Sedimentology (1999) **46**, 985–1000

Postglacial growth history of a French Polynesian barrier reef tract, Tahiti, central Pacific

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ABSTRACT

The internal structure and growth pattern of Tahiti reefs over the last 14 ka is reconstructed using sedimentological, morphological and palaeobiological data coupled with radiometric dates in drill cores through the modern barrier reef. Flooding of the volcaniclastic deposits or the karst surface of a Pleistocene reef started at ≈ 14 ka BP, and coral growth began shortly after inundation. The sequence in the Tahiti barrier-reef edge has formed predominantly through long-term keep-up growth controlled by stable environmental conditions, while the adjacent backreef deposits did not start to accumulate before sea-level stabilization, around 6 ka. The dominance of *Porites* communities and the coeval occurrence of branching gracile *Lithophyllum* in the lowermost part of the postglacial reef sequence (14–11 ka) suggest the prevalence of uniformly moderate- to low-energy conditions and/or growth in slightly deeper waters all over the drilled area during the early reef stages. During the last 11 ka, the reef frameworks developed in a high-energy environment, at maximum water depths of 5–6 m, and were dominated by an *Acropora robusta/danai*–*Hydrolithon onkodes* association; the local interlayering of other coralgal assemblages (dominated by tabular *Acropora* or domal *Porites*) reflects distinct diversification stages, resulting either from the palaeotopographic control of the substrate or from slight and episodic environmental changes.

Keywords French Polynesia, Holocene, reef framework, reef, sea-level change.

INTRODUCTION

The development of drilling capabilities and radiometric dating techniques in the last 20 years has greatly increased the knowledge of the growth history of Holocene coral reefs, including reef growth rates and the distribution of biofacies. Studies have been carried out on continental margins (e.g. New Caledonia: Coudray, 1976; Cabioch *et al.*, 1995; Belize: Macintyre *et al.*, 1981; Great Barrier Reef: Hopley, 1982; Marshall & Davies, 1982; Davies & Hopley, 1983; Hopley *et al.*, 1983; Hopley & Barnes, 1985; Johnson & Risk, 1987; Partain & Hopley, 1989; Abrolhos Islands: Collins *et al.*, 1993), microcontinents, subduction zones (e.g. Caribbean: Adey & Burke, 1976; Fairbanks, 1989) and various Indo-Pacific islands (e.g. Easton & Olson, 1976; Marshall & Jacobson, 1985; Montaggioni, 1988; Pirazzoli & Montaggioni, 1988; Cabioch *et al.*, 1995; 1998; Kan *et al.*, 1995; Ebren, 1996; Camoin *et al.*, 1997; Montaggioni & Faure, 1997). Regional patterns of reef growth in response to sea-level change have been deduced from these studies, but some unifying generalizations have also emerged regarding relationships between reef growth and sea level (Chappell, 1980; Davies *et al.*, 1985; Davies & Montaggioni, 1985; Neumann & Macintyre, 1985). Some reefs, or parts of reefs, kept pace with rising sea level, maintaining themselves in a shallow-water environment (keep-up growth), whereas other reefs, or parts of reefs, were able to catch up with sea level either before (catch-up style 1) or after sea-level stabilization (catch-up style 2) (Davies *et al.*, 1985). Their accretion was primarily controlled by the increasing accommodation resulting from rapid sea-level rise during the last deglaciation.

Only in three deglaciation curves derived from coral reef records has the interval containing the Pleistocene–Holocene boundary been dated accurately. In Barbados (Fairbanks, 1989; Bard *et al.*, 1990), it lies between 19 and 8 thousand calendar years BP (ka); in New Guinea between 13 and 6 ka (Chappell & Polach, 1991; Edwards *et al.*, 1993); and in Tahiti between 13·75 ka and 2·38 thousand ^{14}C years BP (Bard *et al.*, 1996; Montaggioni *et al.*, 1997). Coral reef records from Vanuatu (Cabioch *et al.*, 1998) and Mayotte (Dullo *et al.*, 1998) have also provided fragmentary information concerning the 9–20 ka time span. Of special interest is the possibility of reef-drowning events (Blanchon & Shaw, 1995) related to catastrophic sea-level rises during deglaciation (Fairbanks, 1989; Bard *et al.*, 1990). However, most of the studied sites (i.e. Papua New Guinea, Barbados and Vanuatu) are located in active subduction zones, where vertical tectonic movements are large and often discontinuous, so that apparent sea-level records may be disturbed by a tectonic component. Such records are inadequate for a proper analysis of the impact of rapid sea-level and related environmental changes on reef growth and geometry.

The present study concerns a series of vertical and inclined drill holes carried out through the barrier reef tract off Papeete (Tahiti, French Polynesia; Fig. 1), in which we recovered an expanded, continuous, reef sequence encompassing the last 14 ka. Earlier studies on reef cores from the backreef area concerned the last 7 ka (Deneufbourg, 1971; Montaggioni & Delibrias, 1986; Montaggioni, 1988; Camoin & Montaggioni, 1994). This paper seeks to identify the response of a growing barrier reef to sea-level rise and to document the reef internal structure and growth pattern over the last 14 ka.

METHODS

The barrier reef edge has been cored at several points by a Sedidrill drilling machine and coring system. Cores with diameters ranging from 48 to 64 mm were recovered from one vertical (P7) and three inclined (P8, P9 and P10; from 30° to 33° with reference to the vertical) drill holes. Cores P6, P7 and P8 are located on the outer barrier-reef flat, whereas P9 and P10 were on the edge of Papeete Pass (Figs 1–3). Data from drilling investigations in the backreef were re-examined, in particular those from a 40-m-long core penetrating the detrital talus close to the reef edge (core ETM; Fig. 4). Recovery in the P-series cores was dependent upon framework type and on the size of internal cavities, but ranged from 50% to 95%; sections with poor or no recovery generally correspond to unconsolidated sands. During drilling, the tube barrel was advanced in 1·5 m increments; core depths were estimated with ± 0·3 m accuracy. The depths are given here with reference to the reef surface. The reliability of the criteria for identifying in-place coral colonies are generally unambiguous, especially when the tips of branching acroporids and pocilloporids are oriented upwards and also when colonies or branches are capped by centimetre-thick coralline algal crusts. The environmental interpretation of coralgal communities and associated reef-dwelling organisms recovered in cores is based on the ecological distribution of their modern counterparts.

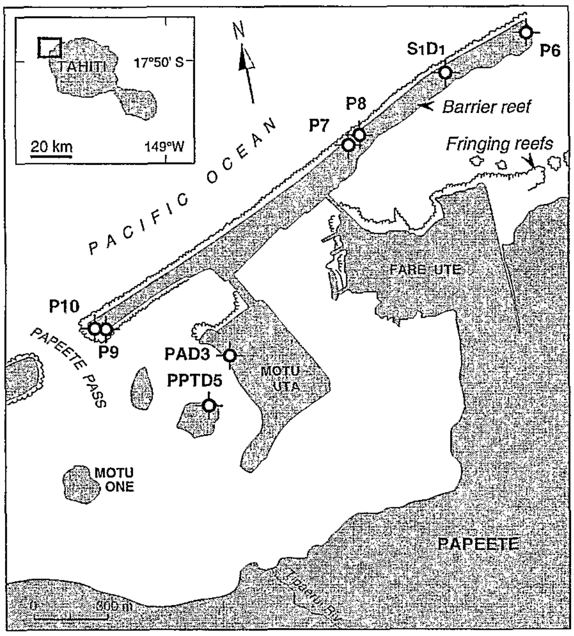

Fig. 1. Location of studied drill cores on the Tahiti reef.

Samples were examined using standard petrographic methods, scanning electron microscopy (SEM), X-ray diffraction and specific staining techniques. Point counting from thin sections

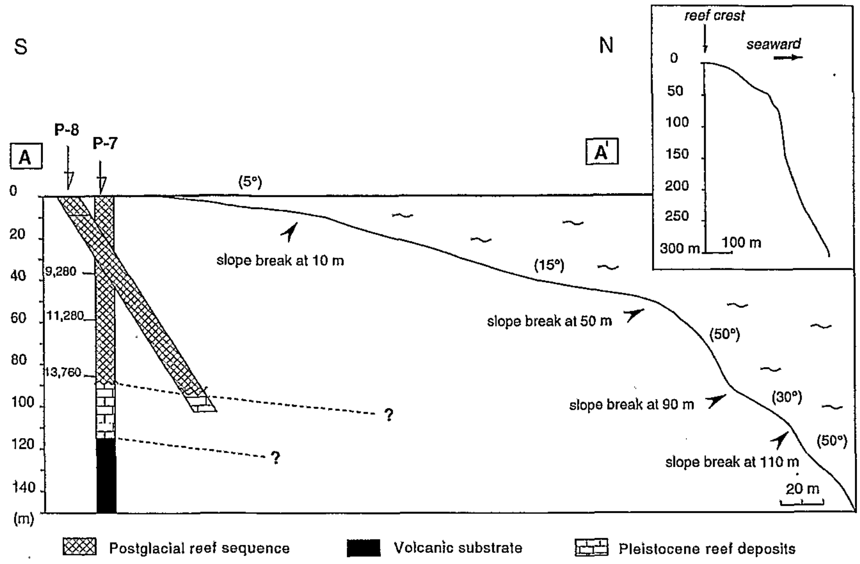

Fig. 2. Cross-section of Tahiti barrier reef at the P7 and P8 drill sites (see Fig. 1 for location).

was carried out in order to quantify the composition of the biological assemblages, especially the algal associations. The data are reported on Fediaevski curves representing cumulative percentages (Fediaevski, 1963). The following components have been distinguished: undifferentiated corallines, *Hydrolithon*, *Neogoniolithon*, *Dermatolithon*, *Lithophyllum*, *Mesophyllum*, *Lithoporella*, *Tenarea*, *Peyssonnelia*, *Halimeda*, vermetid gastropods, encrusting foraminifera (victoriellinids, acervulinids and homotrematids), serpulids and echinoids. Corals and microbialites have been excluded. Diagrams of various levels of the core logs are presented in Fig. 5 to clarify correlations between sites and to identify general environmental gradients (correspondence factor analysis). From a total of 121 observations on cores P7, P8, P9 and P10 using 11 variables (Fig. 6), four groups of major reef encrusters (*Hydrolithon*, *Neogoniolithon*, *Dermatolithon*, *Mesophyllum*, *Lithophyllum*, *Tenarea*, *Lithoporella*, *Peyssonnelia*, acervulinids, victoriellinids and homotrematids) have been identified by R-mode factor analysis and interpreted as environmental sets.

ENVIRONMENTAL SETTING

Prevailing physical conditions

Tahiti is located (17°50′S; 149° 20′W) in French Polynesia, in the tropical zone of the mid-Pacific Ocean. It is a high volcanic island forming the NW–SE Society linear chain. Volcanic activity on Tahiti occurred from 1·37 to 0·19 Ma (Le Roy, 1994), and suggested subsidence rates for the island range from 0·15 mm year^{-1} (Le Roy, 1994) up to 0·25 mm year^{-1} (Bard *et al.*, 1996) or 0·4 mm year^{-1} (Montaggioni, 1988).

The climate is typically tropical, with two distinct seasons: a warm rainy season from November to April (austral summer), with maximum sea surface temperatures from 28 °C to 29 °C, and a cool and dry season from May to October (austral winter), with lower sea-water temperatures of 24–25 °C (for further information, see Delesalle *et al.*, 1985). Although the annual rainfall averages 1500 mm at Papeete, there are marked variations in rain intensity throughout the year: minimum monthly values are less than 50 mm in winter, while maximum monthly values, up to 400 mm, occur in January and February. The south-east and north-east winds are the prevailing systems that influence the hydrological regime, and swells, more than 2 m in amplitude, generated by these trade winds occur along the long axis of the island. The tides are semidiurnal, and their amplitude averages 0·5 m; reef flats emerge at spring tides, while waves commonly break on the central areas of reef flats at high tide. The barrier reef investigated is exposed to high-energy conditions.

Reef zonation

Tahiti is surrounded by discontinuous and poorly developed fringing reefs that grade locally into a chain of barrier reefs. These are frequently interrupted and sometimes submerged, locally enclosing a narrow backreef area. The barrier reef

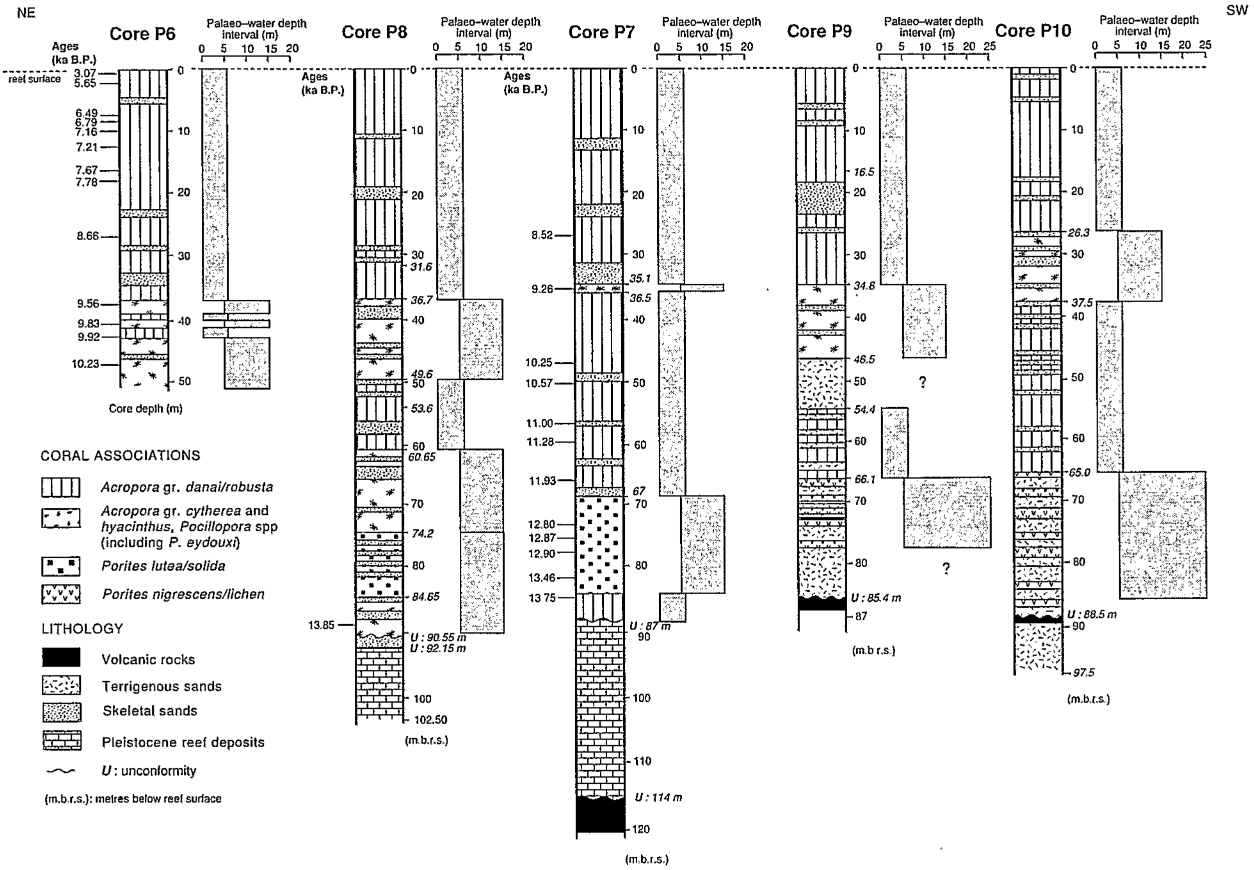

Fig. 3. Distribution of coralgal communities and interpreted palaeowater depth intervals in cores P6, P7, P8, P9 and P10.

complex can be subdivided into three zones, from the open sea landwards:

1 The outer reef slope consists of coral-built spurs and grooves, and is characterized by several scarps. The slope is relatively gentle (15° average) to a water depth of about 15 m and then steepens (to about 20°) down to 50 m water depth, and forms an almost vertical wall between 50 and 100 m (Fig. 2). Two prominent terraces at 50 m and 90–100 m bearing living coral reef were observed during a survey by the submersible Cyana (Salvat *et al.*, 1985). In the upper part of the spur-and-groove system (less than 5–6 m deep), biological communities are characterized by abundant branching and massive scleractinian corals (*Acropora* of the *robusta/danai* group, *Pocillopora verrucosa, Montipora erythraea, Montastraea curta, Porites lobata*) and hydrocorals (*Millepora platyphylla*) with subordinate domal forms (*Favia, Favites*); secondary framebuilders (i.e. encrusters) are dominated by the coralline alga *Hydrolithon onkodes* associated with *Neogoniolithon, Hydrolithon* sp., *Lithothamnium* and *Lithophyllum*) and vermetid gastropods (*Dendropoma maximus, Serpulorbis annulatus*).

2 The reef-flat zone is relatively narrow (130 m maximum width) and consists of three distinct subzones. The outermost subzone (the reef edge) exhibits centimetre-thick crusts of coralline algae (mostly *Hydrolithon*) associated with robust branching acroporids (*Acropora* gr. *danai/robusta*). The intermediate subzone (patchy reef flat) has scattered coral heads including branching (*Acropora* gr. *danai/robusta, A. cytherea, Pocillopora verrucosa*) and massive (*Porites australiensis, P. lutea*) forms. In the innermost subzone (rubble reef flat), the floor is chiefly covered by coralgal rubble, and living coral colonies are rare (*Acropora, Porites*). The reef flat is connected to the backreef floor through a gently dipping biodetrital talus apron, extending over 50 m.

3 The backreef zone corresponds to a 1-km-wide bay, reaching a maximum depth of 20 m. Two large flat-topped patch reefs of about 90 000 and 15 000 m^2 in areal extent, respectively, occur in the central part of the backreef zone. The windward slopes of these are steep with nearly vertical

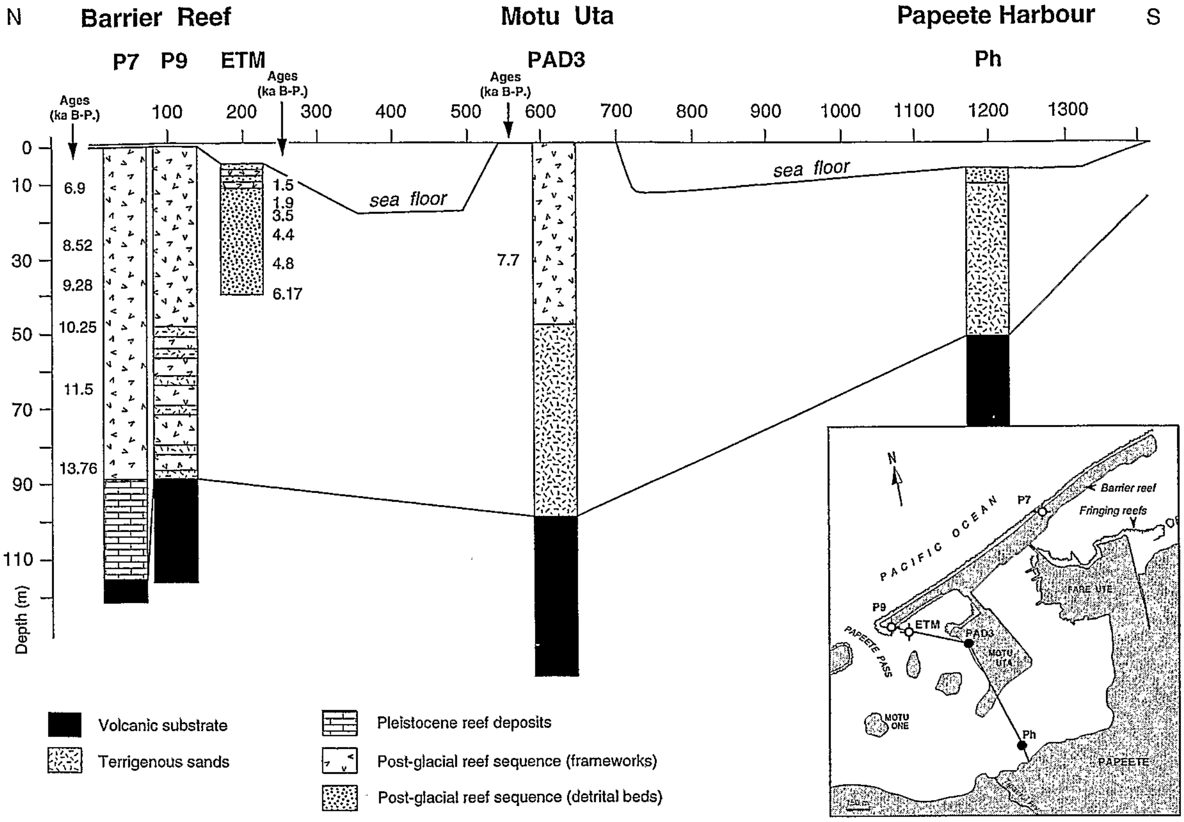

Fig. 4. Stratigraphic correlation along a transect extending from the barrier reef to Papeete Harbour. Data concerning lithology in drill holes performed in the lagoon (Motu Uta and Papeete Harbour) are from Deneufbourg (1971).

drop-offs along the northern and western margins; relatively gentle leeward slopes occur on the southern and eastern margins. The top of these patch reefs corresponds to an exposed reef-flat zone dominated by branching corals (*Acropora* gr. *danai/robusta*, *Pocillopora*), associated with scattered massive *Porites* and faviids. Patchy algal meadows composed of chlorophytes (*Halimeda*) and rhodophytes (*Amphiroa*) are also present.

RESULTS

Core lithology and distribution of coralgal assemblages and associated sediments

Except for cores ETM (biodetrital talus) and P6, all of the studied cores penetrated the entire postglacial carbonate sequence beneath the reef edge and reached the antecedent substrate. The volcanic bedrock that lies beneath the reef has a general SW–NE slope of 6° and dips gently seawards (10° average; Deneufbourg, 1971). Below the barrier reef, the depth of the basaltic or terrigenous substrate ranges from 85·4 m (core P9) to 114·0 m (core P7), deepening towards the north-east. In cores P9 and P10, the basalt is overlain by brownish clay including pebbles of volcanic rocks, which may correspond to the weathering profile of the basalts (Fig. 3). Correlations between the drill holes on the barrier reef and those in Papeete Harbour (cores ETM, PAD3, PPTD5 and Ph; Deneufbourg, 1971; Montaggioni, 1988; Camoin & Montaggioni, 1994) indicate that the terrigenous deposits form an 18- to 45-m-thick wedge below the modern backreef zone, thinning both seawards and landwards (see Camoin *et al.*, 1999; Fig. 4).

The overlying sequence may be subdivided into two units separated by a clear unconformity with evidence of subaerial exposure (Fig. 3):

1 The lower unit, probably late Pleistocene in age, occurs in cores P7 and P8, at 87·0 and 92·0 m deep respectively. It is characterized by massive or branching acroporids (*Acropora* sp. from 100·0 to 103·0 m and *Acropora* gr. *danai/robusta* in the interval 103·0–107·0 m), branching *Pocillopora* sp. and *Leptoria phrygia*; *Halimeda* fragments are relatively abundant. Coatings of coralline algae can be thick but are commonly composed of a succession of thin thalli (Fig. 7A). This

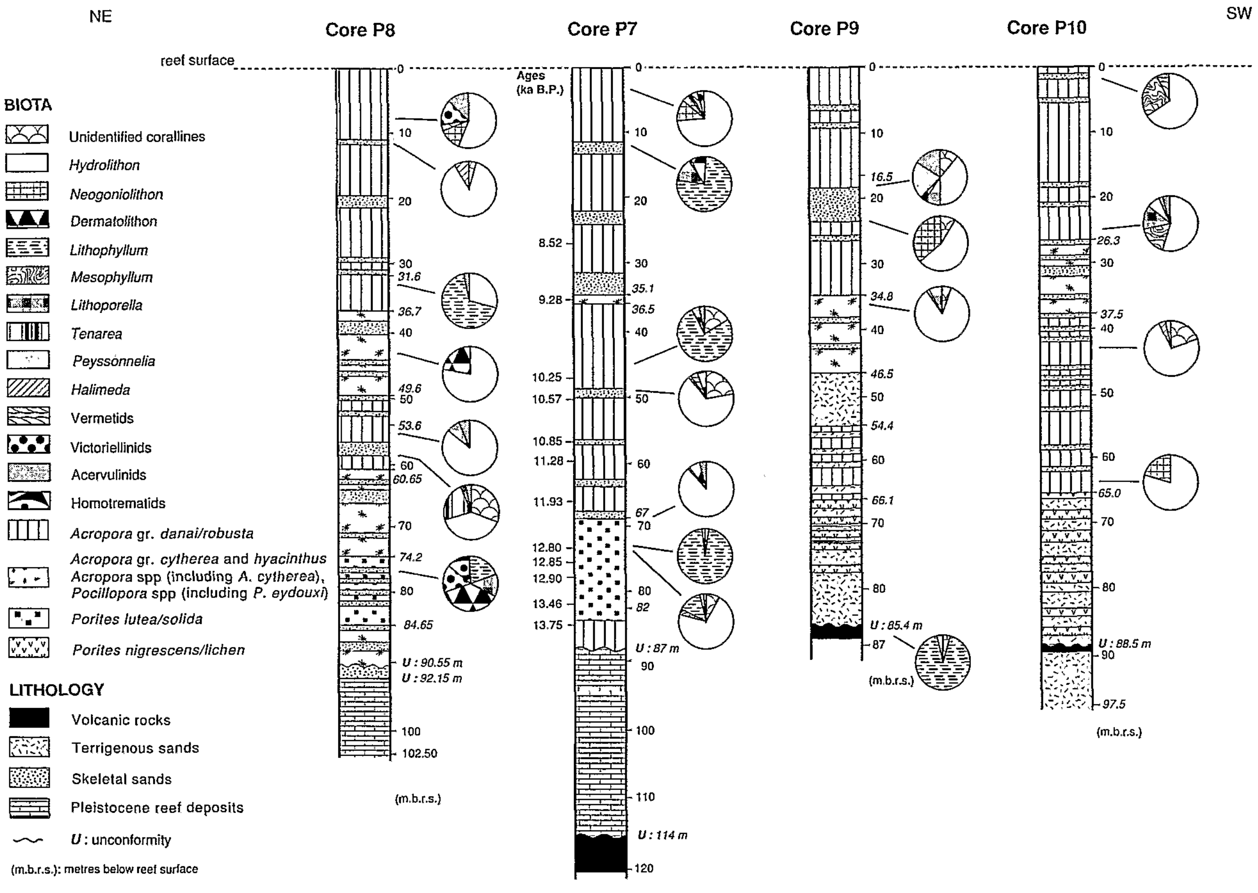

Fig. 5. Vertical distribution of the main coral associations (logs) and characteristic associations (circular diagrams) of coralline and secondary reef builders in cores P7, P8, P9 and P10.

Pleistocene limestone is interpreted as deposited in a reef-flat environment and capped by a karst surface. It is absent in the area of P9 and P10, where the substrate is much shallower.

2 The upper unit is younger than 13·7 ka and exhibits stratigraphically consistent ages with no reversals (Fig. 3; Bard *et al.*, 1996). It ranges in thickness from 85·4 m to 92·15 m in cores P9 and P8 respectively. It is primarily composed of *in situ* 0·1- to 6-m-thick coral frameworks generally thickly encrusted with red algae and microbialites (see Montaggioni & Camoin, 1993; Camoin & Montaggioni, 1994; Camoin *et al.*, 1999). The coralgal frameworks alternate locally with unconsolidated coral rubble and skeletal sands, terrigenous sands and silts. These are present, for example, between 50 m and 87 m (corresponding to the time span 10·5–13·7 ka) in cores P9 and P10 at the edge of Papeete Pass.

There is a clear differentiation of the gross facies distribution of the framework in this sequence (Fig. 3; Table 1):

P-series cores

1 The lower part of the reef sequence contains two distinct coralgal assemblages:

In the south-western part of the barrier reef complex (66·1–78·0 m in core P9; 65–88·5 m in core P10), coralgal communities are predominantly composed of branching colonies of *Porites* cf. *nigrescens* and *P.* cf. *lichen* associated with scarce colonies of *Pocillopora*, *Porites* cf. *lobata* and faviids. The red algal association includes *Lithophyllum* sp., *Mesophyllum* sp. and rare *Neogoniolithon* sp. and *Hydrolithon onkodes*.

In the central part of the barrier-reef complex (67·0–82·0 m in core P7 and 74·2–84·7 m in core P8), coralgal assemblages are composed of domal *Porites* cf. *lutea* and *P.* cf. *lobata* with scattered *Pocillopora* cf. *verrucosa* and tabular acroporids. The red algal association is dominated by gracile branching *Lithophyllum*, forming veneers thinner than 1 cm over *Porites* colonies (Fig. 7D). When present, *Hydrolithon onkodes* is mingled with

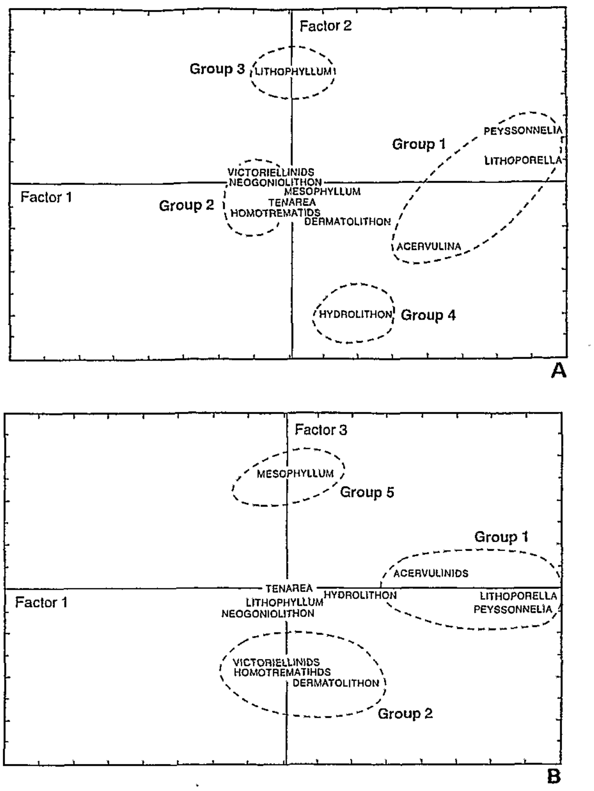

Fig. 6. (A) Correspondence factor analysis (R-mode). Plot of the factor axes 1 and 2 with projection of 11 variables (encruster types). (B) Correspondence factor analysis (R-mode). Plot of the factor axes 1 and 3 with projection of 11 variables (encruster types).

Dermatolithon cf. *tesselatum* and *Neogoniolithon fosliei* and forms millimetre-thick crusts.

2 The prevailing coralgal framework between 65–70 m and the reef surface comprises massive branching species of *Acropora* gr. *danai/robusta* (Fig. 8A) associated with branching *A. humilis, Pocillopora eydouxi* and *P. verrucosa*, and scarce domal *Leptastrea* sp., *Porites* cf. *lobata, Favia stelligera, F.* gr. *abdita* and *Montastrea annuligera.* Coral colonies are heavily encrusted with coralline algae (mainly *Hydrolithon onkodes* and, to a lesser extent, *Neogoniolithon fosliei* and *Mesophyllum* sp.; Fig. 7B); *Lithophyllum* sp., *Dermatolithon* cf. *tesselatum* and *Mesophyllum* sp. occur locally. *Lithoporella melobesioides* is relatively abundant at some levels (e.g. P9: from 13 m to 20 m; P10: from 10·0 m to 16·5 m). Associated with the algae are sessile vermetid gastropods (*Serpulorbis annulatus* and *Dendropoma maximus*) and encrusting foraminifera (*Homotrema rubrum, Carpenteria* cf. *monticularis* and *Acervulina inhaerens*). Cavities, up to 10 cm in size, are common and are locally occupied by large fragments of the echinoid *Heterocentrotus trigonarius*, various skeletal detritus and micritic cements (Fig. 7C).

3 A tabular branching *Acropora* community is recorded from 37·0 m to 50·0 m in core P6, from 35·1 m to 36·5 m in core P7, at three distinct levels in core P8 (36·7–49·6 m, 60·7–74·2 m and 84·7–90·6 m), from 34·8 m to 46·5 m in core P9 and from 26·3 m to 37·5 m in core P10. It consists mainly of *Acropora hyacinthus, A. cytherea* and *A. clathrata* (Fig. 8B) with subordinate, plate-shaped A. *danai/robusta* ecomorphs and domal *Montastrea annuligera.* Coralline algae have developed only as millimetre-thick crusts and include *Neogoniolithon* cf. *absimile, N. propinquum, Dermatolithon* cf. *tesselatum* and *Mesophyllum* cf. *prolifer*; *Hydrolithon onkodes* is rare or absent. Tabular branching acroporids are locally interlayered with robust branching *Acropora* of the *danai–robusta* group in the lowermost part of core P6 (see Montaggioni *et al.*, 1997).

Core ETM

In this core, the carbonate sequence is dominated by detritus, locally with large pieces of *Porites* and *Acropora.* The base of the core has been dated at 6·2 ka. From 0 m to 14·0 m, biofacies are dominated by gravel to silt-sized detritus mainly composed of fragments of branching acroporids, massive poritids and faviids, mixed with mollusc shells. Apparently in-place *Acropora* and *Porites* colonies are observed at 2·2 m, 6·5 m, 7·7 m, 8·6 m and 11·2 m. From 14·0 m to 23·0 m, shelly sands contain scattered coral fragments. These are replaced from 23·0 m to 29·0 m by poorly sorted molluscan-rich sands and acroporid gravels. From 29·0 m to 40·0 m, the recovered deposits consist of coral sands and gravels, mixed with sandy muds at the base.

Environmental significance of coralgal assemblages

Little is known of the general distribution of coral and coralline algal communities in the Tahiti reefs, but studies have been conducted on the neighbouring island of Moorea (Chevalier & Kühlmann, 1983; Bouchon, 1985; 1996) and many French Polynesian atolls (Chevalier, 1976, 1977; Bouchon, 1983; Faure & Laboute, 1984; Kühlmann & Chevalier, 1986). French Polynesian reefs have a poor coral fauna (see review by Coudray & Montaggioni, 1982; Pichon, 1985; Veron, 1995) compared with

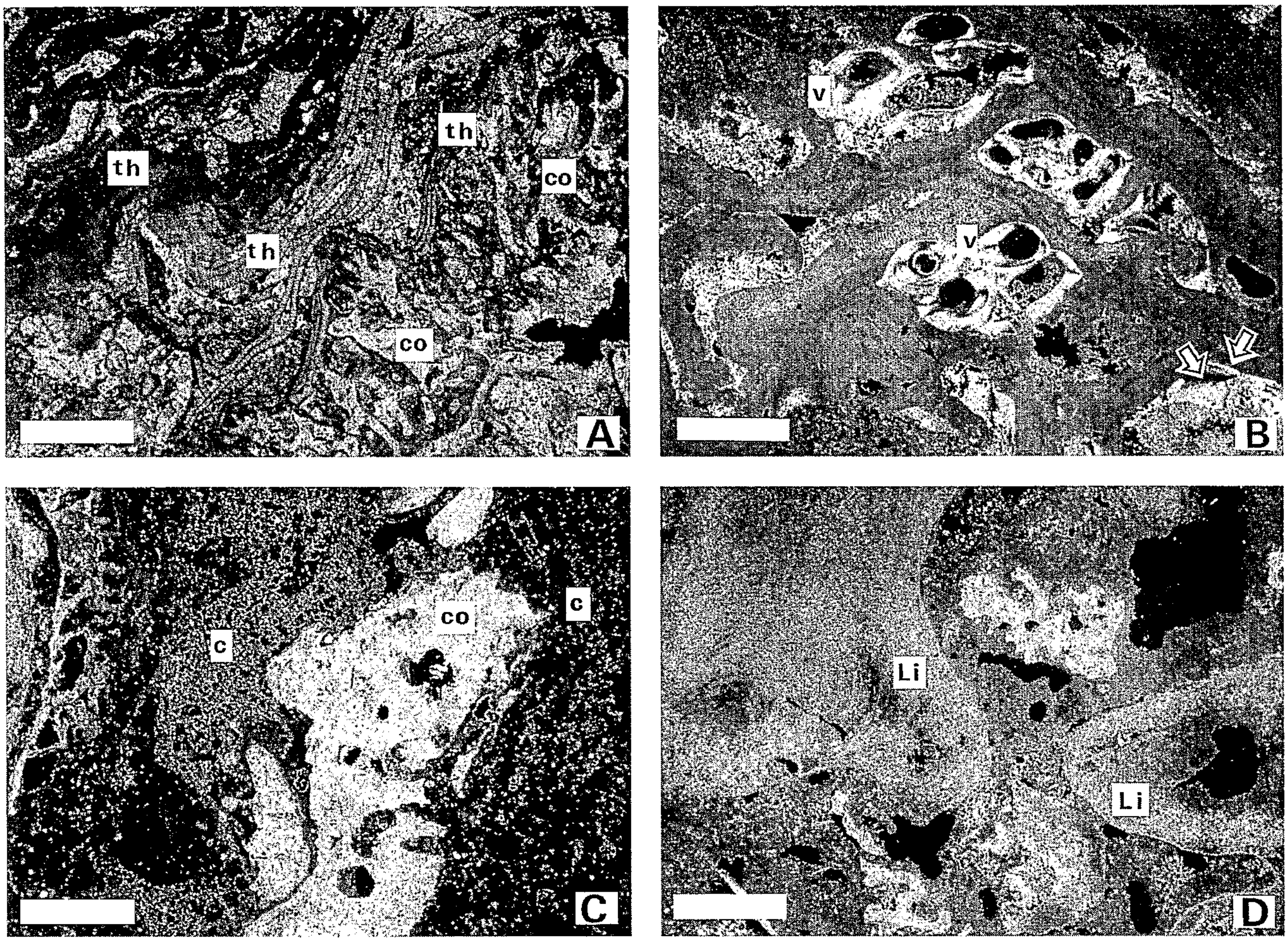

Fig. 7. (A) Thin-section photomicrograph of coralgal framework characterized by the encrustation of coral skeletons (co) with numerous thin red algal thalli (th). Core P7; 90·8 m (Late Pleistocene). Scale bar = 1 mm. (B) Thin-section photomicrograph of coralgal biofacies characterized by thick veneers of coralline algae associated with sessile vermetid gastropods (v) at 4·6 m (between 5·5 and 5·0 ka) in core P7. The arrows indicate aragonite spherulitic cement infilling some cavities. Scale bar = 1 mm. (C) Thin-section photomicrograph of coralgal biofacies in which corals (co) are strongly bioeroded. The cavities are filled with micritic peloidal cements (c). Core P7; 8·8 m (between 5·7 and 6 ka). Scale bar = 1 mm. (D) Thin-section photomicrograph of algal biofacies characterized by the occurrence of branching *Lithophyllum* (Li) at 73·0 m (at around 12·8–13·0 ka) in core P7. Scale bar = 1 mm.

Indian and west Pacific areas (see Veron, 1986; Hopley, 1989), because of the prevailing westward currents and winds and the remoteness of the islands from continental masses.

Four distinct but poorly diversified coralgal communities can be delineated in the Tahiti postglacial reef sequence (Fig. 3), and can be classified according to their depth range, relative light level and water energy by analogy with the distribution patterns of their modern analogues.

1 A coralgal community dominated by robust-branching *Acropora* of the *danai–robusta* group, thickly encrusted with *Hydrolithon (Porolithon) onkodes*, with the vermetid gastropods *Dendropoma maximus* and *Serpulorbis annulatus* characterizes the upper part of the postglacial reef sequence, between 65·0 m and the top, but also occurs at its base in core P7 (from 82 m to 87 m). As on the modern barrier reef off Papeete, no real algal ridge was identified. In Indo-Pacific reefs, the *Acropora danai–robusta* assemblage occurs on the high-energy reef front or upper forereef zone exposed to strong wave action, at depths of less than 6 m or even less than 3 m below low-tide level when vermetid gastropods are associated (Adey *et al.*, 1982; Faure, 1982; Richard, 1982; Bouchon, 1985; Delesalle *et al.*, 1985; Laborel, 1986). Robust-branching acroporids are considered to be the most reliable finite recorders of water depth in the Indo-Pacific province (see Pirazzoli & Montaggioni, 1988;

Table 1.

Coralgal associations	Distribution	Modern depositional environment
Branching *Porites (P. nigrescens/lichen)–Lithophyllum*		
Corals *Porites* cf. *nigrescens, P.* cf. *lichen;* scarce *Pocillopora, Porites* cf. *lobata* and faviids	Core P9: 66.1–78 m Core P10: 65–88.5 m	Moderate- to low-energy conditions relatively independent of the zonation and water depth (0–30 m; 5–30 m in the study area) adapted to low irradiance
Algae Branching *Lipthophyllum* sp., *Mesophyllum* sp.; rare *Neogoniolithon* sp. and *Hydrolithon onkodes*		
Domal *Porites (P. lutea/solida)–Lithophyllum*		
Corals *Porites* cf. *lutea* and *P.* cf. *lobata;* scattered *Pocillopora* cf. *verrucosa* and tabular acroporids	Core P7: 67–82 m Core P8: 74.2–84.7 m	Outer reef flat and forereef zone and windward zone of lagoonal pinnacles in moderate- to high-energy conditions, at depths shallower than 15 m (6–15 m in the study area)
Algae Gracile-branching *Lithophyllum.* *Hydrolithon onkodes, Dermatolithon* cf. *tesselatum* and *Neogoniolithon fosliei*		
Robust-branching *Acropora (A. gr. danai/robusta)–Hydrolithon*		
Corals *Acropora* gr.*danai/robusta;* branching *A. humilis, Pocillopora eydouxi* and *P. verrucosa;* scarce domal *Leptastrea* sp., *Porites* cf. *lobata, Favia stelligera, F.* gr. *abdita* and *Montastrea annuligera*	Core P6: 0–37 m + some intervals between 37 and 50 m Core P7: 0–67 m (except between 35.1 and 36.5 m) and 82–87 m Core P8: 0–36.7 m and 49.6–60.7 m Core P9: 0–34.8 m and 54.4–66.1 m Core P10: 0–26.3 m and 37.5–65 m	Reef front or upper forereef zone in high-energy conditions at depths less than 6 m (even less than 3 m in the study area)
Algae Thick crusts of *Hydrolithon onkodes, Neogoniolithon fosliei, Mesophyllum* sp. Locally: *Lithophyllum* sp. *Dermatolithon* cf. *tesselatum, Lithoporella melobesioides* and *Mesophyllum* sp. Vermetid gastropods (*Serpulorbis annulatus* and *Dendropoma maximus*); encrusting foraminifer (*Homotrema rubrum, Carpenteria* cf. *monticularis* and *Acervulina inhaerens*)		
Tabular Acropora (A. gr. cytherea/hyacinthus)–Neogoniolithon		
Corals Tabular *Acropora hyacinthus, A. cytherea* and *A. clathrata;* plate-shaped *A. danai/robusta ecomorphs* and domal *Montastrea annuligera*	Core P6: 37.0–50.0 m Core P7: 35.1–36.5 m Core P8: 36.7–49.6 m, 60.7–74.2 m and 84.7–90.6 m Core P9: 34.8–46.5 m Core P10: 26.3–37.5 m	Forereef zone in moderate-energy conditions at depths shallower than 15 m (6–15 m in the study area)
Algae Thin crusts of *Neogoniolithon* cf. *absimile, N. propinquum, Dermatolithon* cf. *tesselatum* and *Mesophyllum* cf. *prolifer;* rare *Hydrolithon onkodes*		

Fig. 8. (A) Section of a robust-branching *Acropora* (*A.* gr. *danai–robusta*). Core P6; 5·30 m. (B) Slab of *Acropora* gr. *hyacinthus/cytherea* framework. Note the thin red algal crusts and the widespread development of microbialite coatings (in grey). Sample P6; 34·3 m. Scale bar = 2 cm.

Camoin *et al.*, 1997; Montaggioni & Faure, 1997) and can be regarded as the Indo-Pacific counterparts of the Caribbean *Acropora palmata*. This assemblage is typical of reefs with a keep-up growth style and can grow upwards at rates of about 15 mm year^{-1} (Montaggioni, 1988; Montaggioni & Faure, 1997).

2 A coral assemblage dominated by tabular acroporids (*Acropora hyacinthus* and *A. cytherea*), associated with plate-shaped *Acropora* gr. *danai/robusta* ecomorphs, branching *Pocillopora eydouxi*. Coralline algae consist of either *Neogoniolithon* sp., *Lithophyllum* sp. and *Dermatolithon* cf. *tesselatum* (core P7) or *Hydrolithon* (*Porolithon*) *onkodes* (cores P8, P9 and P10). They form only a thin interval in core P7 (between 35·1 m and 36·5 m) but are more developed in cores in the middle part of the sequence, in cores P8 (36·7–49·6 m and 60·7–74·2 m), P9 (34·8–46·5 m) and P10 (26·3–37·5 m). On modern Indo-Pacific reefs, this assemblage occurs in moderate-energy settings (i.e. the middle part of the forereef zone), at depths of 6–15 m, according to local water energy level (Adey *et al.*, 1982; Done, 1982; Faure, 1982; Marshall & Davies, 1982; Bouchon, 1985; Adey, 1986; Veron, 1990).

3 A domal *Porites* community, including *Porites* cf. *lutea* and *P.* cf. *lobata* veneered with gracile branching *Lithophyllum* and with *Hydrolithon* cf. *onkodes* and *Dermatolithon* cf. *tessellatum*, characterizes the lower part of the sequence at sites P7 (67·0–82·0 m) and P8 (74·2–84·7 m). This assemblage is reported on modern outer slopes, in moderate- to high-energy conditions, at depths of 6–15 m (Chevalier, 1978; Done, 1982; Faure, 1982; Bouchon, 1985). In atolls, this community occurs on the outer reef flat and on the windward zone of lagoonal pinnacles (Faure & Laboute, 1984; Kühlmann & Chevalier, 1986; Bouchon, 1996). Interlayering with the robust-branching *Acropora* community in core P7 suggests that the water depth probably never exceeded 6 m in this core.

4 A community dominated by branching *Porites* (*Porites* cf. *nigrescens* and *P.* cf. *lichen*), branching *Lithophyllum* and veneers of *Hydrolithon onkodes* characterizes the lowermost part of the sequence at sites P9 (66·1–78·0 m) and P10 (65–88·5 m). In modern Indo-Pacific reefs, this community is diagnostic of moderate-energy conditions on reef slopes, at depths of 15–30 m (Done, 1982; Faure & Laboute, 1984; Bouchon, 1985; Kühlmann & Chevalier, 1986). However, depending on local ecological conditions, it also flourishes in shallower environments, at depths of 6–20 m, on the windward side of lagoonal pinnacles (Bouchon, 1996) and in lagoonal or shallow backreef environments (Veron, 1986). In southern Tahiti (Vairao), the *Porites* cf. *nigrescens* – *P.* cf. *lichen* community develops between 10 m and the surface. The occurrence of this peculiar community at the base of the Tahiti postglacial reef sequence suggests the prevalence of reduced light intensity and water energy in the vicinity of the present pass (holes P9 and P10), which corresponds to a previous river mouth.

Statistical discrimination of groups of reef encrusters

In order to obtain a more accurate differentiation of the major secondary reef builders into environmentally significant groups, the initial raw point-counting data have been analysed statistically.

A correspondence factor analysis (R-mode) was performed on a data matrix including 121 observations (thin sections) and 11 variables (numerical percentages of the major framework-contributing genera or families of calcareous red

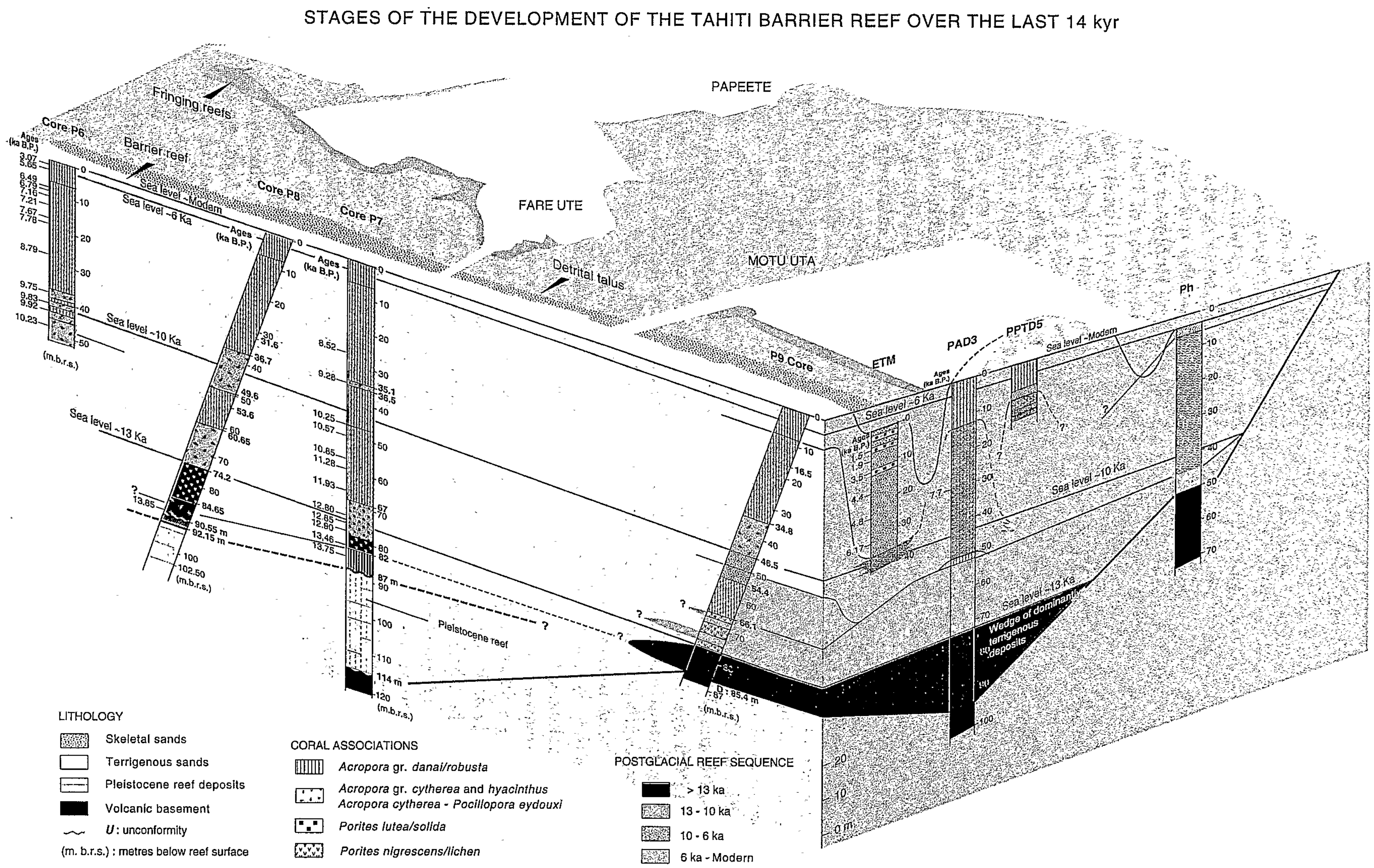

Fig. 9. Stages of the development of the Tahiti barrier reef over the last 14 kyr. Lithology has been simplified.

algae and foraminifera; Fig. 6). The first three factors account for 37·6% of the total variance.

Factor 1, explaining 15·5% of the variance, is largely controlled by *Lithoporella–Peyssonnelia* and acervulinids, which have the highest loadings on factor axis 1 [absolute contribution (AC) = 0·84, 0·81 and 0·46 respectively]. This association is opposed to *Neogoniolithon* (AC = 0·13), victoriellinids (AC = 0·12) and homotrematids (AC = 0·12) located along the negative side of factor 1.

Factor 2, extracting 11·7% of the variance, is mainly defined by the reverse relationship between *Lithophyllum* (AC = 0·67) and *Hydrolithon* (AC = 0·73).

Factor 3, extracting 10·4% of the variance, depends upon the variable *Mesophyllum* (AC = 0·67), which is opposed to *Dermatolithon* (AC = 0·50), homotrematids (AC = 0·46) and victoriellinids (AC = 0·42). The variable *Tenarea,* systematically located close to the barycentre, contributes weakly to defining the three axes (AC varying between 0·09 and 0·08).

The arrangement of the variable points within the three-dimensional space delineates five distinct groups (Fig. 6). Group 1 is composed of the phylloid algae *Lithoporella* and *Peyssonnelia* and orbitoid foraminifera (acervulinids), developing as very thin veneers. Group 2 includes the crustose corallines *Neogoniolithon* and *Dermatolithon* and arborescent foraminifera (victoriellinids, homotrematids), which form crusts millimetres-to-centimetres in thickness. Group 3 is characterized by the dominance of gracile-branching *Lithophyllum* forming veneers of less than 1 cm thick. Group 4 is strictly defined by the prevalence of *Hydrolithon* (mainly *Hydrolithon onkodes*), which develops as thick crusts over corals. Group 5 is typified by the dominance of the crustose *Mesophyllum* as millimetre-thick veneers.

Groups 2 and 4 are related to shallow open water, high- to moderate-energy environments. Groups 1, 3 and 5 are regarded as characterizing deeper and/or more protected habitats, subjected to lower light intensity.

DISCUSSION

Initiation and settlement of the postglacial reef sequence

The prereefal basement is composed of lava flows (Le Roy, 1994), dipping at about 10° seawards (Deneufbourg, 1971). The postglacial reef sequence overlies either terrigenous sediments (reddish to brown clays), which represent the weathering products of basalts in the vicinity of Papeete Pass (cores P9 and P10), or the karst surface of a Pleistocene reef-flat unit (cores P7 and P8). The nature of the substrate may have controlled the timing of reef initiation through its influence on the recruitment of coral larvae, as suggested by Hopley *et al.* (1983). It seems likely that the roughness of Pleistocene karst surfaces may have favoured the attachment of coral larvae, promoting coral growth (for Holocene counterparts, see Partain & Hopley, 1989; Cabioch *et al.*, 1995). Flooding of the substrate started in Tahiti at ≈ 14 ka throughout the drilled area, and may correspond to the end of Meltwater Pulse-1A demonstrated in Barbados (Bard *et al.*, 1990). Coral growth probably began 200–300 years later (Montaggioni *et al.*, 1997), and reef frameworks were established relatively quickly. The rapid initiation of Holocene reefs on Pleistocene karst surfaces has been reported in many areas (Davies & Marshall, 1979; Marshall & Davies, 1982; Davies & Montaggioni, 1985; Davies *et al.*, 1985; Montaggioni, 1988; Walbran, 1994; Collins *et al.*, 1996; Camoin *et al.*, 1997). However, in Tahiti, there is no significant difference in the timing of the onset of reef accretion across the study area whatever the nature of the substrate colonized.

These data confirm those reported from other Indo-Pacific sites (e.g. Papua New Guinea: Chappell & Polach, 1991; Comoro Islands: Dullo *et al.*, 1998; Vanuatu: Cabioch *et al.*, 1998), which document an almost continuous reef sequence for the last 18 ka, implying that there was no major break in reef development during the last deglaciation. They contrast with previous interpretations, which assumed that Holocene reef initiation occurred within the same time frame, between 8·3 and 7·0 ka, throughout the world (Davies *et al.*, 1985; Davies & Montaggioni, 1985; Montaggioni, 1988). It was believed that such a narrow start-up envelope represented a real phenomenon in postglacial reef growth resulting from either abnormal nutrient levels during glacial low sea-level stands or the lack of larval replenishment centres (Davies *et al.*, 1985; Marshall, 1988; Montaggioni, 1988), both suggesting a global scale turn-off in reef growth during the early stages of the postglacial transgression. Thus, we consider that the retardation in reef initiation reported in a number of Holocene reef complexes (e.g. New Caledonia: Cabioch *et al.*, 1995; Great Barrier Reef: Hopley *et al.*, 1983; Johnson & Risk, 1987) is probably related to regional causes, such as a lack of suitable substrates, inimical water conditions or poor larval recruitment.

Postglacial reef growth pattern

It has been demonstrated that, during the last 13·5 ka, environmental conditions in Tahiti were optimal for reef development, and no long-term environmental changes occurred. This interpretation is based on the ecological characteristics of the biological associations involved, reef growth rates, $CaCO_3$ accumulation rates and geochemical signals in coral skeletons (Camoin & Montaggioni, 1994; Montaggioni *et al.*, 1997; Camoin *et al.*, 1999). Terrigenous inputs in the vicinity of the barrier reef (in the Papeete channel entrance) has not affected general reef development.

The Tahiti postglacial reef sequence does not record any significant reef-drowning events comparable with those described by Blanchon & Shaw (1995) in the same time period (0–13 ka) in the Caribbean, dated at 11·5 and 7·6 ka respectively (Montaggioni *et al.*, 1997). In contrast to most postglacial reef records, the Tahiti reef formed predominantly through long-term (14 ka) continuous, keep-up growth. Such a steady state, where reef growth keeps pace with rising sea level, can develop when conditions remain uniform for a long time. During this time, reef growth was dominated by aggradation.

The pattern of postglacial reef growth can be reconstructed using radiometric dates coupled with sedimentological, morphological and palaeobiological data (Fig. 9). It was strongly controlled by accommodation space available as a result of the progressive flooding of pre-Holocene foundations during deglaciation. The response of reef growth to sea-level rise and related environmental changes (in water energy, light intensity, turbidity, nutrient contents, etc.), in both time and space, may have varied significantly within the outer barrier reef edge, as indicated by the variety of coral associations (see also Montaggioni, 1988; Camoin & Montaggioni, 1994; Montaggioni *et al.*, 1997).

The postglacial reef sequence is predominantly composed of coralgal frameworks, with the exception of the lower section at the edge of the Papeete channel entrance (cores P9 and P10), where terrigenous sediments disturbed reef growth. The common pattern in the Holocene of the Indo-Pacific is for frameworks to dominate in prevailing high-energy environments, whereas reefs from relatively protected areas are detritus dominated (see Davies & Hopley, 1983; Davies *et al.*, 1985; Montaggioni, 1988; Partain & Hopley, 1989; Cabioch *et al.*, 1995; Camoin *et al.*, 1997). During reef growth, the composition of successive coralgal assemblages was primarily controlled by external parameters, in particular hydrodynamic energy and light intensity.

The dominance of *Porites* communities and the coeval occurrence of branching gracile *Lithophyllum* in the lowermost part of the postglacial reef sequence suggest uniform moderate- to low-energy conditions over the entire drilled area during early reef development. The differentiation of a *Porites nigrescens/P. lichen* assemblage near the pass (cores P9 and P10), and domal *Porites* gr. *lutea/solida* in the central part of the barrier reef complex (cores P7 and P8), appears to be independent of the water depth, but is probably related to the specific ecological conditions (especially low light intensity) prevailing near the Tahiti pass at that time. The development of *Porites* communities is commonly related to unfavourable ecological conditions (for instance, see Chevalier, 1978 for the Marquesas Islands). Temporary influxes of continental weathered material during reef building are indicated by pockets and beds of volcanic sands and silts in the lower part of the cored sequences (e.g. 50–87 m, corresponding to a time 10·5–13·7 ka) and by trapped sediments (clay minerals and volcanic grains) and high concentrations of Si, Fe and Al in microbialites (Camoin *et al.*, 1999).

The *Acropora danai/robusta–Hydrolithon onkodes* association that persisted at all sites for more than 11 ka indicates that, throughout this period, the reef frameworks developed in a high-energy environment, at maximum water depths of 5–6 m, and that the barrier reef margin was able to keep pace with rising sea level (a keep-up growth strategy). At that time, environmental conditions were optimal for reef development. Such a dominance of branching corals, especially *Acropora*, has been reported in Holocene reefs from the south-western Indian Ocean (Montaggioni, 1977; Camoin *et al.*, 1997; Montaggioni & Faure, 1997) and the Caribbean (Macintyre *et al.*, 1977 1985; Fairbanks, 1989). However, this situation contrasts with that in many Caribbean and Indo-Pacific areas, where massive corals commonly replace branching corals in the upper sections of reefs (for instance, see Rosen, 1971; Davies & Hopley, 1983; Cortès *et al.*, 1994; Cabioch *et al.*, 1995). The local interlayering in all cores of coralgal assemblages dominated by tabular *Acropora* or domal *Porites* with robust-branching acroporids around 9·5 ka is probably a specific response in the build-up to changing physical conditions related to substrate topography (Montaggioni *et al.*, 1997).

From the available dates in the various drill cores (Camoin & Montaggioni, 1994; Bard *et al.*, 1996), we can deduce that the modern backreef zone was flooded around 10 ka, acting as a sediment trap and producing an accumulation of terrigenous deposits shorewards (see also Deneufbourg, 1971). From 6 ka onwards, it was then partly filled by the accumulation of reef-derived detritus as sea level reached its present position.

The growth rates recorded in the Tahiti post-glacial reef sequence over the last 13·5 ka average 6·10 and 6·56 mm year^{-1} in cores P7 and P8, respectively, and are substantially higher than those reported in Holocene reef complexes, other than those in Caribbean areas (10–15 mm year^{-1} in Alacran reef, Macintyre *et al.*, 1977; and in the St Croix reef, Adey, 1975). The highest rates (20·6 mm year^{-1}) coincide with the development of tabular *Acropora* communities. The growth rates of the robust *Acropora* gr. *danai/robusta* assemblage did not exceed 11 mm year^{-1} and are therefore similar to those reported in Barbados for *Acropora palmata* during the same time interval (see Blanchon & Shaw, 1995). The domal *Porites* communities grew at 13·6 mm year^{-1}. The lowest rates (≈0·4 mm year^{-1}) reflect the growth stabilization event when the reef surface reached a level within 2 m of the present sea surface about 5·5 ka.

ACKNOWLEDGEMENTS

This work was supported financially by the PNRCO (Programme National sur les Récifs Coralliens) and by IRD (Institut de Recherche pour le Développement). Gratitude is expressed to J. Récy, leader of the PNRCO Tahiti programme, and to Y. Join, J.-L. Laurent and C. Ihilly for their contribution in core drilling. We are grateful to G. Faure (UPRESA 6019) for the identification of corals, and F. Rougerie (IRD) for the use of his material previously recovered by drilling on the barrier reef in Tahiti and for fruitful conversations. We also wish to thank the administration of the Papeete Harbour for permits to drill and for assistance, B. Boccas (director of the IRD centre in Tahiti), L. Chungue and J. Pagès for their assistance in the preparation of field work, and for their help in logistical support. We also acknowledge J.-J. Motte (CEREGE) for drafting, and Y. Assante (Université de Provence) for assistance in the preparation of thin sections. Suggestions and comments by the reviewers, C. J. R. Braithwaite and L. Collins, helped to improve the manuscript.

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Manuscript received 21 May 1998;
revision accepted 6 January 1999