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Thematic Article

Modern carbonate sedimentary facies on the outer shelf and slope around New Caledonia

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Abstract We investigated surface carbonate sediments at 33 sites on the outer shelf and slope around New Caledonia (163°–167°E, 20°–23°S), at water depths of 75–720 m. Four carbonate sedimentary facies are recognized on the basis of sediment size fractions and predominant constituents: Facies 1, encrusted grains (rhodoliths and macroids), bryozoa, and benthic foraminifera; Facies 2, bryozoa, benthic foraminifera, and mud; Facies 3, plankton and mud; and Facies 4, ahermatypic corals. Facies distributions were constrained primarily by water depth, and secondarily by local seafloor geomorphology that, in some areas, allows transport of sediments to deeper water. Because the dominant facies (Facies 1 and 3), as well as lagoon and basin facies, are distributed worldwide at similar latitudes, facies around New Caledonia can be considered as representative of carbonate sedimentary facies distributed in tropical–subtropical regions.

Key words: carbonate sediment, coral reef, rimmed shelf, New Caledonia.

INTRODUCTION

Outer shelves and slopes occur in transitional zones from continental/island shelves to deep basins; water depths in these zones are in the range of tens to several thousands of meters (e.g. Uchupi 1968). In tropical to subtropical areas, outer shelves and slopes are generally composed of carbonate sedimentary facies (e.g. Ginsburg & James 1974). On rimmed shelves with coral reefs (e.g. in Belize and on the Great Barrier Reef of Australia), the transition from shallow water to deep-sea basin, which is marked by a distinct break in slope, occurs over relatively short distances of up to a few kilometers, and slope angles in this zone vary from approximately one degree to nearly vertical (Read 1985). Despite the importance of outer-shelf and slope sedimentary facies, studies of these transitional zones are scarce compared with the number of studies conducted on shelf sediments (e.g. Ginsburg & James 1974; Marshall & Davies 1978; Scoffin & Tudhope 1985; Chevillon 1996) and basin sediments (e.g. Swift 1977; Berger 1978; Liu & Cotillon 1989; Schmucker & Schiebel 2002).

Isolated carbonate platforms provide ideal conditions for examining carbonate sedimentary facies, as these environments are not influenced by large inputs of terrestrial sediments, as occurs on shelves and basins near continents, which are subject to discharges from large rivers (Ginsburg & James 1974; Swift 1977; Balsam & Beeson 2003). This study examines modern carbonate sedimentary facies on the outer shelf and slope around New Caledonia, which is located in a tropical–subtropical region. In combination with studies of shelf-lagoon sediments (e.g. Debenay 1987; Chevillon 1996), platform-reef sediments (Yamano *et al.* 2014), barrier-reef slope sediments (Flamand

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et al. 2008), and shelf-slope and basin sediments (Cotillon *et al.* 1989; Lambert & Roux 1991), our results contribute to a more comprehensive understanding of modern carbonate sedimentary facies, both in New Caledonia and worldwide.

SETTING

New Caledonia consists of several tropical to subtropical islands located in the southwest Pacific islands, ca. 1500 km east of Australia (Fig. 1). The main island, Grande Terre, is 400 km long and 50 km wide, and is surrounded by exceptional reef tracts. Southeast trade winds predominate during more than 70% of the year around New Caledonia (Ouillon *et al.* 2004). The southern part of New Caledonia is influenced by the eastward-flowing Subtropical Countercurrent, which branches from the East Australian Current, whereas the northern part is influenced by the westward-flowing South Equatorial Current

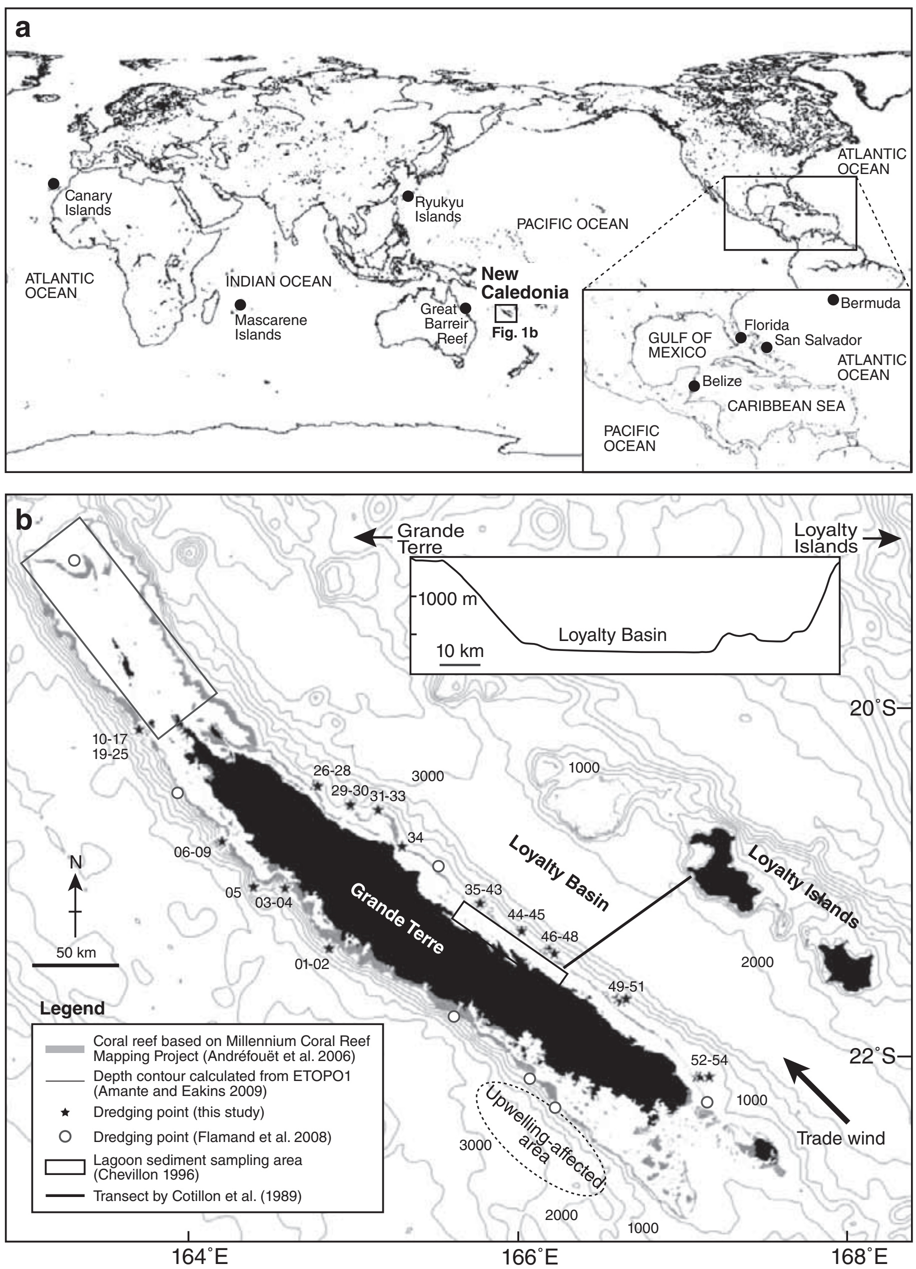

Fig. 1 (a) Locations of New Caledonia and other sites referred to in this study. (b) Map of New Caledonia showing dredging points in this study (numbers by the stars and contours indicate sample numbers and water depths, respectively), and sampling sites in previous studies (Cotillon *et al.* 1989; Chevillon 1996; Flamand *et al.* 2008). The inset shows a topographic profile along the transect of Cotillon *et al.* (1989), located along the island shelf/slope and basin, from New Caledonia to Loyalty Islands.

(Couvelard *et al.* 2008). Except for in southwestern New Caledonia, mean sea-surface temperatures (SSTs) are 27–28°C in summer and 23–25°C in winter. Sea-surface salinities (SSSs) are relatively stable throughout the year at 35.1–35.7 (Vega *et al.* 2006). During the summer, upwelling caused by strong trade wind events causes anomalous SSTs and SSSs in southwestern New Caledonia (Hénin & Cresswell 2005; Alory *et al.* 2006; Marchesiello *et al.* 2010). The vertical structure of the water mass in the region shows three distinct water layers: a shallow water layer at 0–150 m, with temperatures of 22–28°C and salinities of 35.1–35.7; a southern subtropical water layer at 150–500 m, with temperatures of 12–22°C and salinities of 34.8–35.7; and an intermediate deep Antarctic water layer at 600–2800 m, with temperatures of 2–10°C and salinities of 34.4–34.7 (Guevel 1983; Roux *et al.* 1991). Annual mean significant wave height around New Caledonia was estimated to be 1.5–2.0 m (Cox & Swail 2001). The intensity of cyclones threatening directly New Caledonia was not high, showing 12 cyclones in the past 20 years (Guillemot *et al.* 2010).

New Caledonia is surrounded by ca. 31 300 km^2 of shelf lagoon extending 5–40 km offshore (Andréfouët *et al.* 2009) to water depths of ca. 40 m; where substrates are available, fringing reefs are preferentially developed along eastern coasts (Coudray 1976). Barrier reefs are located at the shelf margin (Coudray 1976; Cabioch *et al.* 1999; Andréfouët *et al.* 2009); thus, the shelf is classified as a rimmed shelf (*sensu* Read 1985; Tucker & Wright 1990). The eastern portion of the slope is ca. 15 km wide and has a slope angle of ca. 7.5° (Liu & Cotillon 1989). Recently, several bathymetric surveys along the shelf edge to slope (Pelletier *et al.* 2002) have revealed details of submarine geomorphic features, including the existence of cliffs and mounds on the slope, some of which may be hard-substrate features, based on evidence from seafloor observations (Vanney 1991). The basin is an extremely flat abyssal plain with an average depth of 2350 m (Liu & Cotillon 1989) and subsurface sediments composed of terrigenous clay derived from past intensive erosion of Grande Terre (Bitoun & Récy 1982; Cotillon *et al.* 1989; Liu & Cotillon 1989).

Surficial carbonate sediments have been examined at sites in the lagoon all around New Caledonia (Debenay 1987; Chevillon & Clavier 1988; Chevillon & Richer de Forges 1988; Chevillon 1996) and in the eastern portion of the shelf slope in Loyalty Basin (Fig. 1b) (Cotillon *et al.* 1989; Liu & Cotillon 1989; Lambert & Roux 1991). Chevillon (1996) showed that the major constituents of lagoon sediments are benthic mollusks (bivalves and gastropods), benthic foraminifera, and *Halimeda*. Terrestrial mud fractions are restricted to bays, and the mud fraction decreases progressively offshore to the barrier reef, where the mud content of the sediments is less than 5% (Chevillon & Richer de Forges 1988). This indicates poor transport of terrestrial materials to the shelf slope.

Outside the barrier reefs, dredging has been conducted at water depths of 40–200 m at several places on the barrier-reef slope. Analyses of hand specimens obtained from the dredged samples reveal that the dominant encrusting organisms are composed mainly of coralline algae and/or foraminifera (Flamand *et al.* 2008). Based on surface-sediment data along a transect across the shelf slope and basin (Fig. 1b), Cotillon *et al.* (1989) suggested that the facies at water depths of 300–1000 m are dominated by planktonic foraminifera, along with pteropods and benthic organisms. In the Loyalty Basin, where water depths are >2000 m, surface sediments collected at ten sites were dominated by planktonic foraminifera, and the sand fraction constituted >85% of the sediment. The scarcity of pteropods in the basin sediments has been attributed to the dissolution of aragonite at depths of >2000 m (Berger 1978; Betzer *et al.* 1984; Byrne *et al.* 1984).

METHODS

Dredging was conducted at 54 sites around New Caledonia between 30 May and 7 June 2005, during a research cruise by the Institut de Recherche pour le Développement (IRD) R/V ALIS (see Fig. 1b and Table 1; Pelletier *et al.* 2006). The positions of the sampling sites and the water depth at each site were determined by GPS (Leica MX 400, Heerbrugg, Switzerland) and multibeam sounder (Simrad EM 1002, Horten, Norway), respectively; all instruments were equipped with ALIS. Because the sampling sites are not in areas subject to upwelling (Hénin & Cresswell 2005; Alory *et al.* 2006; Marchesiello *et al.* 2010), the SSTs and SSSs were expected to be similar among sites. Currents at the sites were calculated using a regional oceanic model (ROMS; Marchesiello *et al.* 2010), originally developed by Shchepetkin and McWilliams (2005).

Table 1 Characteristics of samples and locations of sampling sites investigated in this study. After Pelletier *et al*. (2006). Initial and end locations indicate those where the dredger was put and recovered, respectively

ID	Initial location			End location			Remarks	Sediment analysis
	Latitude (°S)	Longitude (°E)	Depth (m)	Latitude (°S)	Longitude (°E)	Depth (m)		
DR01	21.393	164.875	240	21.391	164.874	165	Cemented carbonate fragment	
DR02	21.396	164.867	350	21.398	164.868	240	Ahermatypic coral	†
DR03	21.043	164.605	250	21.041	164.604	100	Encrusted grain	†
DR04	21.041	164.604	100	21.038	164.602	100	No recovery	
DR05	21.028	164.418	660	21.033	164.417	590	Sand + mud	‡
DR06	20.778	164.195	650	20.778	164.195	650	Sand + mud	‡
DR07	20.773	164.205	560	20.773	164.205	560	Rock fragment	
DR08	20.767	164.213	460	20.767	164.213	460	No recovery	
DR09	20.761	164.223	250	20.761	164.223	250	Encrusted grain + sand	‡
DR10	20.157	163.778	90	20.154	163.778	85	Encrusted grain	†
DR11	20.148	163.769	200	20.148	163.771	75	Encrusted grain + sand	‡
DR12	20.136	163.758	500	20.136	163.760	390	Encrusted grain + sand	‡
DR13	20.133	163.753	640	20.133	163.755	490	Dredger lost, no recovery	
DR14	20.131	163.762	200	20.131	163.763	100	Encrusted grain + sand	‡
DR15	20.120	163.751	450	20.120	163.753	280	Cemented carbonate fragment	
DR16	20.115	163.751	430	20.115	163.753	250	Dredger lost, no recovery	
DR17	20.114	163.763	245	20.118	163.761	205	Sand + mud	‡
DR19	20.103	163.753	260	20.105	163.750	205	Encrusted grain	†
DR20	20.102	163.764	250	20.099	163.764	100	Cemented carbonate fragment	
DR21	20.094	163.756	200	20.093	163.758	100	Cemented carbonate fragment	
DR22	20.092	163.748	250	20.093	163.747	140	Encrusted grain	†
DR23	20.096	163.740	480	20.094	163.741	360	Cemented carbonate fragment	
DR24	20.088	163.736	520	20.088	163.739	440	Cemented carbonate fragment	
DR25	20.090	163.731	600	20.089	163.733	545	Rock fragment	
DR26	20.418	164.773	520	20.419	164.773	450	Ahermatypic coral, sand + mud	‡
DR27	20.423	164.789	510	20.424	164.790	465	Sand + mud	‡
DR28	20.427	164.795	520	20.427	164.797	480	No recovery	
DR29	20.547	164.989	450	20.546	164.990	345	Sand + mud	‡
DR30	20.540	164.998	450	20.541	164.996	355	Sand + mud	‡
DR31	20.566	165.141	450	20.567	165.143	375	Cemented carbonate fragment, sponge	
DR32	20.572	165.155	400	20.571	165.157	300	Ahermatypic coral	†
DR33	20.569	165.161	400	20.571	165.162	305	Ahermatypic coral, sponge	†
DR34	20.787	165.307	300	20.788	165.308	250	Sand + mud	‡
DR35	21.137	165.756	170	21.137	165.758	75	Encrusted grain + sand	‡
DR36	21.125	165.764	150	21.131	165.762	80	Encrusted grain + sand	‡
DR37	21.117	165.766	370	21.119	165.767	290	Cemented carbonate fragment	
DR38	21.120	165.766	295	21.121	165.767	260	Cemented carbonate fragment	
DR39	21.111	165.779	450	21.112	165.779	420	Cemented carbonate fragment	
DR40	21.115	165.791	500	21.117	165.792	500	Sand + mud	‡
DR41	21.120	165.784	425	21.122	165.785	425	Sand + mud	‡
DR42	21.125	165.778	350	21.128	165.779	350	Sand + mud	‡
DR43	21.129	165.770	250	21.131	165.771	250	Mollusc, bryozoa	†
DR44	21.275	166.020	680	21.276	166.018	550	Rock fragment, sand+mud	‡
DR45	21.293	166.023	410	21.295	166.022	300	Rock fragment	
DR46	21.403	166.170	380	21.404	166.170	295	Encrusted grain + sand	‡
DR47	21.404	166.183	380	21.405	166.183	295	Encrusted grain + sand	‡
DR48	21.426	166.220	400	21.426	166.219	290	Encrusted grain + sand	‡
DR49	21.698	166.598	500	21.701	166.596	400	Sand + mud	‡
DR50	21.712	166.619	530	21.715	166.617	410	Sand + mud	‡
DR51	21.700	166.647	720	21.704	166.647	650	Sand + mud	‡
DR52	22.163	167.067	110	22.170	167.068	110	Encrusted grain + sand	‡
DR53	22.163	167.092	280	22.168	167.093	280	Cemented carbonate fragment	
DR54	22.163	167.143	360	22.167	167.143	360	No recovery	

† Only hand specimens were examined, as no mud- or sand-sized fractions were present in the sample.
‡ Both hand specimens and mud- and or sand-sized fractions were examined.

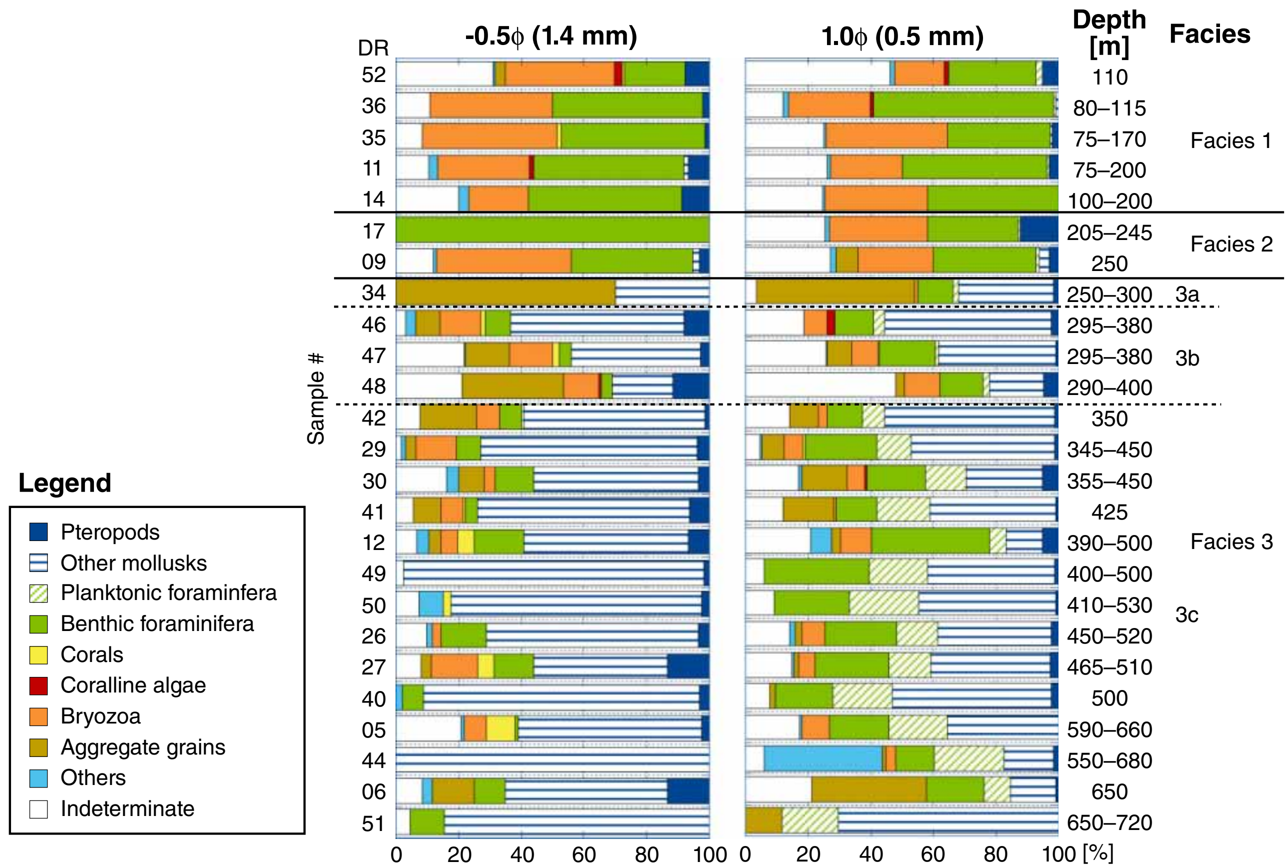

Fig. 2 Sediment constituents in the –0.5ϕ (diameter, 1.4 mm) (left) and b + 1.0ϕ (diameter, 0.5 mm) (right) size fractions. The sampling sites, shown in Fig. 1 and Table 1, are arranged according to increasing water depth. Sedimentary facies recognized on the basis of constituents are indicated on the right. See the text for facies descriptions.

Sediment samples were obtained at 33 of the 54 sampling sites, at water depths of 75–720 m on the outer shelf and slope around New Caledonia (Fig. 1 and Table 1). Fragments of hard blocks (bedrock and/or fossil reefs) were not analyzed, as the purpose of the study was to examine modern sedimentary facies. Sediments were analyzed for texture and composition. Whereas Flamand *et al.* (2008) examined hand specimens on the barrier reef slope, we analyzed both sand-sized fractions and hand specimens for the 25 samples that contained sand-sized sediments (Table 1). Sieving and constituent analyses were conducted after Chevillon (1996). After homogenization, the samples were dried and weighed, and the mud fraction was removed by washing through a 3.98ϕ sieve. The remaining sediment fraction was dried, reweighed, and dry sieved using the following mesh sizes: 3.98ϕ, 3.00ϕ, 2.00ϕ, 1.00ϕ, 0.00ϕ, –0.50ϕ, –1.00ϕ, –1.32ϕ, –2.00ϕ, –2.32ϕ, –3.00ϕ, –3.32ϕ, –4.00ϕ, and –4.32ϕ. At least 200 grains in each size class coarser than 2.00ϕ were identified and point counted under a binocular microscope. If the number of grains was less than 200, we identified and counted all grains. Encrusted grains (rhodoliths and macroids) were slabbed and thin sectioned, and internal structures were examined under a petrographic microscope.

RESULTS AND DISCUSSION

CHARACTERISTICS OF SEDIMENTARY FACIES

We recognize four sedimentary facies around New Caledonia on the basis of sediment size fractions and constituents (Fig. 2).

Facies 1: encrusted grain, bryozoa, and benthic foraminifera facies

This facies, which is characterized by encrusted grains (Fig. 3b), is composed mainly of cobbles and cobble- and pebble-sized sediments and sands, and is generally distributed at depths of 75–200 m (Figs. 2,3a). The average gravel-, sand- and mud-

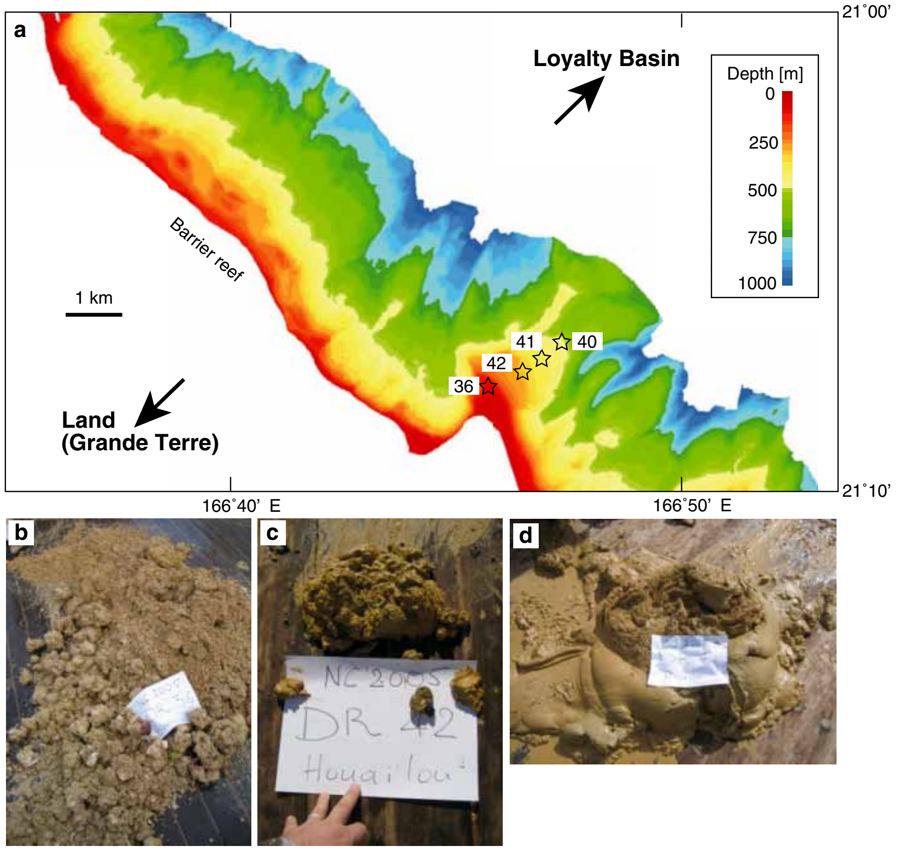

Fig. 3 (a) Map showing the locations of sites DR36, DR40, DR41, and DR42, and the bathymetry of the surrounding outer shelf and slope (from Pelletier *et al.* 2002). (b) Photograph of sample DR36. (c) Photograph of sample DR42. (d) Photograph of sample DR41. The photographs are from Pelletier *et al.* (2006).

sized fractions are 53%, 45% and 2%, respectively. The gravel-sized sediments are dominated by encrusted grains (rhodoliths and macroids) with diameters of 4–10 cm. The encrusted grains, which comprise more than 80% of the sediment mass, are composed of crusts of coralline algae and foraminifera (e.g. *Gypsina plana*), but foraminifera can constitute more than 80% of the mass and form macroids. Most rhodoliths and macroids are irregular-shaped, and whitish envelope overlies the inner part, which has been bioeroded. Some of the bioeroded parts are filled with a mixture of bioclast and micrite. The sand-sized sediments are composed mainly of bryozoa and benthic foraminifera. Planktonic foraminifera and mollusks are minor constituents. Larger benthic foraminifera are dominant, and are characterized by *Cycloclypeus carpenteri*. Encrusted grains of coralline algae and foraminifera are restricted to water depths of 200 m or less, which may be explained by the extinction of light at depths greater than approximately 200 m, as observed in the Loyalty Islands area (Roux *et al.* 1991). The calculated maximum and average current speeds at the sites where Facies 1 is found are 14 cm/s and ca. 3 cm/s, respectively.

Facies 2: bryozoa, benthic foraminifera, and mud facies

This facies, which is characterized by bryozoa and benthic foraminifera, is composed of sand and mud, and is distributed at depths of 200–250 m. The average gravel-, sand- and mud-sized fractions are 1%, 69% and 30%, respectively. Bryozoa and benthic foraminifera are the main constituents of sand-sized sediments, similar to those of Facies 1; specimens of *C. carpenteri* are, however, less abundant in Facies 2 than in Facies 1, and *Amphistegina radiata* is the dominant large benthic foraminifera. The calculated maximum and average current speeds are 10 cm/s and 3 cm/s, respectively.

Facies 3: plankton and mud facies

This facies, which is characterized by planktonic mollusks (pteropods) and foraminifera, is distrib-

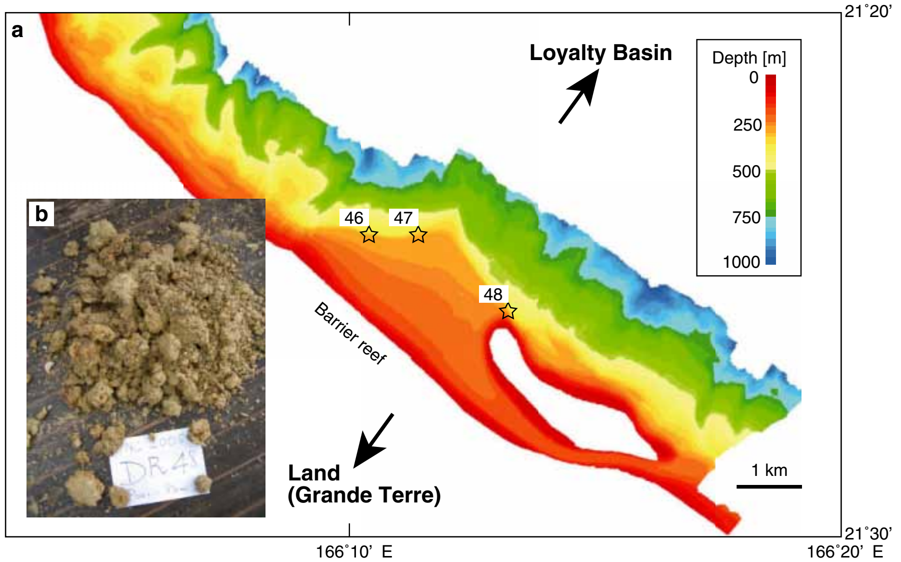

Fig. 4 (a) Map showing the locations of sites DR46, DR47, and DR48 and the bathymetry of the surrounding outer shelf and slope (from Pelletier *et al.* 2002). (b) Photograph of sample DR48. The photograph is from Pelletier *et al.* (2006).

uted at depths of 250–720 m (Figs. 3a,c,d,4a). The average gravel-, sand- and mud-sized fractions are 7%, 27% and 66%, respectively. A substantial amount of mud (33–94%) is present in unconsolidated samples. Pteropods and planktonic foraminifera comprise 10–65% and 5–25% of the sand-sized fraction, respectively. Bryozoa and benthic foraminifera combined comprise less than 10% of the sand-sized fraction. Facies 3 can be subdivided into three subfacies (Fig. 2). Facies 3a (DR34) contains aggregates of mud, and occurs at depths of 250–300 m. Facies 3b (DR46, DR47, and DR48) includes 10 cm-diameter encrusted grains and benthic organisms (bryozoa and foraminifera), in addition to planktonic organisms, and is observed at depths of 290–400 m (Fig. 4). Though cements potentially originated from mud dominate the grains, some of the grains are similar to those found in Facies 1 (Fig. 4b). Facies 3c is composed mainly of pteropods and planktonic foraminifera, with a small proportion of benthic foraminifera, including *C. carpenteri* and *A. radiata*, also suggesting transport from Facies 1. In all subfacies, the calculated maximum and average current speeds are 15 cm/s and 1–4 cm/s, respectively.

Facies 4: ahermatypic coral facies

This facies, which was found in three samples (DR02, DR26, and DR32), is characterized by dominant ahermatypic corals and sponges (Fig. 5b). However, the dominant species of coral varies from site to site. Caryophylliidae [*Paracyathus*? sp. (juv.), *Dendrophyllia*? sp., and unidentified species] are found on the western coast, (DR02), whereas Caryophylliidae (*Eguchipsammia* sp.) (DR26), *Cladocora* cf. *pacifica* and *Dactylotrochus cervicornis* (DR32) are found on the eastern coast. Facies 4 occurs on cone-like mounds distributed at depths of 240–520 m (Fig. 5a). Maximum and average current speeds at the sites where Facies 4 is found, calculated at nearby grid nodes (the parameters could not be calculated for the specific sampling sites), are ca. 10 cm/s and ca. 1 cm/s, respectively.

FACTORS CONTROLLING FACIES DISTRIBUTIONS

The modern facies on the outer shelf and shelf slope around New Caledonia appear to be constrained primarily by water depth (Figs. 2,6). The distribution of Facies 1, which consists of foraminiferal–algal encrusted grains with bryozoa and the foraminifera *C. carpenteri*, is generally limited to water depths of less than 200 m. At water depths greater than 200 m, encrusted grains are less abundant and the mud fraction increases, although the coarse sediments are still dominated by benthos (bryozoa and foraminifera). At water depths greater than 250 m, where the mud fraction dominates the sediment mass, the fraction of sediments of planktonic origin increases significantly, and reaches up to 90% of the coarse sediment mass.

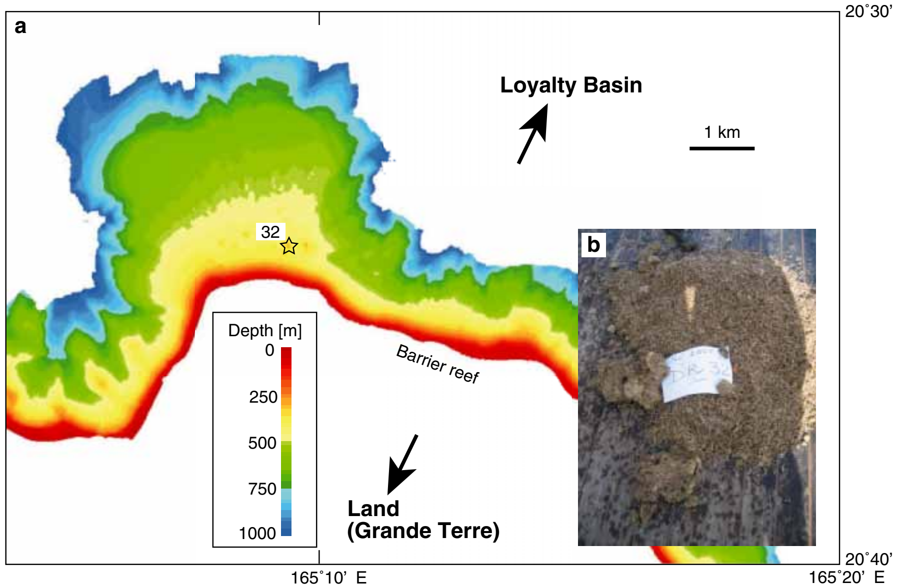

Fig. 5 (a) Map showing the location of site DR32 and the bathymetry of the surrounding outer shelf and slope (from Pelletier *et al.* 2002). (b) Photograph of sample DR32. The photograph is from Pelletier *et al.* (2006).

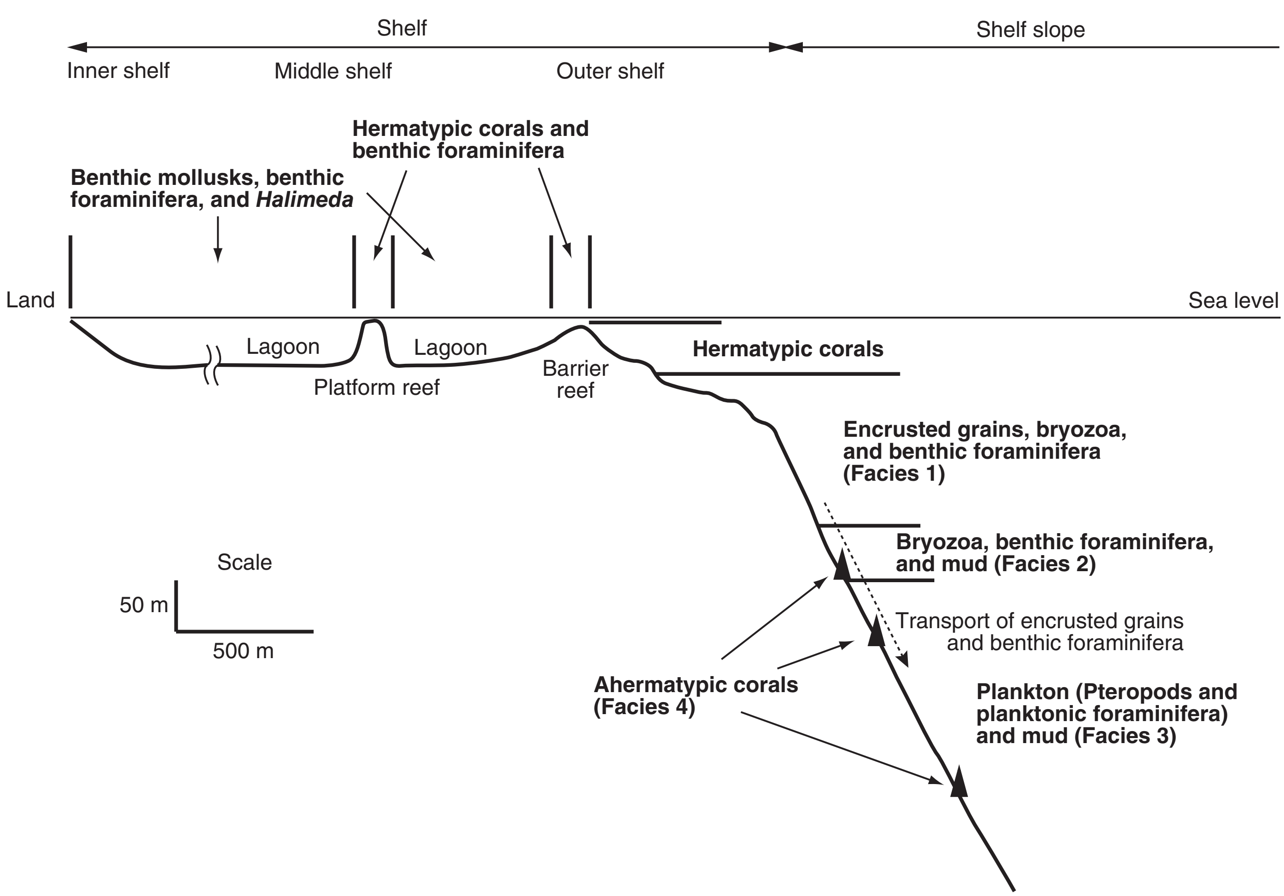

Fig. 6 Schematic figure of the geomorphology and facies distributions around New Caledonia, based on previous studies (Cotillon *et al.* 1989; Chevillon 1996; Flamand *et al.* 2008; Yamano *et al.* 2014) and this study. This figure was derived mainly for the eastern coast of New Caledonia, and may be most applicable to oligotrophic water conditions.

Facies distributions similar to those observed on the outer shelf and shelf slope around New Caledonia, especially those of Facies 1 and 3, may be found in other tropical–subtropical regions in oligophotic environments (Fig. 6). Facies with foraminiferal–algal encrusted grains (rhodoliths and macroids), which corresponds to Facies 1, are distributed widely in the Indian and Pacific oceans (e.g. the Ryukyu and Mascarene islands) and the Atlantic Ocean and Caribbean Sea (e.g. the Gulf of Mexico, Florida, San Salvador, eastern Caribbean Sea, Bermuda, and the Canary Islands; reviewed by Matsuda & Iryu 2011), at water depths of 30–150 m (Matsuda & Iryu 2011). Specifically, in the Ryukyu Islands, Japan, distributions of bryozoan sands and the foraminiferan *C. carpenteri* (equivalent to Facies 1 of this study) are restricted to water depths of 60–200 m and 50–135 m, respectively (Tsuji 1993; Iryu *et al.* 1995). However, in the tropical–subtropical Great Barrier Reef region (Scoffin & Tudhope 1985; Marshall & Davies 1988) and Belize (James & Ginsburg 1979), abundant *Halimeda* occur within the depth ranges observed for Facies 1 and 2. The occurrence of *Halimeda* could be due to differences in trophic resources that affect the distributions of marine organisms in different areas (Hallock 1987). Nutrient-rich environments on the Great Barrier Reef and in the Caribbean Sea, which occur because of upwelling (Hallock *et al.* 1988; Marshall & Davies 1988), could allow the luxuriant growth of *Halimeda* in these areas, whereas potentially nutrient-poor environments without significant upwelling (Iryu *et al.* 1995; Alory *et al.* 2006) could produce facies with characteristics that are similar to those found around New Caledonia and the Ryukyu Islands. Facies with pteropods and planktonic foraminifera (Facies 3) are also broadly distributed at water depths greater than ca. 200 m in the Pacific Ocean and the Caribbean Sea (e.g. James & Ginsburg 1979; Tsuji 1993).

Secondary constraints on facies distributions may be related to local geomorphic features. Although foraminiferal–algal encrusted grains (rhodoliths and macroids) are generally restricted to depths of less than ca. 200 m (Matsuda & Iryu 2011), Facies 3b, which includes the grains, occurs at depths of 290–400 m; however, sampling sites for Facies 3 (DR46, DR47, and DR48) are situated on a steep slope (Fig. 4a), suggesting that the grains have been transported from the reef slope. Ahermatypic coral facies (Facies 4) are found only on cone-like mounds (DR02, DR26, and DR32; Fig. 5a).

Two additional factors should be considered further. First, the transport of reef and reef-slope materials to deeper regions (e.g. by typhoons) may play an important role in facies formation. As we discussed above, foraminiferal–algal encrusted grains and benthic foraminifera in Facies 3 could have been originally distributed in shallower waters (<200 m) and transported, a process that could have been enhanced by local geomorphology (Fig. 4a). Cotillon *et al.* (1989) showed that relatively shallow water (<250 m) symbiotic benthic foraminifera (*Amphistegina*, *Cycloclypeus*, *Baculogypsina*, *Heterostegina*, *Peneroplis*, and *Planorbulina*) occur in deeper waters northeast of the Loyalty Islands. In addition, small but ubiquitous occurrences of reef-derived materials (e.g. hermatypic corals) have been observed in cores collected from the slope and basin to the northeast of Grande Terre (Cotillon *et al.* 1989; Liu & Cotillon 1989).

Second, current speed may affect the distributions of foraminiferal–algal encrusted grains (rhodoliths and macroids), as they require a certain speed of rotation in the formation process. High-energy environments influenced by strong tidal and/or boundary currents (65 cm/s; Tsuji *et al.* 1993, and 130 cm/s; Harris *et al.* 1996) probably contribute to the formation of rhodoliths and macroids, on account of the large rotational forces present in these environments. Flume experiments support this, showing current speed of 80 cm/s is needed for rotation of 5-cm diameter rhodoliths (Harris *et al.* 1996), which would be similar to those included in Facies 1. In contrast, rhodoliths and macroids may also develop in low-energy environments (currents of 5–25 cm/s; Prager & Ginsburg 1989). Our regional oceanic model (ROMS) calculations show a maximum current speed of 14 cm/s for the sites at which rhodoliths and macroids are present. These results support the low-energy formation hypothesis of Prager and Ginsburg (1989). Harris *et al.* (1996) showed significant wave heights on the Fraser Island continental shelf of eastern Australia, where rhodoliths occur, were 1.53–1.66 m, and suggested that the waves would generate near-bed oscillatory flows that could initiate movement of the rhodoliths. Because wave climates are similar between eastern Australia and New Caledonia (Cox & Swail 2001), the same initiation mechanism could work for New Caledonia. In addition, though not frequent (Guillemot *et al.* 2010), typhoons and bioturbation could also contribute to rotation. Further investigations into the formation mechanisms of rhodoliths and macroids are required.

MODERN CARBONATE SEDIMENTARY FACIES AROUND NEW CALEDONIA

Because geomorphic features around New Caledonia have been identified by optical remote sensing and acoustic multibeam observations (Andréfouët *et al.* 2009), general outer-shelf and shelf-slope facies patterns in the region, as defined by water depth and geomorphology, can be integrated with the distributions of lagoons (Chevillon 1996), platform reefs (Yamano *et al.* 2014), reef slopes (Flamand *et al.* 2008), and basin facies (Cotillon *et al.* 1989) (Fig. 6). Major constituents of lagoon sediments are benthic mollusks (bivalves and gastropods), benthic foraminifera, and *Halimeda*, whereas hermatypic corals are minor constituents except in areas close to patch and barrier reefs (Chevillon 1996) and to platform reefs in lagoons, where hermatypic corals and shallow-water foraminifera (*Baculogypsina sphaerulata*; Yamano *et al.* 2014) are abundant. Barrier-reef facies are likely similar to those of the platform reefs. Reef slopes may be dominated by hermatypic corals (cf. Iryu *et al.* 1995). Facies on the outer shelf and slope are composed of foraminiferal–algal encrusted grains, bryozoa, and benthic foraminifera (mainly *C. carpenteri*), to a water depth of ca. 200 m. The proportions of coralline algae and foraminifera in the grains vary according to water depth; at depths greater than ca. 90 m, encrusting foraminifera progressively replace coralline algae in the encrusted grains (Flamand *et al.* 2008). Though material in the outer-shelf and slope facies (e.g. encrusted grains and benthic foraminifera) can be transported to greater depths, pteropods and planktonic foraminifera dominate shelf-slope and basin sediments to a depth of ca. 2000 m (Cotillon *et al.* 1989); at depths greater than 2000 m, pteropods are absent, probably because their aragonitic skeletons dissolve at these depths (Berger 1978; Betzer *et al.* 1984; Byrne *et al.* 1984). In the basin, at depths greater than 2000 m, planktonic foraminifera are dominant. Ahermatypic corals may occur on cone-like mounds on the shelf slope.

As discussed in the previous section, foraminiferal–algal encrusted grain facies and planktonic facies are distributed worldwide. In addition, minor proportions of hermatypic corals in the lagoon are also found in lagoons with similar depths in other areas of the world (e.g. Yamano *et al.* 2002; Gischler 2006). Therefore, facies distributions around New Caledonia may provide representative examples of carbonate facies distributions in tropical–subtropical regions throughout the world.

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