Dustan 1979; Hubbard and Scaturo 1985; Huston 1985), *Porites asteroides* and *Diploria labyrinthiformis* (Logan and Tomascik 1991). Equivalent patterns are also reported for Indo-Pacific species such as *Porites lutea*, *Favia pallida*, and *Goniastrea retiformis* (Buddemeier et al. 1974). Bosscher (1992) could demonstrate that the growth rate of *Montastrea annularis* is exponentially linked to depth as well as Heiss (1994) did for *Porites*.

Growth rates of scleractinian corals decrease also generally with increasing latitude (Grigg 1982; Crossland et al. 1991; Logan and Tomascik 1991; Heiss and Dullo 1997). For the Caribbean region *Montastrea annularis* is the major object to evaluate coral growth and carbonate production (Hubbard and Scaturo 1985) while for the Indo-Pacific region *Porites* is regarded as the key coral (Buddemeier et al. 1974; Heiss 1995). Schlichter et al. (1997) measured quantitatively growth rates of selected zooxanthellate corals from the Gulf of Aqaba in relation to available light intensities.

Table 1 presents some selected data from literature including results which were achieved during our research within the framework of the German Priority Programme “Evolution of Reefs” (Dullo et al. 1994; Heiss 1995). In this table the geographical region is listed as well as the water depth and whenever available, few indications of the reef setting. All growth rate calculations presented in Table 1 are given in mm/year.

Generally, the coral growth falls into two major groups. The first one comprises all quickly and rapidly growing corals which mainly belong to the family Acroporidae and Pocilloporidae. Their growth rates reach around 100–150 mm/year for the Acroporidae, while for the Pocilloporidae it is a little less than 50 mm/year. The second group comprises the slower growing corals which have a more massive appearance. For the Caribbean region *Montastrea annularis* and *Montastrea cavernosa* are the major constituents. Their annual growth increments are in the order of 5–10 mm/year. *Porites* which also occurs in the Caribbean region, exhibits also quite a substantial annual growth increment in the order of 10 mm/year for the shallow-water region. In more deeper water settings, annual growth increments decrease to 4 mm/year. *Porites* species from the Indo-Pacific region have almost the same growth increments like their counterparts in the Caribbean Sea. However, it is noticed that even in the deeper water environment, for example between 10 and 25 m, the annual growth rate is still high with up to 7 mm/year respectively. Figure 1 presents these data graphically. The most surprising result, however, is that there is no real difference in the mean growth rate of the corals between the two reef provinces (Table 1).

Table 1 Growth rates of selected zooxanthellate scleractinian corals from the Caribbean and Indo-Pacific region

Species	Locality Caribbean Reef Province rate	Maximum mm/year	Reference
<i>Montastrea annularis</i>	Inshore <6 m, Florida	8.2	Shinn et al. 1989
	Offshore >6 m, Florida	6.3	Shinn et al. 1989
	Platform margin <3 m, Florida	11.2	Shinn et al. 1989
	Key West, Florida	5.8	Weber and White 1977
	Florida, 0–5 m	6.0	Huston 1985
	Virgin Islands, 9 m	10.4	Baker and Weber 1975
	Virgin Islands, 13.5 m	9.6	Baker and Weber 1975
	Virgin Islands, forereef, 10 m	7.6	Gladfelter et al. 1978
	Jamaica, 5 m	7.4	Huston 1985
	Jamaica, 45 m	1.6	Dustan 1979
	Curacao, 6–15 m	7.8	Huston 1985
	Belize	12.0	Weber and White 1977
	Pleistocene, Florida	5.0	Shinn et al. 1989
	Pleistocene, Florida	5.2	Landon 1975
<i>Montastrea cavernosa</i>	Jamaica, 10 m	3.6	Huston 1985
	Jamaica, 20 m	6.8	Huston 1985
	Jamaica, 30 m	4.1	Huston 1985
	Key West Florida	4.1 5.7	Weber and White 1977 Ghiold and Enos 1982
<i>Acropora palmata</i>	average Caribbean	90.0	Shinn et al. 1989
	Florida, <5 m	40.0	Huston 1985
	Curacao, <5 m	88.0	Huston 1985
	Virgin Islands, 1/2 m, leeward Virgin Islands, 9 m, windward	56.9 77.0	Gladfelter et al. 1978 Gladfelter et al. 1978
<i>Acropora cervicornis</i>	Jamaica, windward	180.0	Buddemeier and Kinzie 1976
	Jamaica, <5 m, windward	159.0	Tunncliffe 1983
	Jamaica, 6–15 m, windward	140.0	Tunncliffe 1983
	Jamaica, 25 m, windward	148.0	Tunncliffe 1983
	Virgin Islands, 10 m, Windward	71.0	Gladfelter et al. 1978
	Florida, <5 m, windward	105.0	Shinn 1966
	Florida, 1 m, leeward	45.0	Shinn 1966
	Florida, <5 m Barbados leeward	45.0 145.0	Huston 1985 Buddemeier and Kinzie 1976
<i>Colpophyllia natans</i>	Jamaica, 5 m	9.0	Huston 1985
	Jamaica, 10 m	8.1	Huston 1985
	Jamaica, 20 m	4.2	Huston 1985
<i>Diploria strigosa</i>	Bermuda	3.5	Dodge and Vaisnys 1980
<i>D. labyrinthiformis</i>	Florida	3.5	Ghiold and Enos 1982
<i>Solenastrea bournoni</i>	Florida Bay, leeward	8.9	Shinn et al. 1989
<i>Porites porites</i>	Florida	17.0	Landon 1975
	Caribbean	36.0	Landon 1975
	Pleistocene, Florida	10.5	Landon 1975
<i>Porites furcata</i>	Florida and Bahamas	23.0	Ghiold and Enos 1982
<i>Porites asteroides</i>	Jamaica, 0–1 m	5.0	Huston 1985
	Jamaica, 5 m	5.0	Huston 1985
	Jamaica, 10 m	3.3	Huston 1985
	Jamaica, 30 m	2.3	Huston 1985
	Virgin Islands, 2 m	3.4	Gladfelter et al. 1978
	Virgin Islands, 10 m	3.0	Gladfelter et al. 1978
	Florida	4.3	Ghiold and Enos 1982
	Florida, Bahamas	13.0	Ghiold and Enos 1982
<i>Dendrogyra cylindrus</i>	Florida	5.0	Shinn et al. 1989

Table 1 Continued

Species	Locality Caribbean Reef Province rate	Maximum mm/year	Reference
<i>Siderastrea siderea</i>	Jamaica, 10 m	7.1	Huston 1985
	Jamaica, 20 m	3.0	Huston 1985
	Jamaica, 30 m	3.1	Huston 1985
	Florida	2.7	Landon 1975
	Pleistocene, Florida	1.5	Landon 1975
<i>Favia fragum</i>	Florida	3.8	Ghiold and Enos 1982
<i>Manicina</i> sp	Florida	8.7	Ghiold and Enos 1982
<i>Agaricia agaricites</i>	Jamaica, 0–30 m	1.1	Huston 1985
	Average of all species	25.0	
Indo-Pacific Reef Province			
<i>Acropora</i> sp	Average	150.0	Buddemeier and Kinzie 1976
<i>Acropora</i> sp	Samoa	165.0	Huston 1985
<i>Acropora abrantooides</i>	Yapp	130.0	Huston 1985
<i>Astreopora myriophthalma</i>	Enewetak, 6–15 m	13.0	Huston 1985
	Enewetak, 16–25 m	5.5	Huston 1985
<i>Pocillopora</i> spp	Samoa, 0–5 m	35.0	Huston 1985
<i>Pocillopora damicornis</i>	Guam, 0–5 m	33.3	Huston 1985
	Guam, >25 m	18.1	Huston 1985
	Panama, 3 m	39.6	Glynn 1976
	Panama, 6 m	33.6	Glynn 1976
	Panama, 0–15 m	44.3	Huston 1985
<i>Pocillopora eydouxi</i>	Enewetak, 0–5 m	50.0	Huston 1985
<i>Psammocora</i> sp	Enewetak, 0–5 m	30.0	Huston 1985
<i>Pavona</i> sp	Samoa, 0–5 m	32.0	Huston 1985
<i>Pavona clavus</i>	Panama, 0–5 m	23.0	Huston 1985
	Panama, 6–15 m	19.0	Huston 1985
<i>Pavona gigantea</i>	Panama, 0–5 m	19.5	Huston 1985
	Panama, 6–15 m	17.0	Huston 1985
<i>Fungia fungites</i>	Enewetak, 6–15 m	12.0	Huston 1985
<i>Porites lutea</i>	Enewetak, 0–5 m	13.5	Huston 1985
	Enewetak, 6–15 m	11.0	Huston 1985
	Enewetak, 16–25 m	9.5	Huston 1985
	Enewetak, >25 m	6.0	Huston 1985
	Enewetak, 6–15 m	11.5	Huston 1985
<i>Porites lobata</i>	Enewetak, 16–25 m	6.0	Huston 1985
	Enewetak, 0–5 m	7.5	Huston 1985
<i>Favia pallida</i>	Enewetak, 6–15 m	7.0	Huston 1985
	Enewetak, 16–25 m	7.0	Huston 1985
	Enewetak, 26–30 m	6.5	Huston 1985
	Enewetak, 0–5 m	4.6	Huston 1985
<i>Favia speciosa</i>	Enewetak, 6–15 m	8.5	Huston 1985
	Enewetak, 16–25 m	7.0	Huston 1985
	Enewetak, 0–5 m	10.0	Huston 1985
<i>Goniastrea retiformis</i>	Enewetak, 6–15 m	9.5	Huston 1985
	Enewetak, 16–25 m	6.0	Huston 1985
	Enewetak, 0–5 m	12.5	Huston 1985
<i>Goniastrea parvistella</i>	Enewetak, 6–15 m	8.0	Huston 1985
<i>Platygyra lamellina</i>	Aqaba, 0–5 m	8.4	Heiss 1994
	Aqaba, 5–10 m	6.2	Heiss 1994
	Aqaba, 10–20 m	4.6	Heiss 1994
	Aqaba, >30 m	3.0	Heiss 1994
	Average of all species	25.7	

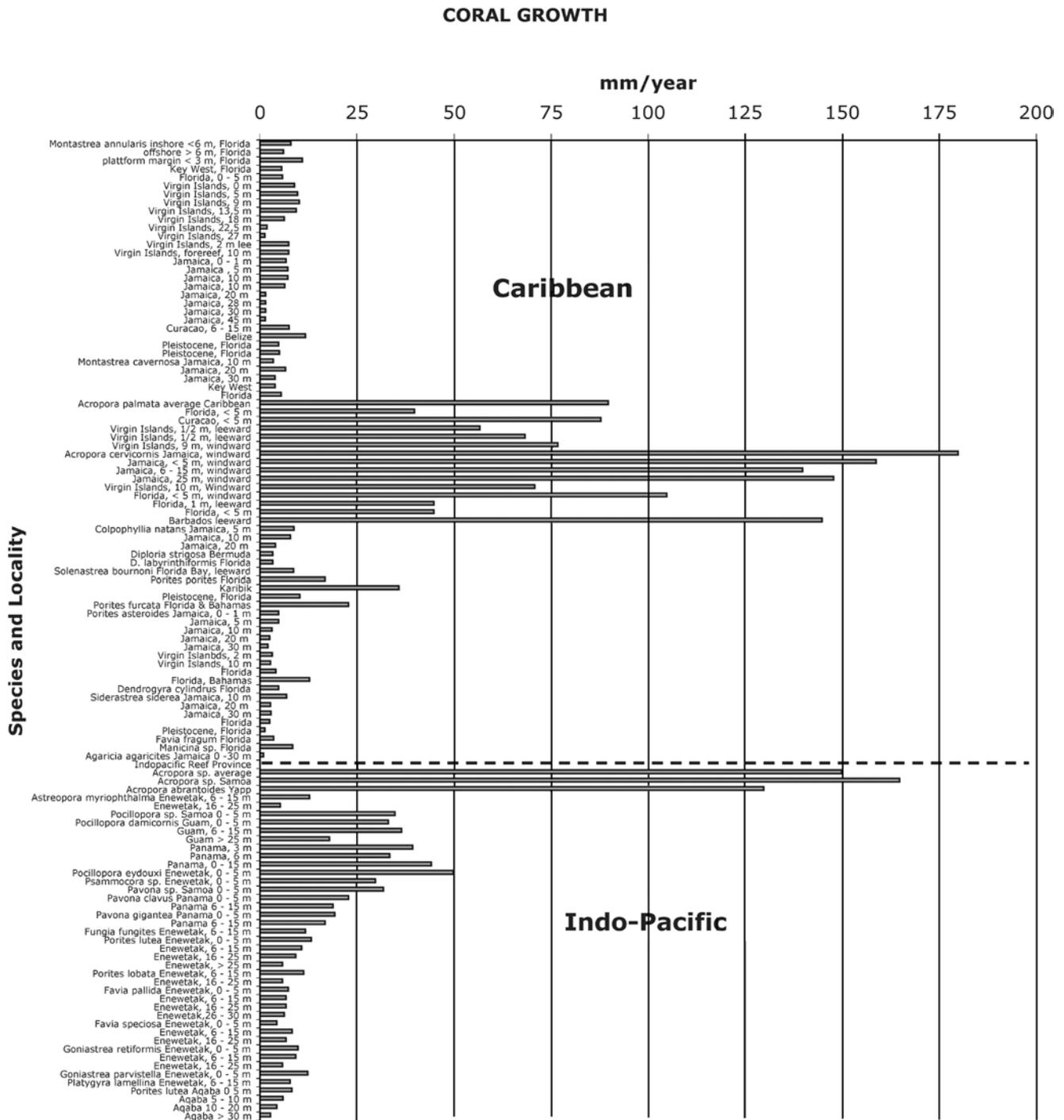


Fig. 1 Growth rates of selected zooxanthellate scleractinian corals from the Caribbean and the Indo-Pacific region. For references see Table 1

Holocene reef growths

The study of modern coral reefs started with the introduction of submersible rock drills by Macintyre (1975). A number of papers described in detail the lithologies and accretionary histories of reefs in a variety of different geological and geographical settings: Great Barrier Reef (Davies and Kinsey 1977; Hopley 1977; Hopley et al.

1978; Davies and Marshall 1979; Davies and Hopley 1983; Davies et al. 1985), Central Pacific (Marshall and Davies 1982; Montaggioni 1988; Cabioch et al. 1995, 1999; Bard et al. 1996; Montaggioni et al. 1997), Indian Ocean (Eisenhauer et al. 1993; Camoin et al. 1997; Braithwaite et al. 2000), Caribbean (Adey and Burke 1976; Macintyre and Glynn 1976; Adey et al. 1977; Halley et al. 1977; Macintyre et al. 1977; Adey 1978; Lighty et al.

Table 2 Growth rates of selected shallow-water coral reefs from the Caribbean and Indo-Pacific region

Holocene Reef growth			
Locality	Time-intervall	mm/kyr	Reference
Caribbean			
Alcaran, Mexico	8.9–7 ky	12000	Macintyre et al. 1977
Alcaran, Mexico	6.0–5 ky	6000	Macintyre et al. 1977
Galeta Point reef, average		3900	Macintyre and Glynn 1976
Belize		6000	Shinn et al. 1982
Panama		5000	Macintyre and Glynn 1976
Barbados	8.8–7 ky	13000	Fairbanks 1989
St. Croix	9.4–5 ky	15200	Adey et al. 1977
St. Croix		6000	Adey et al. 1977
St. Croix	9.4–6 ky	10000	Adey 1978
St. Croix, lagoon	6–3 ky	730	Hubbard et al. 1990
Florida		4850	Shinn et al. 1981
Florida, lagoon		1300	Shinn et al. 1981
Florida Bay		6500	Lighty et al. 1978
Florida long reef lagoon		650	Shinn et al. 1981
Caribbean average		6090	
Indo-Pacific			
Central GBR	7,5 ky	8000	Davies et al. 1985
Cook Islands	ca 9–1 ky	2200	Gray et al. 1992
Houtman Abrolhos	9.8–6.5 ky	7570	Eisenhauer et al. 1993
Aqaba	5 ky	670	own data
Aqaba	2.8–2.0 ky	1690	own data
Sanganeb	9.6–0.0 ky	1600	own data
Sanganeb	9.6–5.5 ky	6000	own data
Mayotte	9, 8–2 ky	2820	own data
Mayotte	9.6–7.2 ky	8570	own data
Réunion	8.0–1.0 ky	1700	Camoin et al. 1977
Réunion	7.4–6.9 ky	4400	Camoin et al. 1977
Indo-Pacific average		4411	

1978; Macintyre 1988; Hubbard et al. 1990) to cite a few. These studies provided substantial insights into the facies geometries of modern reefs and the processes shaping Holocene reef formation in relation to sea-level changes.

While the majority of these reef drillings were driven vertically into the reef crest, only the Holocene strata overlying the Eemian limestones of Marine Isotope Stage (MIS) 5 were recovered in the bore holes. The development of inclined drilling techniques provided new insights into the reef architecture and intermediate reef stages, even of glacial low sea-level stands. The most spectacular and most comprehensive reef history was recovered, when applying the techniques of inclined drilling into the Mururoa Atoll. Camoin et al. (2001) were able to demonstrate that during all marine isotope stages reefs existed back to MIS 11. Even the MIS 4 showed reefs in these inclined drill holes, a time during which reefs are believed to be absent (see Camoin et al. 2001).

Apart of this interesting new insight into the reef geometry, these reef drillings provided also important information of the growth potential and the recorded carbonate production. The major framebuilders and carbonate producers in terms of volume of carbonate in modern tropical shallow-water reefs are the scleractinian corals (Hubbard et al. 1990; Vecsei 2004). When comparing the growth rates

of the Indo-Pacific species *versus* the Caribbean species in Table 1 and Fig. 1, one might expect a higher accretion rate of the Caribbean reefs. In fact, the extremely quick growing species *Acropora cervicornis* and also the shallower species *Acropora palmata* are the dominating species of the Caribbean reef province providing this huge growth rate. The evaluation of data from the literature show that the average reef growth rate in the Caribbean is in the order of 6 m ka⁻¹ which equals 6,000 Bubnoff units (1 Bubnoff unit = 1 m Ma⁻¹ or 1 mm ka⁻¹; Fischer 1969). Table 2 presents a list of selected modern reefs of the Caribbean region and the Indo-Pacific region. The data presented in this table also indicate distinct time windows for some reefs for which the growth rate is given. Higher growth rates can be observed during Early Holocene. This is essentially valid for the time shortly after the onset of the Holocene reef growth. Their growth rates range up to 12,000 or even 15,000 Bubnoff Units.

Figure 2 shows the different growth rates of Holocene reefs graphically. This graph also displays the different growth rates for distinct reefs with respect to the time. Especially the data sets from Alcaran (Macintyre et al. 1977), St. Croix (Adey et al. 1977), Mayotte (Dullo et al. 1998; Zinke et al. 2003) and La Réunion (Camoin et al. 1997) demonstrate the difference between Early Holocene

HOLOCENE REEF GROWTH

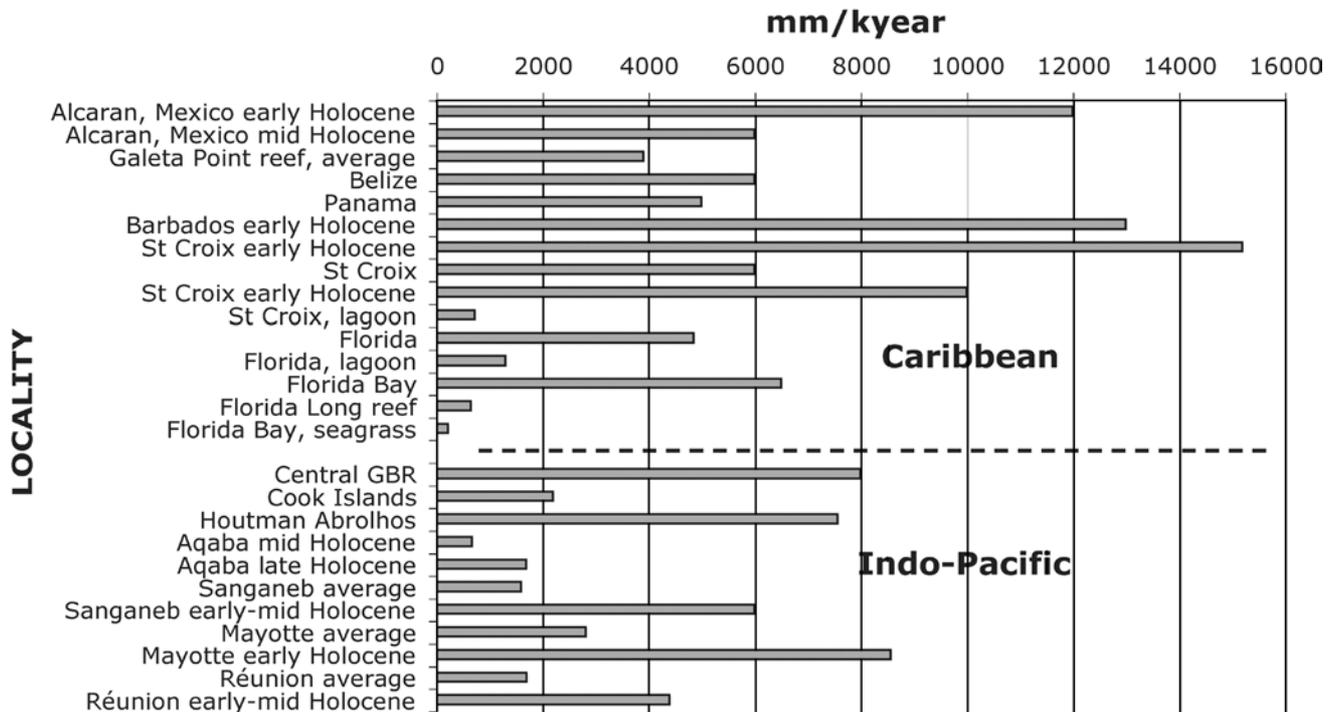


Fig. 2 Growth rates of selected shallow-water coral reefs from the Caribbean and the Indo-Pacific region. For references see Table 2

and Mid or Late Holocene clearly. The overall growth rate for example of the barrier reef of Mayotte is in the order of 2,800 Bubnoff Units while during the Early Holocene period, the reef growth was much accelerated and exhibited 8,570 Bubnoff Units.

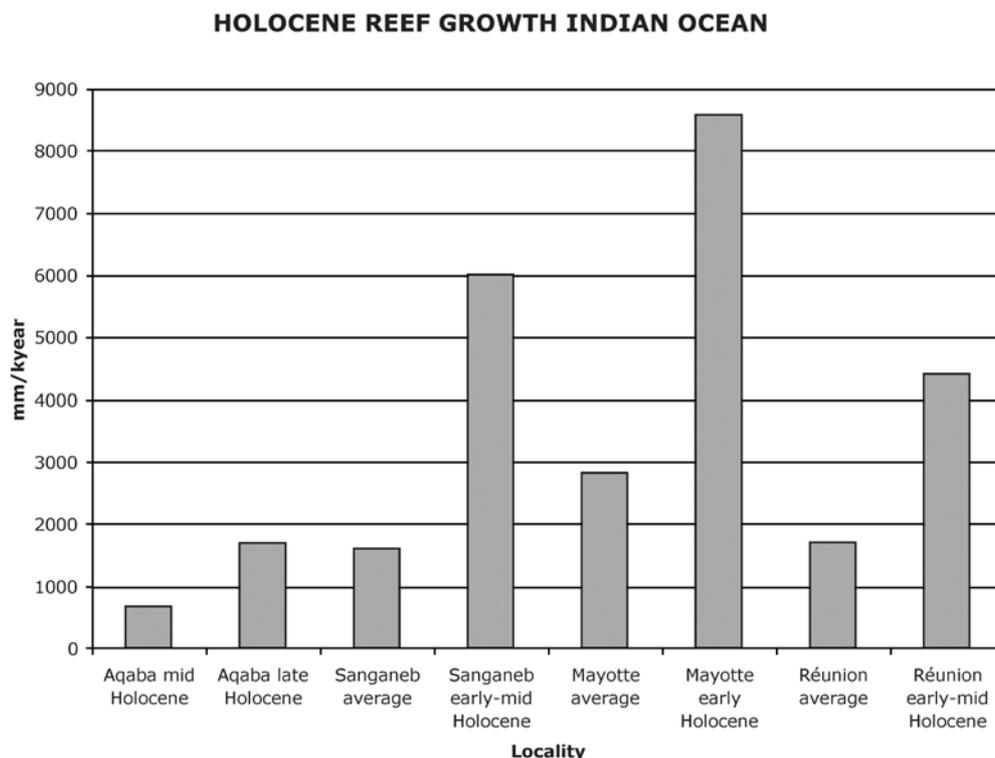
It is obvious that almost all Caribbean reefs exhibit a much higher growth rate, both during Early Holocene as well as during the entire Holocene period, which is not portrayed in the growth rate of their reef building corals. The global high growth potential of reefs during Early Holocene is sea level driven. However, during Mid Holocene time, sea level reached almost its present position in the Indo-Pacific (Camoin et al. 1997). The higher growth potential of Caribbean reefs in Mid and even Late Holocene time result from the siphoning effect of the Atlantic Ocean which still causes a rising sea level in the Caribbean region until today (Peltier 1991, 1999). Due to this effect, water masses are deviated from the Indo-Pacific into the Atlantic and mainly into the North Atlantic. This process, which is not restricted to the Holocene but is of general importance in relation to deglaciation, may have impacted on the growth rates of Caribbean reef corals as well.

In conclusion, the ratio of modern reef growth in the Caribbean *versus* the Indo-Pacific region is 3:2 (Table 2), unless unusual subsidence is involved (Montaggioni et al. 1997). Morphologically this is displayed in the fact that Indo-Pacific reefs are characterised by a well-established, highly cemented reef-flat, which is barren of living corals. Furthermore, most of the reefs all have a significantly re-

duced reef growth since Mid Holocene time when the siphoning effect enhanced its impact on modern sea level with respect to the inter-regional differences. In contrast, Caribbean reefs maintained their growth potential until present-day conditions. However, the onset of Holocene reef growth in both provinces occurred almost simultaneously around 9,800 years before present, exhibiting typical catch up reef growth rates, -geometries, and -patterns. Few exceptions may occur in both regions.

There is a gradient of coral growth rates with respect to latitude. This variation is also reflected in a different reef growth. Along a line through the western Indian Ocean, ending up in its northern appendix, the Red Sea, this gradient is well exhibited. Figure 3 displays the reef growth rates from Aqaba in the North to La Réunion in the southern Indian Ocean at the southern limit of reef formation. The data are compiled from the publication from Camoin et al. (1997) and own data. The graph displays two growth rates for the same reef according to two different time windows. One data set displays the entire reef growth from the Holocene onset up to present day, while the other data set focuses only on the time of accelerated reef growth of the Early Holocene. This graph demonstrates the reduced reef growth in the Indo-Pacific region for the last 5,000 years due to a stable or even lowered sea level (Peltier 1991). Furthermore, the latitudinal difference is clearly displayed. Mayotte with its closest position to the Equator exhibits the highest reef growth. In contrast, the reefs around La Réunion and the Sanganeb Atoll in the central Red Sea,

Fig. 3 Growth rates of selected shallow-water coral reefs from the Western Indian Ocean and the Red Sea region. For references see Table 2



both exhibit reduced values. The data of Aqaba demonstrate that this reef is located almost at the northern end of the tropical reef belt.

Modern deep-water scleractinian coral reefs and reef mounds are mainly formed by the azooxanthellate species *Lophelia pertusa*. This coral has an annual growth rate of about 10 mm y^{-1} (Freiwald et al. 1997). Based on these growth rates and an evaluation of the coral density and few absolute ages, Dorschel et al. (2005) concluded that these modern reef mounds have a growth rate between 6 and 7 cm ka^{-1} . As these data are the first and absolute ages from these modern mounds are still rare, any further discussion on this existing reef system is excluded from this review.

Growth rates of fossil reefs and carbonate platforms

The growth potential of fossil reefs and carbonate platforms is very difficult to evaluate. The major problem lies in the fact that absolute dating of these carbonate bodies is difficult to assess. Furthermore, with increasing age the uncertainty of biostratigraphical and absolute dating increases as well. Several authors published comparative accumulation rates for carbonates (Schwab 1976; Sadler 1981; Schlager 1981; Sarg 1988). However, these compilations do not consider all stratigraphic intervals and one of the most comprehensive studies covering the whole Phanerozoic was presented by Bosscher (1992).

The growth rate of reefs and carbonate platforms is mainly limited by the space available for accommodation. Therefore, the maximum rate at which a carbonate plat-

form can grow upward with its rim, or even flat top is directly linked to sea-level changes. On the other hand, the growth potential can also be evaluated by the rate at which the system can produce sediments. This last measure is an important factor in basin modelling programmes. Apart of the external sea-level control on the growth rates of fossil reefs and carbonate platforms, there also exist an internal control of the growth rates of the frame-building organisms. Growth rates may vary through time in relation to the evolution of the reef-building organisms (Fagerstorm 1987; Copper 1988; Wood 1999).

The data presented derive from the literature and mainly from the comprehensive compilation of Bosscher (1992). He used given stratigraphic thicknesses from cross sections and lithologic columns. The growth rate then was calculated by dividing the thickness of the carbonate platform or the fossil reef by the interval duration. The absolute duration of the stratigraphic interval was determined from stratigraphic boundaries and the international geological time scale (provided by Harland et al. 1982). The important factor of compaction was not corrected because the overlying rock column frequently is not well known for most of the given examples. Therefore, most of the rates presented are underestimated. All rates are given in m Ma^{-1} , which is equivalent to Bubnoff Units. The results of this compilation are given in Fig. 4; absolute values including the references are presented in Table 3.

From his data set Bosscher (1992) concluded that only a few carbonate platforms reach a growth rate of 200 Bubnoff Units or a little more. Most of the platforms, however, show growth rates in the order of 100 to 150 Bubnoff Units. Figure 4 exhibits a kind of rhythmicity

ACCUMULATION RATES OF REEFS

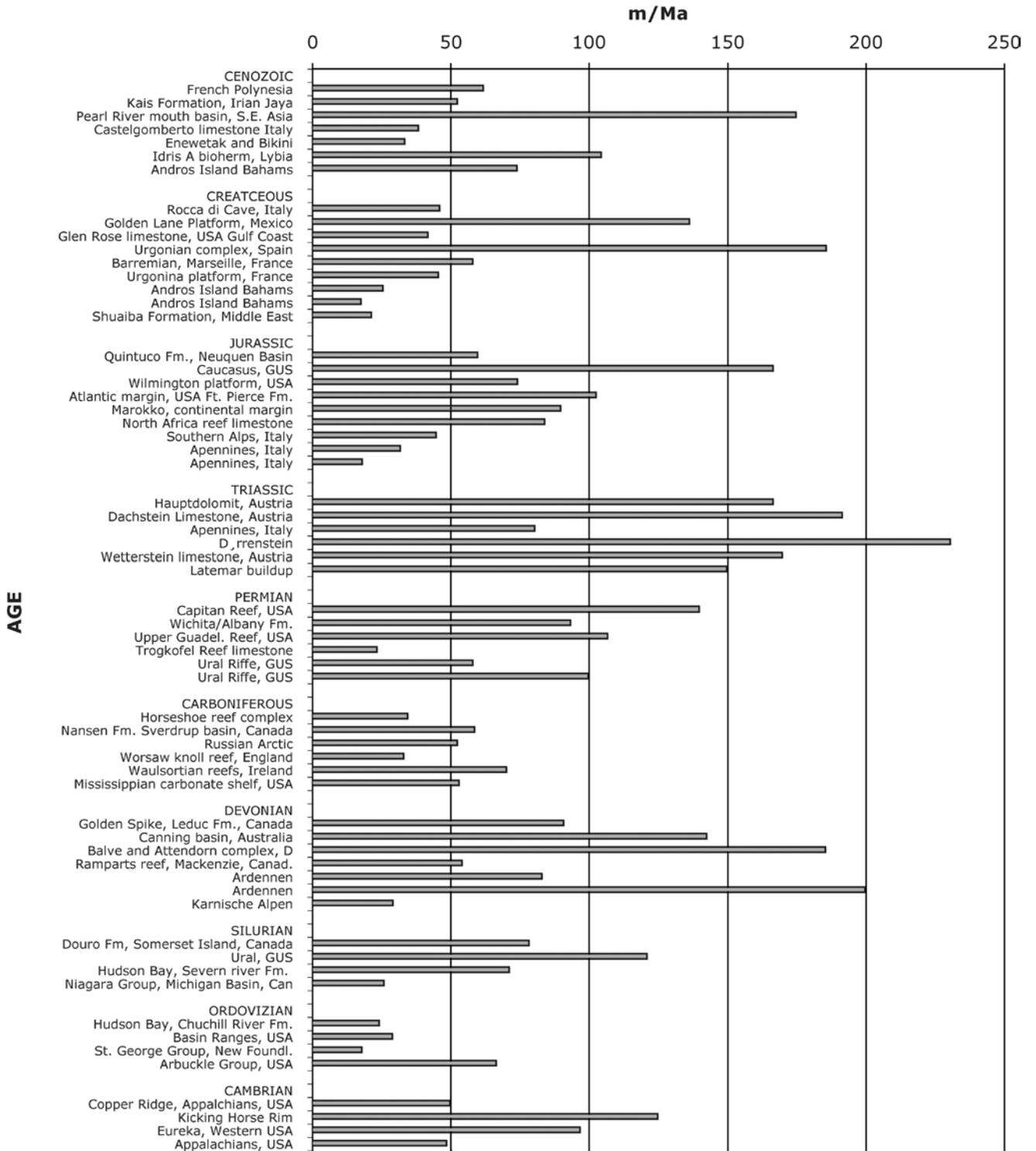


Fig. 4 Growth rates of selected reefs of the geological record. For references see Table 3

Table 3 Growth rates of selected reefs from the geological record

Locality	Acc. rate (m/Ma)	Reference
Cenozoic		
French Polynesia	62	Chevalier 1973
Kais Formation, Iran Jaya	52.7	Vincelette and Soeparjadi 1976
Pearl River Mouth Basin, S.E. Asia	175	Erlich et al. 1990
Castelgomberto limestone, Italy	38.5	Frost 1981
Enewetak and Bikini	33.5	Ladd 1973
Idris A bioherm, Lybia	104.6	Terry and Williams 1969
Andros Island Bahamas	74.1	Goodell and Garman 1969
Andros Island Bahamas	17.6	Goodell and Garman 1969
Cretaceous		
Rocca di Cave, Italy	46.2	Carbone and Sigma 1981
Golden Lane Platform, Mexico	136.4	Wilson 1975
Glen Rose limestone, USA Gulf Coast	42	Perkins 1985
Urgonian complex, Spain	186	Garcia-Mondejar 1985
Barremian, Marseille, France	58.3	Arnaud-Vanneau et al. 1982
Urgonina platform, France	45.8	Masse and Alleman 1982
Andros Island Bahamas	25.7	Goodell and Garman 1969
Andros Island Bahamas	17.8	Goodell and Garman 1969
Jurassic		
Quintuco Fm., Neuquen Basin	60	Mitchum and Uliana 1988
Caucasus, GUS	166.7	Wilson 1975
Wilmington platform, USA	74.4	Meyer 1989
Atlantic margin, USA Ft. Pierce Fm	102.7	Owens 1983
Marokko, continental margin	89.9	Ranke et al. 1982
North Africa reef limestone	84.2	Wilson 1975
Southern Alps, Italy	45	Winterer and Bosellini 1981
Apennines, Italy	32	D'Argenio et al. 1975
Apennines, Italy	18.2	D'Argenio et al. 1975
Triassic		
Hauptdolomit, Austria	166.7	Czurda 1972
Dachstein Limestone, Austria	191.7	Schwarzacher and Haas 1986
Apennines, Italy	80.6	D'Argenio et al. 1975
Dürrenstein	230.8	Schlager 1991
Wetterstein limestone, Austria	170	Ott 1972
Latemar buildup	150	Goldhammer and Harris 1989
Permian		
Capitan Reef, USA	140	Ross 1986
Wichita/Albany Fm	93.5	Ward et al. 1986
Upper Guadelupe Reef, USA	107	Saller et al. 1989
Trogkofel Reef limestone	23.6	Flügel 1981
Uralian mountains, reef limestone, GUS	58.3	Chuvashov 1983
Uralian mountains, reef limestone, GUS	100	Chuvashov 1983
Carboniferous		
Horseshoe reef complex	34.6	Wilson 1975
Nansen Fm. Sverdrup basin, Canada	58.8	Davies 1977
Russian Arctic	52.6	Nalivkin 1973
Worsaw knoll reef, England	33.3	Parkinson 1957
Waulsortian reefs, Ireland	70.4	Lees 1961
Mississippian carbonate shelf, USA	53.3	Rose 1976
Devonian		
Golden Spike, Leduc Fm., Canada	91	Walls et al. 1979
Canning basin, Australia	142.8	Playford 1980
Balve and Attendorn complex, D	185.7	Krebs 1974
Ramparts reef, Mackenzie, Canada	54.3	Muir et al. 1985
Beauchateau reef	83.3	Burchette 1981

Table 3 Continued

Locality	Acc. rate (m/Ma)	Reference
Couvain reef	200	Burchette 1981
Carnic Alps	29.3	Cantelli et al. 1982
Silurian		
Douro Fm, Somerset Island, Canada	78.6	Narbonne and Dixon 1984
Ural mountains, GUS	121.2	Nalivkin 1973
Hudson Bay, Severn river Fm	71.4	Dimian et al. 1983
Niagara Group, Michigan Basin, Can	26.1	Mesolella et al. 1974
Ordovician		
Hudson Bay, Churchill River Fm	24.4	Dimian et al. 1983
Basin Ranges, USA	29.2	Ross et al. 1989
St. George Group, New Foundl	18.1	Pratt and James 1982
Arbuckle Group, USA	66.7	Wilson 1975
Cambrian		
Copper Ridge, Appalchians, USA	50	Frazier and Schwimmer 1987
Kicking Horse Rim	125	Bond and Kominz 1984
Eureka, Western USA	97	Bond et al. 1989
Appalachians, USA	48.7	Read 1989

in that way that periods with growth rates of 100 to 150 Bubnoff Units alternate with longer periods of around 50 Bubnoff Units and even less. These periods of lower reef growth rates may also include more “deep-water” type reefs than others and therefore impacting on the growth rate pattern of through Earth history. A first cycle which shows a gradual and alternating increase in growth rates, ranges from the Cambrian up to the Devonian. The following Carboniferous and Permian time window exhibits again more reduced growth rates whereas in the Triassic, there is a kind of culmination of the second cycle, especially during the time of the Upper Triassic period. These Upper Triassic reefs show the maximum growth rates of all the carbonate platforms evaluated. However, the Jurassic, the Cretaceous and the Cenozoic display their own non-cyclic pattern.

The displayed accumulation rates or growth rates in Fig. 4 do not match the growth potential of the platforms. Most of the platforms in geological history show a strong progradation pattern even while growing upward. This clearly demonstrates that the vertical growth is limited by the availability of space for accommodation rather than by the growth potential of the frame-building organisms themselves.

The growth potential of a carbonate platform is the key function whether the platform can keep up with the creation of space for accommodation, in other words whether it can keep up with the rising sea level, or has to give up and may finally drown. Platform drowning is obviously a relatively short-term process (Mutti and Hallock 2003; Schlager 2003). As the optimum growth potential occurs bathymetrically in the range between 10 and 35–40 m of water depth, minor changes in sea level, but continuing in the same direction, may lead to the complete drowning of a platform (Schlager 1981) in connection with a significantly reduced carbonate production (Vecsei 2004).

Carbonate production by frame-building organisms has a major impact on the growth potential of reefs and platforms.

Therefore, the observed fluctuations may also represent evolutionary steps within the reef-building biota (Wood 1999). The dominant influence of the reef margins on the platform as a whole system may reduce the growth potential of the entire platform during a reef crisis. On the other hand, we have to note that during periods of decreasing sedimentation rates there is no parallel increase of drowning events. With respect to the Middle Cretaceous drowning events, which belong to the most pronounced ones in Earth history, we observe a very high platform accumulation rate (Schlager 1989). Although there is strong evidence that the subsidence rate during Earth history varied considerably (Ronov et al. 1980), there is no indication that these variations coincide with the variation in platform growth and carbonate production (Bosscher and Schlager 1993).

There is an obvious difference in the growth rate potential of modern reefs in comparison to their fossil counterparts. One of the major reasons for this can be attributed to the different amplitude in sea-level change. Only during the last 5 Million years of Earth history, the amplitude and frequency of sea-level fluctuations increased drastically (Tiedemann et al. 1994). However, we have to take into account that for all fossil data presented in Fig. 4, no correction for any compaction was calculated. The evaluation of the growth potential of fossil reefs on the base of measured and estimated growth rates of their constituting reef biota seem to be another approach.

Growth rates of few selected reefs being studied within the German Priority Research Programme “Evolution of Reefs”

Within the German Priority Research Programme “Evolution of Reefs” few authors addressed this question of reef growth and platform growth potential by measuring the individual growth rates of the major reef-building organisms.

Table 4 Growth rates of selected fossil reefs studied within the German Priority Research Programme: “Evolution of Reefs”

Locality	Reef growth (mm/ky)	Framebuilders (mm/year)	Reference
Portugal Upper Kimmeridge coral reef	1500	2	Nose (pers. com.)
Arnegg/Ulm Kimmeridge coral reef	4000	10	Latenser (pers. com.)
Rocha Unter Kimmeridge microbial reef	1000	1	Schmid (pers. com.)
Istein/Lörrach Oxford coral biostrome	4300	11	Latenser (pers. com.)
Gosheim Oxford sponge reef	2000	5	Krautter (pers. com.)
Lorraine Oxford coral reef	1600	11	Latenser (pers. com.)
Rumelange Bajoc coral reef	1800	2.3	Geister 1989
Capitan Guadelup—Kazan sponge reef	300	4	Weidlich/Noe (pers. com.)

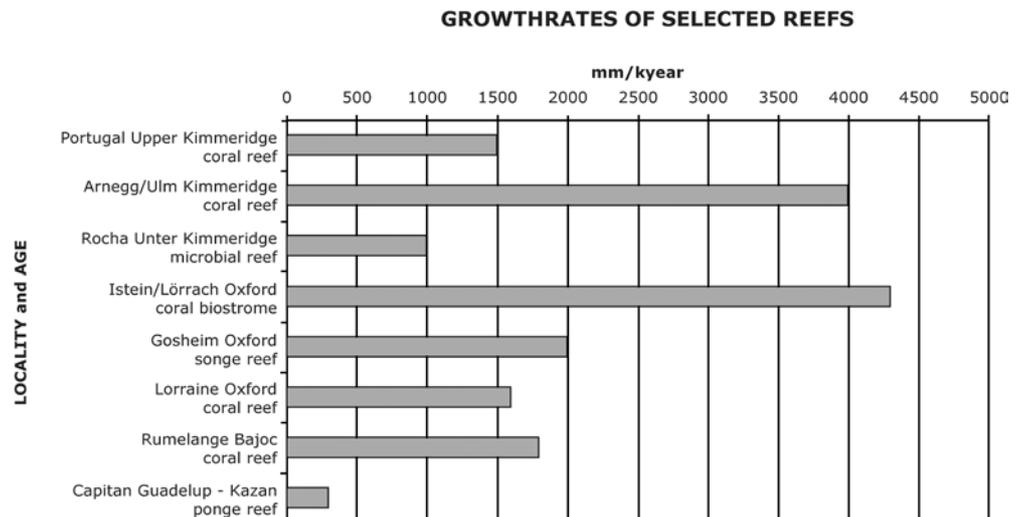
The first attempt to evaluate a fossil reef body under this point of view was given by Geister (1989). Table 4 lists the average growth rates of the major frame-building organisms of a few selected reefs. Furthermore, the major investigators are also indicated because most of these data are not published so far. The striking result of this table is that quite a number of Jurassic reefs exhibit growth rates of their frame-building organisms which are quite similar to those of modern massive scleractinian corals. Similar growth rates for some stony corals were published by Schäfer (1979) from Triassic reefs. However, these sponge-dominated reefs exhibit much lesser growth rates in total. They range in the order of 5 mm y^{-1} and even less. It is interesting to note that also the Middle Jurassic coral reef from Rumelange is characterised by reduced growth rates. Figure 5 shows these results graphically.

On the base of these average growth rates of frame-building organisms, the authors cited in Table 4, evaluated the overall growth potential of their studied reefs. A major factor controlling the growth rate of the reefs is the density of *in situ* frame-building organisms. These data were gained by applying a simple point-counting technique in the field. When compiling all these data, very different growth rates of these fossil reefs are the result. Most of the Jurassic reefs show a growth potential in the order of 1,500 to almost 2,000 Bubnoff Units. Two examples are displayed showing growth rates in the order of 4,000 and even 4,500 Bubnoff Units. These results are quite comparable to those growth

rates seen in modern reefs. Of course, there are many reefs, which exhibit much higher growth rates but in average they fit quite well (compare Figs. 2 and 5). Only few reefs from the Caribbean region exhibit double and even triple growth rates due to the special history of the Holocene sea level in this region.

This kind of estimate for growth rates based on point counting and individual growth-rate analysis of framebuilders of fossil reefs seems to be a more realistic approach than simply measuring the thickness of a carbonate platform or reef and dividing the thickness by the time interval of duration. This is because such a measure does not account for the huge volume of exported carbonate (Hubbard et al. 1990). Our attempt presented herein focuses more on the biological control of the carbonate production and the ability of the frame-building organisms to build-up carbonate structures. Hence, the still ongoing debate about drowning events in fossil reefs gets new input. As Schlager (1989) already pointed out, all reefs which existed during Earth history, had the ability to grow quicker than any sea-level change which occurred within the corresponding time window. The new data of fossil reefs (Table 5) which are one order of magnitude higher than those reported in the compilation of Bosscher (1992) clearly demonstrate that drowning events observed in Earth history are not the prime reason to impact seriously on the reef ecology itself. Therefore, drowning events can only occur if a reef community is already weakened. This

Fig. 5 Growth rates of selected fossil reefs studied within the German Priority Research Programme “Evolution of Reefs”. For references see Table 4



again stresses the fact of the ecological succession of reefs which were already discussed by Walker and Alberstadt (1975). The ecological life span of a reef could be a major control for the vulnerability by drowning events. In other words, if the climatic and oceanographic conditions do not permit the rejuvenation of a reef community, the whole community turns into a domination stage which is entirely characterised by reduced growth rates of framebuilders and reef growth at any given time during Earth history. In such a stage, rapidly changing sea levels may lead to the frequently observed drowning events in connection with a considerably reduced carbonate production.

Conclusions

Modern scleractinian corals show high growth rates in both of the present-day coral reef provinces. However, there is a significant higher growth rate, especially among the Acroporidae within the Caribbean. The higher growth rate of corals is also recorded in an enhanced reef growth potential of Caribbean reefs in contrast to their Indo-Pacific counterparts. Moreover, Caribbean reefs exhibit a prolific reef growth until present, without taking anthropogenic impacts into account, resulting in a flourishing reef crest and even reef flat. Indo-Pacific reefs flourish and grow mainly in the forereef area, while their reef crest is barren and well cemented. This results from the siphoning effect from the Atlantic increasingly deviating water masses from the Indo-Pacific region since the Mid Holocene. This is the time, when sea level reached almost its present position in the Indo-Pacific, while in the Atlantic sea level is still rising.

In comparison to fossil reefs, modern reefs exhibit much higher growth rates. Even, if one compares the highest growth rates, occurring in the Triassic, they are still 1.5 orders of magnitude lower than of recent scleractinian shallow-water coral reefs. These growth rates of fossil reefs derive from numerical division of the thickness of the reef body by the age, which in many cases is uncertain. However, a combination of point-count mapping of fossil framebuilders with known individual growth rates and carbonate accumulation may result in fossil growth rates almost identical to modern ones, as demonstrated by the few recently available studies on fossil reefs within the German Priority Research Programme "Evolution of Reefs," a fact which should be taken into account for global models.

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