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Reef coralgal assemblages as recorders of paleobathymetry and sea level changes in the Indo-Pacific province

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Abstract

The coralgal framework within the outer reef margin of many Indo-Pacific reefs exhibits three main shallow-water communities, the environmental significance of which can be inferred by comparison with their modern counterparts. A community dominated by tabular *Acropora* gr. *hyacinthus/cytherea* with branching *Pocillopora damicornis*, *P. eydouxi*, *Montipora digitata*, occasional domal faviids and mm-thick crusts of the coralline algae *Lithophyllum* and *Mesophyllum* (mainly), typical of the 6 – 15 m paleodepth range; a community including robust-branching *Acropora* gr. *danai/robusta*, *A. humilis*, *A. digitifera* and subordinate *Favia stelligera*, *Echinopora gemmacea*, associated to vermetid gastropods and thick coralline crusts of *Hydrolithon* cf. *onkodes* and *Neogoniolithon* cf. *fosliei* flourishing in depths less than 6 m; in medium-to-high water-energy settings, a community composed of domal *Porites* cf. *lutea* and *P.* cf. *lobata* with occasional *Acropora* gr. *danai/robusta* and cm-thick crusts of coralline algae in sheltered habitats in depths less than 10 m.

These biological assemblages allow us to determine relationships between reef growth and paleobathymetry and, consequently, to reconstruct regional relative sea-level curves. High water-energy reefal assemblages provide stronger evidence for reconstructing sea-level curves than low-energy buildups, because they have generally been controlled by a keep-up growth mode. Subsiding reef sites seem to be more reliable indicators of sea-level variations because they usually present expanded reef sequences. © 1999 Elsevier Science Ltd. All rights reserved.

1. Introduction



During the last few decades, our knowledge of postglacial sea-level changes has been greatly enhanced through studies of reef sites (Fairbanks, 1989; Bard *et al.*, 1990,1996; Chappell and Polach, 1991; Edwards *et al.*, 1993). The tropical zone offers the opportunity to examine sea-level changes and the melting history of continental ice sheets far from the polar zones (Bard *et al.*, 1996). Among sea level indicators available in tropical areas, morphological or diagenetic features such as marine notches and terraces, peats, benches or beach-rocks (Van de Plassche, 1986), and occasionally archeological remains have been the principal focus (Pirazzoli, 1991). Nevertheless, organic assemblages, and especially reef-

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building coral communities, are regarded as one of the most reliable sea-level markers (Lighty *et al.*, 1978; Davies and Montaggioni, 1985; Hopley, 1986; Montaggioni and Faure, 1997).

Corals older than 6 ka BP are not generally directly accessible from rapidly subsiding (e.g. intraplate volcanic islands) or slowly uplifting coasts (e.g. hydro-isostasyexperiencing areas). As a result, the only way to recover Early Holocene to Late Pleistocene samples is using drilling methods (Macintyre *et al.*, 1977; Hopley, 1982; Davies *et al.*, 1985; Montaggioni, 1988; Fairbanks, 1989; Chappell and Polach, 1991; Bard *et al.*, 1996); these provide opportunities to identify the paleocommunities involved in reef building (Marshall and Davies, 1982; Davies and Montaggioni, 1985; Davies *et al.*, 1985; Montaggioni 1988; Cortés *et al.*, 1994; Cabioch *et al.*, 1995; Kan *et al.*, 1995). Coral assemblages and coralline algae as well, can characterize reef biozones, because the distribution of many species depends mainly upon light levels

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and wave energy (Morton and Challis, 1969; Morton, 1973; Done, 1982; Faure et al., 1982; Davies and Montaggioni, 1985; Adey, 1986; Laborel, 1986). It is therefore relatively easy to reconstruct the successive stages of reef development, vertical growth and lateral accretion (Marshall and Davies, 1982; Partain and Hopley, 1989) reflecting variations in accommodation (i.e. space available for sedimentation; James and Bourque, 1992; Montaggioni and Faure, 1997). In addition to local climatic and hydrodynamic conditions, the initiation and development of coral reefs is also controlled by geodynamic factors; coastal subsidence, uplift or stability yield differing reef morphotypes (Chappell, 1980) and growth patterns. Two main reef growth strategies can be distinguished (Davies and Montaggioni, 1985; Davies et al., 1985; Neumann and Macintyre, 1985): (1) A keep-up strategy, in which reefs are able to maintain pace with sea-level rise. The relevant reef assemblages are composed of shallow-water, high-wave energy communities. (2) A catch-up strategy, in which reefs are not initially able to keep pace with sea-level rise, but catch up prior to coevally with, or after sea-level stabilization. The resulting reef assemblages typically include relatively deeper and less wave-resistant communities, which are progressively replaced upwards by shallower water forms, forming a shoaling-upward sequence.

In the frame of this study, three reef sites were selected: (1) Mauritius (Western Indian Ocean), a slowly subsiding, intraplate volcanic island (mean subsidence rate: 0.03 mm yr^{-1} , Montaggioni, 1978); (2) Tahiti (French Polynesia), a rapidly subsiding, intraplate volcanic island (0.25 mm yr^{-1} , Pirazzoli and Montaggioni, 1988; Bard *et al.*, 1996); and (3) New Caledonia (South West Pacific), a slowly subsiding passive margin (0.1 mm yr^{-1} , Coudray, 1976) (Fig. 1). The aim of this paper is to compare the responses of reef growth during postglacial sea-level rise in these different geodynamical settings, to discuss the validity of the paleodepth ranges determined from the



Fig. 1. General map of the Indo-Pacific realm, showing the reef areas studied. (A) location of the investigated sites; (B) La Pointe-au-Sable reef, Mauritius, western Indian Ocean; (C) Ricaudy reef, Nouméa, New Caledonia, south west Pacific Ocean; (D) Papeete reef, Tahiti, French Polynesia, central Pacific Ocean.

organic assemblages (corals, coralline algae and vermetids) and, finally, to assess the accuracy of the regional sea-level curves inferred.

2. Material and methods

In each area, only the material cored through the outer part of the reefs has been taken into account, in order to compare equivalent data sets. The nature and reliability of the criteria used to identify in situ coral samples varies according to growth shapes. The tips of branching colonies or the concave surfaces of tabular corals are normally oriented upwards during growth. There is little doubt as to their growth position in cores. In contrast, domal and plate-shaped colonies may simu-

CORALLINE ALGAE

late normal growth position after displacement (Lighty et al., 1982). The coralline algae generally form thick crusts over corals or subordinate builders; so, they cannot easily be reworked. Examination of the associated sediments may provide information on possible storminduced reworking.

Identification of the organisms forming reef communities in the cored reef sequences was performed at a specific level. By comparing the biozonation of their modern counterparts (see monographs and articles by Morton and Challis, 1969; Pichon, 1973; Adey et al., 1982; Faure, 1982; Richard, 1982; Delesalle et al., 1985; Adey, 1986; Laborel, 1986; Done and Navin, 1990; Veron, 1990), the different fossil assemblages were used as tools to paleoenvironmental reconstruction on the basis of depth range and water energy (Fig. 2).

Lower Mesophyllum prolifer Lithoporella melobesioides Lithophyllum moluccense ш Dermatolithon tessellatum ≥ Neogoniolithon fosliei Higher Hydrolithon onkodes

CORALS

Echinophyllia aspera Porites nigrescens Porites lutea Montipora digitata Acropora hyacinthus Acropora cytherea Acropora tenuis Pocillopora damicornis Platygyra daedalea Platygyra pini Echinopora gemmacea Millepora platyphylla Goniastrea retiformis Favia stelligera Leptoria phrygia Pocillopora verrucosa Acropora humilis Acropora digitifera Acropora danai Acropora robusta

VERMETIDS

Fig. 2. Modern distributional patterns of corals, coralline algae and vermetid gastropods recognized in the Postglacial/Holocene reef sequences studied.

Samples were examined using standard petrographic, binocular and scanning electron microscopy (SEM), X-Ray diffraction and specific staining techniques. Pointcounting from thin sections was used to determine the relative compositions of the framework-forming communities. Apparently, pristine samples (i.e. devoid of algal encrustations, borings, marine or freshwater cements and containing more than 98% aragonite) were dated using conventional or Accelerator Mass Spectrometry (AMS) ¹⁴C, and Thermal Ionisation Mass Spectrometer (TIMS) U/Th. The ages are given in calendar years BP (cal yr BP). The dates measured by ¹⁴C were converted to cal yr BP, using the calibration methods of Stuiver and Reimer (1993).

3. Reef sites

3.1. Mauritius

Mauritius lies in the western Indian Ocean at latitude 20°20'S and longitude 57°30'E (Fig. 1). The climate is characterized by a warm rainy season from November to May, and a drier season from June to October. Mauritius is regularly affected by cyclones. Sea surface temperatures (SST) range from 22°C (austral winter) to 27°C (austral summer).

The site studied is the 'Pointe-au-sable' fringing reef 1000 m wide, located on the north-west coast in a low-to-medium wave-energy environment. Three distinct zones are present along the reef margin (Montaggioni and Faure, 1980,1997).

The lower section of the outer reef slope (more than 25–20 m depth) is occupied mainly by the *Pachyseris/Oulophyllia* (*Pachyseris speciosa, Oulophyllia crispa*) community, characteristic of outer-reef sheltered habitats. The prevailing growth forms are laminar and domal. The species present are, in order of decreasing abundance, the ubiquitous *Porites lutea* and *P. lobata, Lobophyllia hemprichii, Favia pallida, Echinophyllia aspera, Acropora granulosa, Pocillopopra damicornis (coespitosa)* and *Hydnophora microconos*.

The middle parts of the outer reef slope (about 20 to 6–8 m depth) are occupied by an Acropora 'tabulate' and faviid community, linked to relatively sheltered or semiexposed habitats. Tabular colonies include Acropora gr. hyacinthus/cytherea, and to a lesser extent A. tenuis. Other forms are domal and massive, including Porites lutea, P. solida, Cyphastrea microphthalma, Astreopora ocellata, Goniopora sp., Oulophyllia crispa, Goniastrea retiformis, G. pectinata, Hydnophora microconos, Favites flexuaosa, Favia speciosa, Galaxea fascicularis, and Platygyra daedala. Subordinate coral species are Pocillopora verrucosa and P. eydouxi, Echinopora gemmacea, Lobophyllia hemprichii, Echinophyllia aspera, Montipora sp., Favia sp., and Favites sp. The upper parts of the outer reef slope (less than 6 m depth) are inhabited by a robust-branching *Acropora* community which is dominated by *Acropora robusta* and *A. danai*. This community is adapted to very shallow, wave-exposed settings. The associated builders include *Pocillopora verucosa*, the hydrocoral *Millepora platy-phylla*, *Acropora hyacinthus* and the massive encrusting *Goniastrea retiformis*, *G. pectinata* and *Favia stelligera*.

The reef crest is typified by the Acropora digitifera/A. humilis community, which is adapted to moderate-high water-energy. The main growth forms are characterized by robust branches. Other branching forms are Pocillopora damicornis ecomorph brevicornis, Acropora danai, Stylophora pistillata and Galaxea fascicularis, living in association with massive or encrusting forms (Leptoria phrygia, Porites lutea and Montipora cf. tuberculosa).

The backreef zone is occupied by a *Pavona* community, which is restricted to protected habitats. The dominant corals are foliaceous, *Pavona cactus*, *P. divaricata*, *P. decussata*, in close association with branching or domal colonies of *Porites nigrescens*, *Seriatopora hystrix*, *Synarea iwayamaensis* and *Porites lutea*.

3.2. New Caledonia

New Caledonia lies in the southwest Pacific (Fig. 1) between latitudes $20^{\circ}-23^{\circ}$ S, longitudes $164^{\circ}-167^{\circ}$ E. It is surrounded by one of the largest reef systems in the world. Southeastern trade winds prevail during the austral summer from November to April (Rougerie, 1986). During winter, from May to October, the trade-wind regime is disturbed by westerlies generated by polar air masses. Cyclones originate in the Intertropical Convergence Zone between 8 and 18° S in the Northern Central and Eastern Coral Sea. Sea surface temperatures (SSTs) range from 23°C during the austral winter to 28°C in the austral summer. Fringing reefs on the southwest coasts enjoy relatively sheltered conditions, due to a well developed outer barrier reef.

The study site, Ricaudy reef, 300-400 m wide, is situated in the Nouméa area, SW of the island. The outer reef flat zone is colonized dominantly by branching Acropora and domal Porites. Windward reef slopes, similar to that of Ricaudy, were investigated on neighbouring reefs in the Nouméa lagoon (Faure et al., 1982; Cabioch et al., 1995). The corals on the reef crest are represented by Acropora digitifera, A. humilis, A. millepora, A. variabilis, Pocillopora verrucosa, Acropora abrotanoides and A. robusta. The assemblages from 1 to 2 m depth are composed of Acropora digitifera, Pocillopora damicornis, P. verrucosa, domal faviids and branched or tabular Acropora spp. From 2 to 8 m depth, the assemblages are dominated by Acropora hyacinthus, A. clathrata, A. cytherea, and various other Acropora spp., Pachyseris rugosa, Pavona clavus, P. praetorta, Lobophyllia corvmbosa, Echinopora lamellosa, Pectinia lactuca. The assemblages, from 8 to 10 m, include domal colonies of *Porites lutea*, *Platygyra daedala*, *Leptoria phrygia*, *Stylophora pistillata*, *Pocillopora* cf. *danae*, *Acropora formosa* and *A. palifera*.

3.3. Tahiti

Tahiti which forms part of French Polynesia is situated between latitude 17°50'S and longitude 149°20'W (Fig. 1). The climate is subdivided into two seasons, a hot and rainy summer from November to April, and a drier season from May to October. The nutrient and freshwater inputs in the backreef areas vary greatly according to the season and higher levels are reached during summer time. The southeast and northeast winds influence the hydrological regime significantly; both generate strong swells, along the eastern side of the island. Thus, the reef site selected, facing Papeete harbour, is subject to high-energy-water conditions. Swells are generally up to 2 m in amplitude. Sea surface temperatures (SSTs) range from 24°C in the austral winter to 29°C in the austral summer.

On Papeete reef, the upper parts of the outer reef slope (less than 6 m deep) are composed mainly of robustbranching Acropora spp. (dominantly, Acropora gr. danai/robusta), Pocillopora verrucosa, associated to Montipora erythraea, Montastrea curta, Porites lobata and various domal forms (Favia and Favites sp.), occasionally covered by coralline algae, especially Hydrolithon and Neogoniolithon. The outer parts of the reef flat are characterized seawards by the occurrence of cm-thick coralline algal crusts; there is no true algal ridge in the sense of Adey (1986). Behind the reef front rim is a zone of coral patches composed of branching corals, such as Acropora gr. danai/robusta, Acropora cytherea, Pocillopora verrucosa, and domal forms, Porites australiensis and P. lutea. The reef tract is less than 600 m wide.

4. Lithology and distribution of reef communities in cores

4.1. Mauritius

At Pointe-au-sable, the Holocene reef sequence overlies a karstified Pleistocene coral reef. It is composed mainly of apparently in situ coral colonies intermingled with coarse-grained skeletal detritus (Fig. 3). The coral builders are generally branching and domal forms,

Fig. 3. (A) Distribution of the coral assemblage in La Pointe-au-Sable reef sequence, Mauritius island. (B) Sea-level curve inferred from the biological data.

encrusted by coralline algae and foraminifera (Montaggioni, 1988; Camoin *et al.*, 1997; Montaggioni and Faure, 1997). Beneath the outer reef margin, the sequence exhibits three main coral units, from the base to top.

The lower unit consists chiefly of tabular and/or branching corals, Acropora gr. hyacinthus/cytherea, Pocillopora verrucosa, P. damicornis and Porites nigrescens. Associated species exhibit various growth forms; they include Echinophyllia aspera, Porites cf. lutea, Echinopora gemmacea, Leptastrea sp., Alveopora sp., Platygyra pini, and Montipora sp.

The upper unit is typified by robust-branching acroporids, Acropora gr. danai/robusta, A. digitifera and A. humilis, associated with branching Pocillopora verrucosa and P. damicornis and domal forms, Porites cf. lutea, Leptoria phrygia, Platygyra daedalea, Goniastrea retiformis and Favia stelligera. Subordinate forms include Millepora platyphylla, Echinopora gemmacea, Cyphastrea sp., and Leptatstrea sp.

4.2. New Caledonia

The cores drilled on the Ricaudy site indicate that the Holocene reef sequence overlies a Pleistocene karst surface. This sequence exhibits three biofacies distributed within two distinct units (Fig. 4) (Cabioch et al., 1995). The lower unit displays a tabular branching coral facies with in-place Acropora gr. hyacinthus/cytherea, Montipora digitata and other acroporids. The upper unit is made up of domal Porites heads, alternating with Acropora rubble. Cores obtained from the tradewind exposed, eastern part of the reef are more cavernous than those recovered in the sheltered western part. Differences lie in the relative abundance of coralgal framework in the most exposed zones and in the prevalence of detrital beds in the most protected areas. An interesting feature is the absence or scarcity of coralline algal veneers, which are only represented by thin Lithophyllum crusts. Encrusting algae are replaced by encrusting foraminifera, which are more abundant in Ricaudy reef than in any other reefs drilled in New Caledonia (Cabioch, 1988).

4.3. Tahiti

Drilling through the outer barrier reef showed that it consists of an about 87 m thick sequence, ranging in age from about 14,000 cal yr BP to the present (Fig. 5) (Bard *et al.*, 1996). The cores exhibit an in situ coralgal-stromatolite framework, locally filled by uncemented

(1): after Baltzer, 1970, Coudray et Delibrias, 1972 & Cabioch et al., 1989.

Fig. 4. (A) Distribution of the coral assemblages in the Ricaudy reef sequence, New Caledonia. (B) Sea-level curve inferred from the biological data.

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Fig. 5. (A) Distribution of the coral assemblages in the Papeete reef sequence, Tahiti, French Polynesia. (B) Sea-level curve inferred from the biological data.

skeletal deposits (Montaggioni and Camoin, 1993; Montaggioni et al., 1997). From the base to top, the coral assemblages are characterized by robust-branching corals, Acropora gr. danai/robusta, A. humilis, Pocillopora cf. verrucosa, with domal Porites spp. At the base, a 1 mthick coral bed is dominantly formed by Acropora gr. danai/robusta colonies. It is sharply replaced by a thick domal Porites buildup (especially Porites cf. lobata). Upwards, the framework consists chiefly of robust-branching Acropora gr. danai/robusta, A. humilis and Pocillopora cf. verrucosa. Coralline algae are intermingled with the corals, locally forming cm-thick encrusting layers. Hydrolithon onkodes is abundant, mixed with Tenarea, Lithophyllum spp. (with L. cf. molluccense as the commonest species), Lithoporella melobesioides, Dermatolithon cf. tesselatum, Mesophyllum cf. prolifer and a few Neogoniolithon cf. fosliei. Subordinate builders include sessile foraminifera (homotremids, victoriellinids and acervulinids) and boring vermetid gastropods (Dendropoma).

5. Discussion

5.1. Reliability of reef biomarkers in reconstructing relative sea-level curves

In the Indo-Pacific province, a number of relative sea-level curves have been reconstructed using a variety of biological markers (Pirazzoli, 1991). Among these, tropical coralgal communities appear to be one of the most helpful tools (Bloom *et al.*, 1974; Hopley, 1986; Montaggioni, 1988; Yonekura *et al.*, 1988; Chappell *et al.*, 1996).

Distributional patterns of reef-building organisms depend essentially on light intensity, wave-energy conditions, nutrient and freshwater inputs (see Morton and Challis, 1969; Pichon, 1973; Adey, 1975; Littler and Doty, 1975; Adey *et al.*, 1982; Faure, 1982; Richard, 1982; Bosence, 1984; Adey, 1986; Laborel, 1986; Hopley, 1989; Done and Navin, 1990). The relative curves based of such patterns vary in reliability because they depend on the accuracy of the estimated paleodepth ranges used. This implies that the species in the biota have to be correctly identified and related to characteristic, well-defined habitats (Fig. 6). Thus, typical forms of coral colonies (tabulate, branching, domal and foliaceous) and of coralline algal thalli (thick or thin encrusting or branching veneers) can be recognized. The distribution of these typical coralgal forms is related to water energy, irradiance and depths and can be summarized as in Fig. 7. In Pacific atolls which are subject to very strong hydrodynamic conditions, the distribution of coral assemblages around the outer rim is dominantly constrained by wave energy. The depth range of a given coral species can vary markedly from windward-to-leeward sides (Fig. 8) (Bablet *et al.*, 1995). This underlines the need to only use biozonation obtained from reef areas close to drilling sites.

In addition, it is necessary to define the status of each organism or community: are they in situ or have they undergone *post-mortem* transport and reworking?

Analyses of the cores available led us to identify three main coralgal assemblages, on the basis of dominant growth forms and specific composition (Chappell, 1980; Montaggioni and Faure, 1997). Paleodepth ranges of these fossil reef communities are given by reference to those of their counterparts at present living in adjacent areas (Fig. 2).

(1) The tabular coral facies (Fig. 6) is mainly composed of Acropora gr. hyacinthus/cytherea associated with Pocillopora damicornis, P. eydouxi, Montipora digitata and

Fig. 6. Idealized reef profile, showing the relationships between the modern biozonation at reef margins, ambient water-energy and the distributional and growth patterns of the coral communities recognized in the drilled postglacial sequences.

Fig. 7. Schematic summary of distribution of the coralalgal assemblages identified in the modern Indo-Pacific reef environments in relation to water energy, irradiance and water depth.

various other acroporids. This facies is encountered in the sequences studied in Mauritius and along the outer slopes of reef islets in Nouméa lagoon (Faure, 1982). By reference with the distribution of its present-day analogs, this assemblage is regarded as typical of open water, low-to-medium wave-energy settings. This is confirmed by underwater observations in other Pacific areas (Done, 1982; Marshall and Davies, 1982; Veron, 1990). Thin coralline algal crusts, less than 5 mm, which cap corals, are generally composed of Hydrolithon onkodes, Lithophyllum sp., Mesophyllum cf. prolifer and Dermatolithon cf. tesselatum, which are diagnostic of low to moderate wave-energy conditions (Fig. 2) (Adey et al., 1982; Adey, 1986). The relevant habitat paleodepth ranges from about 6 - 15 m. When this coralgal assemblage (referred to as the middle forereef, MF assemblage) is encountered in a core section, it indicates that, at the time of growth, the buildup was submerged, i.e. was following a catch-up growth trend (Fig. 6).

(2) The robust-branching coral facies (Fig. 6) is usually formed by *Acropora* gr. *danai/robusta*, *A. humilis*, *A. digitifera*, *Pocillopora verrucosa* and various domal *Porites*. Compared to the modern reef zonation, this assemblage can be regarded as diagnostic of medium to high-energy, reef crest or upper forereef zone, at depths less than 6m below mean low tide level. This assemblage is a common feature on Indian Ocean and Pacific reefs (Faure, 1982; Faure and Laboute, 1984; Delesalle et al., 1985; Camoin and Montaggioni, 1994). Encrusting coralline algae form relatively thick veneers (up to 4 cm thick) over corals. These include Hydrolithon cf. onkodes, Dermatolithon cf. tesselatum Lithophyllum cf. molluccense and Neogoniolithon cf. fosliei, which are abundant in the upper parts of the outer reef zones and on reef edges, as recognized elsewhere, e.g. in the Solomon islands (Morton, 1973) and Hawaiian islands (Adey et al., 1982). This community is associated commonly with vermetid gastropods such as Dendropoma maximus and Serpulorbis annulatus, restricted to less than 3 m depth below spring low tides (Richard, 1982; Laborel, 1986). The robustbranching coral/Hydrolithon/vermetid assemblage (referred to as the reef-edge, RE assemblage) is therefore regarded as characteristic of near-surface settings (0-6 m) (Fig. 6). It is regarded as the bathymetric counterpart of Acropora palmata/Lithophyllum congestum/Hythe drolithon pachydermum assemblage described from the

Fangataufa atoll reef-crest and outer reef slope

Fig. 8. Zonation of the main coral species living on the outer reef margin of Fangataufa atoll (modified from Bablet et al., 1995).

Caribbean (Lighty *et al.*, 1982). Both assemblages generally are related to a keep-up reef growth type.

(3) The domal coral facies (Fig. 6) includes *Porites* spp. (*Porites* cf. *lutea* and *P*. cf. *lobata*) accompanied by occasional *Acropora* gr. *danai/robusta*. By analogy with the environment of its modern counterpart, this assemblage is believed to reflect a more sheltered habitat, corresponding to the inner part of the reef crest or the outermost section of the backreef (Faure and Laboute, 1984; Bouchon, 1985; Kühlman and Chevalier, 1986). The paleodepth interval of these paleocommunities (i.e. the upper to middle forereef assemblage) is presumably less than 10 m. Generally, encrusting algae are not abundant. Locally, thin veneers of *Hydrolithon* cf. *onkodes* or *Dermatolithon* cf. *tesselatum* are found (Fig. 2). This coralgal assemblage is related to reefs having a keep-up growth style.

The composition and distribution of these three assemblages can vary significantly from reef to reef in response to local environmental factors (Fig. 6).

In Mauritius, two coralgal communities are encountered in the Holocene sequence from base to top (Fig. 3). The occurrence of a bed of robust-branching coral facies at the base indicates a short episode of keep-up growth. However, this facies is replaced upward by a tabularbranching coral assemblage which characterizes a catchup growth phase reflecting an increase in the rate of the sea-level rise. The communities at the top of the core correspond to robust-branching coral facies. These clearly reveals that reef growth has operated close to the sea surface. In the Mauritius sequence, the high-diversity coral assemblages include both finite sea level-markers, i.e. corals indicating paleobathymetry, and directional markers, i.e. corals providing data on paleo-reef geometry, in the sense of Montaggioni and Faure (1997). Thus, the robust-branching *Acropora* gr. *danai/robusta*, *A. humilis* and *A. digitifera* are finite indicators; they are considered to be the most reliable of Indo-Pacific paleodepth indicators, living generally within a narrow optimum depth interval from 0 to 6 m. Other coral species may be also finite sea-level recorders (*Goniastrea retiformis*, *G. pectinata*, *Favia stelligera*, *Stylophora pistillata*, *Montipora tuberculosa*, and *Millepora platyphylla*) encountered at depths not greater than 10 m. The remaining coral species studied here, are only directional indicators.

At Ricaudy (New Caledonia), the base of the Holocene sequence is characterized by a tabular coral facies (Fig. 4). This reveals that coral settlement was delayed after flooding of the Pleistocene substrate. The following phase of vertical accretion is typified by domal coral facies replaced by a robust-branching facies, indicating changes in wave energy (i.e. in bathymetry), as the buildup was catching up to rising sea-level. The final phase of reef growth is characterized by an abundance of domal coral heads.

In French Polynesia, the initiation of the Papeete reef occurred at 14 cal ka BP (Bard *et al.*, 1996) with the settlement of a robust-branching coral community, indicating the early ability of the builders to keep-up with sea-level (Fig. 5). However, at 13.5 cal ka BP, the rate of sea level rise increased, precluding the possibility of the reef keeping pace with sea level rise. This event is reflected in the settlement of a domal coral assemblage. At 12.0 cal ka BP, its replacement by a robust-branching coral facies indicates a return to a keep-up growth mode, which has persisted until now.

5.2. Testing the accuracy of paleodepths inferred from reef communities

For each reef site studied, the calendar age of each dated coral sample is plotted against depth below present mean low tide level. The vertical bar above each point (Figs. 3–5) represents the paleodepth interval, defined by reference to its modern community counterpart (see above), and within which the coral could have grown. Samples from robust-branching and domal coral assemblages reflect paleodepths of less than 6 m and less than 10 m, respectively, while samples from tabular coral communities indicate depth-restricted habitat ranges of about 6–15 m.

From the Mauritius data (Fig. 3), a minimum sea-level curve for the past 7500 cal yr BP can be constructed by drawing a line at a median position on the coral time-depth plot (Montaggioni and Faure, 1997).

The accuracy of coralgal assemblages as sea-level recorders can be tested in New Caledonia. In this area, a relative sea-level curve has already been obtained, based on dating of mangrove peats (Baltzer, 1970), notch-encrusting and emerged corals (Launay and Recy, 1972; Coudray and Delibrias, 1972; Cabioch et al., 1989). This curve reveals a continuous sea level rise from 8030 to 6360 cal yr BP, followed by an apparent fall from 6360 cal yr BP to present (Fig. 4). This apparent sea-level course is though to be caused by local isostatic and gravitational adjustments, following the sea level rise 18 kyr ago (Clark et al., 1978; Nakada and Lambeck, 1991). The reef-based curve obtained by drawing a line at a median position on the coral time-depth plot appears to be consistent with this curve (Fig. 4). Although no date older than 6400 yr cal BP is available, we infer that the method, based on the taxonomic identification of biological assemblages, is sufficiently precise to reconstruct any local relative sea-level envelope. This method was successfully applied in Tahiti (Fig. 5). The sea-level curve established for the last 14000 yr BP (Bard et al., 1996), is in good accordance with the sea-level curve obtained for the same period from reef material in Barbados (Fairbanks, 1989; Bard et al., 1990). However, it is important to realize that coralgal and coral assemblages may not record short-term or low-amplitude sea-level fluctuations or the short-term stillstands liable to occur during a period of general sea-level rise, due to the lag in response of coral growth.

In a recent study on the Tahiti barrier reef, we used multivariate methods in order to determine the precise significance of the coralgal assemblages in terms of water depths (Cabioch et al., in press). We do not report details of the analyses herein; we just give the principal features and conclusions. A correspondence factor analysis (Rmode) was performed on 11 variables (major contributing organisms) from 121 observations (thin-sections) extracted from five cores (down to 90 m deep). Two groups can be delineated: a group related to open shallow water, high-to-moderate energy environments, and another group regarded as typical of deeper, and/or more protected habitats, subjected to lower light intensity. The multivariate methods appear to be good discriminators of local ecological conditions, but do not give a more accurate differentiation of reef builders in terms of water depths. Similar analyses were also performed on cores from various reef areas; they lead to similar results (for instance, see Cabioch, 1988, for data sets on New Caledonian reefs).

5.3. Accuracy of relative sea-level curves with respect to the timing of substrate colonization and growth patterns

The rate of coral settlement after substrate inundation is one of the factors determining the characteristics of the internal stucture and the ability of a reef to keep-up or catch-up with sea level (Davies and Montaggioni, 1985; Davies et al., 1985; Montaggioni, 1988). Assessment of the precise timing of reef initiation is a prerequisite for any reconstruction of sea-level curve, because the delay in reef settlement may distort the older sections of a given sea-level curve. On Mauritius, for instance, the flooding of the inner shelf occurred at 8400-7400 cal yr BP, while reef initiation began within a 1000 yr time span, at around 7400 cal yr BP (Montaggioni and Faure, 1997). In contrast, at Ricaudy, the substrate was only colonized as sea level reached its present position; but, growth has been sufficiently rapid for the reef to catch-up with sea level within a time span of less than 1000 yr. For many Indo-Pacific reefs, initiation appears to have occurred within the same period of 9600-7400 cal yr BP (Johnson et al., 1984; Davies et al., 1985; Hopley and Barnes, 1985; Montaggioni 1988; Partain and Hopley, 1989; Eisenhauer et al., 1993; Cabioch et al., 1995; Kan et al., 1995). However, on the rapidly subsiding island of Tahiti (up to 0.25 mm yr⁻¹, see Bard et al., 1996; Montaggioni et al., 1997), and at Huon Peninsula (Papua-New-Guinea), uplifting at the rate of 2 mm yr⁻¹ (Chappell and Polach, 1991; Edwards et al., 1993), the initiation event appears to have occurred earlier, around 14000 cal yr BP, while on the rapidly uplifting Vanuatu site (up to 5.5-6 mm yr⁻¹, see Cabioch *et al.*, 1998), this event occurred at around 20000 cal yr BP. It is noteworthy that Chappell and Polach (1991) and Edwards et al. (1993) do not give any accurate identifications of the reef builders encountered in the core of Papua New Guinea and on their environmental significance. Consequently, their

curves appeared to be a simple reef growth curve. Nevertheless, the brief description given on reef builders seems to indicate a keep-up reef growth strategy and, fortunately, the reef growth curve appears to be very close to the sea-level curve. Given that the rates of vertical motion which affect reef-bearing areas are negligible compared to the rate of postglacial sea-level rise, the regional geodynamical constraints have little influence on the age of reef initiation. However, they can drastically control the thickness of postglacial reef sequences which are expanded in rapidly subsiding areas and condensed in rapidly uplifting zones. In many regions, reef growth appears to have initiated non-uniformly, according to a latitudinal gradient. Such gradients are reported from the Great Barrier Reef (Davies et al., 1985) and the New Caledonian region (Cabioch et al., 1995). One plausible explanation for the time offset of reef initiation in these areas is the occurrence of a karst surface upon which reefs settled (Hopley et al., 1978; Cabioch et al., 1995). The roughness of these karst surfaces may have facilitated the recruitment and attachment of coral larvae and successfully catalyzed coral growth. We infer, therefore, that the best sites for using coral reefs as sea-level indicators should be areas in which modern reefs are settled upon karst substrates.

Another cause of variation in relative sea-level curves can be abrupt changes in reef growth patterns. Reefs may become established shortly after flooding, i.e. have a keep-up growth type. Later, they may not be able to keep pace with the still rising sea level, thus passing briefly from keep-up to give-up growth modes, before again catching up with sea-level rise. This scenario has operated in the Tahiti barrier reef; the duration of the catch-up phase may be long or brief, according to environmental conditions, for instance, the existence - or not - of a global cooling event (Bard et al., 1996) or of local, episodic ecological variations (Montaggioni et al., 1997). The growth pattern may also vary in time within the same reef. The core set from various Indo-Pacific areas shows that the outer parts of reefs are particularly favourable to give an optimal picture of growth pattern, because open sea waters are well oxygenated and far from any terrestrial input (Johnson et al., 1984; Davies et al., 1985; Johnson and Risk, 1987; Montaggioni, 1988; Cortés et al., 1994; Cabioch et al., 1995). This is the case for the three reef sites studied here, although the Ricaudy reef is additionally subject to intralagoonal conditions.

5.4. Reliability of estimate of variations in rates of sea-level rise

The identification of coralgal assemblages in cores provide information on water depth range only, and, consequently, leads to a rough estimate of changes in amplitude and rate of a rising sea level. In reef margins subjected to a keep-up growth style, due to the great homogeneity of the corresponding biological associations over time, it is difficult to recognize any possible decrease in the rate of sea-level rise or any sea-level stabilization. Similarly, in the case of short-amplitude sea-level fluctuations (less than 5–6 m), we will only observe the vertical, continuous superposition of a same coralgal assemblage. In reef margins having developed according to a catch-up growth mode, if the rate and/or amplitude of rise in sea level has changed through time, the biofacies may express a decrease in water depth interval; deeper and shallower coralgal assemblages will alternate vertically in the sequence. In any cases, the framework supplies evidence for mean variations in sea level.

5.5. Accuracy of relative sea-level curves with respect to regional geodynamics

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Until now, the most complete core set providing coral records of the last deglaciation has come from insular arc areas, such as Papua New Guinea (Chappell *et al.*, 1996), Barbados (Fairbanks, 1989; Bard *et al.*, 1990) and Vanuatu (Cabioch *et al.*, 1998). However, these data sets have three related disadvantages.

- 1. The reef sequences may be discontinuous and condensed, as already emphasized above.
- 2. The sequences may have been subjected to exposure, at least in their upper parts, resulting in diagenetic alteration of coral samples (Cabioch *et al.*, 1998).
- 3. The regional tectonic component must be extracted in order to decipher the eustatic signal (Fairbanks, 1989; Chappell *et al.*, 1996). In the insular arcs of the southwest Pacific, it is inferred that the uplift rate has varied during the last 1000 or 10,000 yr (Ota *et al.*, 1993; Taylor *et al.*, 1993; Cabioch *et al.*, 1998). Consequently, it is difficult to separate the eustatic signal from the tectonic component.

In contrast, reef sequences from subsiding areas provide the following advantages:

- 1. They are generally continuous and expanded.
- 2. They have remained permanently under sea water.
- 3. Rates of subsidence are generally negligible compared to rates of sea-level rise; thus, corrections of the tectonic component are unnecessary. Furthermore, in oceanic islands where tectonic movements are isostatically driven, subsidence rates are markedly slower than the rates of uplift in active convergence areas for the same time spans (Ota *et al.*, 1997; Cabioch *et al.*, 1998).

The longest and most continuous postglacial reef sequence drilled has been obtained from the subsiding island of Tahiti (Bard *et al.*, 1996; Montaggioni *et al.*, 1997). In such rapidly subsiding areas, reef colonization can start earlier on shallow-water substrates.

6. Conclusions

(1) Analysis of internal reef structure using drilling on Mauritius, New Caledonia and Tahiti, has provided data on the composition of biological assemblages. By reference to the distribution of modern coralgal communities. three main biofacies can be defined in the reef margin: (1) a lower forereef assemblage, characterized by a tabular coral community (Acropora gr. hyacinthus/cytherea, Pocillopora damicornis, P. eydouxi and/or Montipora digitata), occasionally accompanied with domal shapes (various faviids) and mm-thick coralline algal crusts composed of Hydrolithon onkodes, Lithophyllum sp., Mesophyllum cf. prolifer and Dermatolithon cf. tesselatum; this assemblage is typical of open water, and related to paleodepth range from 6 to 15 m; (2) an upper forereef - reef crest assemblage, including robustbranching coral facies (Acropora gr. danai/robusta and/or A. humilis, A. digitifera) accompanied by Favia stelligera, Echinopora gemmacea and cm-thick crusts of Hydrolithon cf. onkodes or Dermatolithon cf. tesselatum; this association is flourishing in depths less than 6 m, in moderate to high water-energy areas; and (3) An upper forereef assemblage made up of domal coral colonies including Porites cf. lutea and P. cf. lobata and occasional Acropora gr. danai/robusta, in depths presumably less than 10 m.

(2) The reef sequences analyzed show various scenarii of reef initiation, various patterns of biological composition and of growth modes. The vertical successions of the coralgal assemblages occur as a response to sea-level rise or local environmental perturbations. Thus, the accuracy of reconstruction of regional relative sea-level curves depends in part on growth patterns. This is relatively easy in the keep-up reef margins, while in the catch-up ones, it is necessary to knowledge the species-levelled composition and the spatial distribution of the modern coralgal analogs. All emphasizes the need to only use the modern coralgal zonation obtained from reef margins close to a given drilling site.

(3) The accuracy of the paleodepths inferred from biological data have been tested in New Caledonia, where a relative sea-level curve had already been established from non-reefal sea-level indicators. A good consistency is observed between this curve and that obtained from coral communities.

(4) Due to the prevalence of the keep-up growth style, high-energy reefs, e.g. Papeete reef at Tahiti, seem to be more powerful for reconstructing local relative sea-level curves than medium-to-low-energy buildups (e.g. Mautitius and New Caledonia).

(5) The best reef sites for obtaining more complete sea-level curves are rapidly subsiding areas (e.g. Tahiti), because they generally possess expanded postglacial sequences.

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