ATOLL RESEARCH BULLETIN

NO. 299

THE SEAWARD MARGIN OF MAKATEA, AN UPLIFTED CARBONATE ISLAND (TUAMOTUS, CENTRAL PACIFIC)

BY

L. F. MONTAGGIONI, C. GABRIE, O. NAIM,
C. PAYRI, G. RICHARD, B. SALVAT

ISSUED BY
THE SMITHSONIAN INSTITUTION
WASHINGTON, D.C., U.S.A.
AUGUST 1987

RESUME

Après une brève présentation de l'histoire géologique du nord-ouest de l'archipel des Tuamotu, présentation qui prête une attention toute particulière à l'île de Makatea, un pseudo-atoll *sensu* AGASSIZ, l'article décrit les grands traits géomorphologiques et bio-écologiques de la bordure récifale actuelle de cette île.

L'île de Makatea (7 km x 4.5 km) présente une géomorphologie récifale très particulière dont les caractéristiques résultent d'évènements liés à la tectonique globale ou régionale (eustatisme, climat, soulèvement...) survenus principalement durant le quaternaire, les facteurs écologiques intervenant ici de manière particulièrement modérée.

On distingue trois types de formations, en fonction du degré d'évolution et d'exposition: sur les côtes nord et est de l'île, des récifs tabliers assimilables à des trottoirs d'algues calcaires - sur la côte occidentale (baie de Moumu), des récifs frangeants de mode calme - sur les côtes sud-ouest et sud-est, des récifs frangeants de mode battu.

Les caractéristiques écologiques principales de la bordure récifale actuelle sont la monotonie et la pauvreté de la faune benthique, d'une part, et, d'autre part, l'importance des algues brunes (notamment *Turbinaria*).

La flore algale (45 espèces) est constituée d'un mélange d'espèces typiques d'îles hautes volcaniques (Phéophycées) et d'espèces typiques d'îles basses carbonatées (Chlorophycées).

Alors que les colonies de Madrépores vivant sur les platiers et les fronts récifaux sont peu développées (encroûtantes) et peu abondantes, une majorité des pentes externes est caractérisée par la richesse et la vitalité des communautés coralliennes où les formes dominantes appartiennent aux genres *Acropora*, *Porites*, *Pocillopora* et *Astreopora*.

La macrofaune benthique associée (Mollusques, Echinodermes...) est plus pauvre que celle généralement observée le long des récifs extérieurs d'atolls polynésiens; les Mollusques apparaissant particulièrement sous-représentés. Ce fait est probablement dû à la réduction des biotopes réprésentés sur Makatea, et à l'émersion prolongée de nombre de platiers récifaux.

Makatea semble être une île très particulière dans l'ensemble de l'archipel des Tuamotu; aussi, les principaux traits écobiologiques soulignés ici ne peuvent être utilisés comme modèle pour les îles polynésiennes avoisinnantes. En revanche, c'est un champ d'expérimentation très intéressant d'un point de vue géologique, car l'île recèle près de 25 millions d'années d'histoire du Pacifique, à notre portée à la surface de l'océan. De futures recherches sur Makatea devraient se focaliser de préférence sur les dépôts carbonatés Miocène: nature et distribution des principaux constructeurs, croissance récifale et modifications en liaison avec la tectonique globale, premières phases des processus de diagénèse et phosphatogénèse.

THE SEAWARD MARGIN OF MAKATEA, AN UPLIFTED CARBONATE ISLAND (TUAMOTUS, CENTRAL PACIFIC)

BY

L. F. MONTAGGIONI[1,2], C. GABRIE[2,3], O. NAIM[1,2],
C. PAYRI[2,3], G. RICHARD[2,3], B. SALVAT[2,3]

INTRODUCTION

Located at 148°15' West and 15°50' South, in the northwesternmost part of the Tuamotu archipelago (Central Pacific), Makatea island is isolated from its nearest neighbouring atolls, Rangiroa and Tikehau by about 80 km, and it is 245 km from its closest volcanic neighbour, Tahiti. This island rises at least 3,500 m above the sea floor (Figure 1).

Like all Tuamotu islands, Makatea consists of biogenic deposits. But unlike the other islands which rise no more than a few metres above sea level and surround lagoons, Makatea reaches more than 100 m in elevation. Based on foraminiferal assemblages, age determination clearly indicated that the island frame was built up during Early Miocene (Montaggioni *et al.* 1985 a; Montaggioni, 1985).

Makatea, measuring 7 km by 4.5 km, is a crescent - shaped island, irregular in outline (Figure 2). Its northwestern and northeastern faces are more or less concave, respectively occupied by the bays of Temao and Moumu. Makatea is partly surrounded by a reef margin extending outward some 100 metres from the base of the cliffs and ending in subvertical drop-offs.

After presenting the geological history of the northwestern Tuamotu islands with special reference to Makatea as an atoll-like island, the present contribution describes the main morphological, sedimentological and ecological features of the seaward reef margin of this island.

[1] Université de La Réunion, B.P. 5, 97490 Ste Clotilde, France D.O.M.

[2] Antenne du Muséum National d'Histoire Naturelle - Ecole Pratique des Hautes Etudes, Centre de l'Environnement d'Opunohu, B.P. 1013, Papetoai, Moorea, French Polynesia.

[3] Laboratoire de Biologie Marine et Malacologie, Ecole Pratique des Hautes Etudes, 55, Rue de Buffon, 75005 Paris, France.

MAKATEA, A HIGH ATOLL-SHAPED ISLAND FROM THE NORTHWESTERN TUAMOTU RIDGE.

A. GEOLOGICAL HISTORY OF THE NORTHWESTERN TUAMOTUS

According to bathymetric maps (Monti 1974 ; Mammerickx *et al.* 1975)., the northwestern Tuamotu atolls cap the tops of volcanic cones which rise steeply not from the ocean floor, which is 4,000 to 4,500 m deep in this region, but from a huge ridge forming wide shelves ranging in depth from 1,500 to 3,000 m. Summarizing Deep Sea Drilling Project (DSDP) results, Clague (1981), Schlanger (1981) and Schlanger *et al.* (1984) noted that for the Line and northwestern Tuamotu chains, the foundations of extinct volcanoes appear to have been simultaneously, and not sequentially, active. As a result, these results are reviving Menard (1964)'s postulated Darwin Rise, which he envisaged as having gradually foundered after the end of volcanic activity, leaving subsidence reefs in its wake. Geomorphological and geochronological evidence indicates that the formation of the Tuamotu chain is much older than that of the surrounding other French Polynesian islands. The existence of a massive submerged ridge and lack of high volcanic islands are in accordance with average ages deduced from DSPD. At sites 76 (Hays *et al.* 1972) and 318 (Schlanger *et al.* 1976) drilled on the northwestern flank of the Tuamotu ridge, and on the ridge itself, reefal debris of Early to Late Eocene age were sampled. It appears that the Tuamotu reefs have contributed to deep-water sedimentation since Early Eocene (50-51 m.y.). These fossils can be interpreted as indicative of a possible date for cessation of volcanism in the Late Cretaceous to Early Eocene for at least the northwestern part of the Tuamotu chain (Schlanger 1981).

The Tuamotu islands are relatively close to the East Pacific Rise where lithospheric cooling induces most rapid deepening (Heezen *et al.* 1973). Likewise the large number and close spacing of the Tuamotu atolls is indicative of their origin in shallower waters close to the East Pacific Rise; according to Scott and Rotondo (1983), on average more of the newly formed seamounts would have kept pace with sea level here, simply because of the shallower water. Although Farrar and Dixon (1981) think that the Tuamotu volcanic basement is the product of a mechanism consistent with the fixed hot spot hypothesis, the early history of such a bathymetrically complex chain might not have followed a simple pattern. One of the major objectives of drilling in the Line-Northwestern Tuamotu lineation during DSDP Leg 33 was to determine if the volcanism responsible to the building of this chain was age progressive and thereby compatible with a hot spot origin. The results from drilling may be summarized as follows (Clague 1981) : 1) the age data obtained do not allow for an unambiguous test of the hot spot model for the origin of the Line-Northwesternmost Tuamotus. It is possible that the whole chain formed almost simultaneously between 80-85 m.y.B.P.; 2) the carbonate cores of the atolls are probably coeval along the chain ; 3) the chain is older than the oldest seamounts in the Society Islands. Jackson and Schlanger (1976) suggested that the entire ridge underwent epeirogenic uplift 80-85 m.y. ago which moved the preexisting shield volcanoes into shallow water; the Line and Northwestern Tuamotu islands beginned to be capped by reefs about 70-80 m.y. B.P. during subsidence following the epeirogenic pulse. Thus the major volcanic relief of the northwesternmost portion of the Tuamotus may be constructed during a period of widespread volcanic activity which affected the central Pacific region; this period of volcanism may be related to some other type of midplate mechanisms rather than hot spot activity or even to an activity related to old oceanic spreading centres.

A number of atolls are elevated in the northwestern Tuamotu region, all located in the vicinity of recently active volcanoes (Tahiti, Moorea, Mehetia) (Figure 3). As topographic profiles across similar oceanic volcanoes reveal moats and arches in the surrounding bathymetry, Mc Nutt and Menard (1978), Lambeck (1981) argued that the tectonic uplift of these atolls has resulted from the loading effects of the nearby Tahiti volcanic complex. A crustal moat developed peripheral to Tahiti, Moorea and Mehetia volcanoes; beyond the outer edge of the moat, flexuring developed an arch which experienced uplift in the order of tens of metres. Islands situated at various distances from this new loading mass can isostatically respond differentially: those within the developing arch are slowly elevated. It appears that the emerged atolls have been uplifted, with respect to present day sea level, by 3-6 m with the notable exception of Makatea (highest point : 113 m); the latter is also the island closest to the centre of the load and the one which would be expected to be uplifted most (Table 1). The ability to explain the variations in elevations of the arrays of similar atolls is a powerful test of Mc Nutt and Menard's theory. This explanation seems to be far more satisfactory than any hypothesis of a global change in sea level (Veeh 1966) or a regional elevation induced by overriding an asthenospheric bumps (Menard 1973). However, Jarrard and Turner (1979), Lambeck (1981) and Montaggioni (1985), while agreeing with this conclusion, disagree as to the exact amount of resultant elevational displacement. As Moorea, the oldest shield volcano, is dated of about 1.5 m.y. (Duncan and Mc Dougall 1976), the uplift is thought to have initiated during Early Pleistocene (Montaggioni, 1985; Pirazzoli and Montaggioni, 1985) rather than in Miocene times (Doumenge 1963, Chevalier 1973). Irrespective of the duration of vertical deformation of the underlying lithosphere , isostatic equilibrium still has not been reached in this area (Pirazzoli and Montaggioni, 1985).

Finally, Scott and Rotondo (1983) think that, since the larger Tuamotu atolls are in an ideal position south of the equator, many of them will survive for many million years during their slow passage through warm equatorial waters. But, they emphasized, however, that some smaller atolls will not survive even in equatorial waters because island pedestals sink into deeper water the living reef tops will become so narrow that they will no longer support any island form whatsoever.

Table 1 : Observational evidence for uplift of atolls associated with the Tahiti - Moorea volcanic load (modified from Mc Nutt and Menard, 1978 and Lambeck, 1981).

ATOLL	distance from Tahiti (km)	observed uplift (m)	theoretical uplift (m)	Misfit
Makatea	245	113	71.9	- 41.1
Mataiva	325	3.5	3.1	- 0.4
Rangiroa	340	3.5	0.0	- 3.5
Tikehau	345	4.0	0.5	- 3.5
Niau	350	5.0	6.5	+ 1.5
Kaukura	370	3.5	3.0	- 0.5
Anaa	430	6.0	5.3	- 0.7

B. MAKATEA AND THE ATOLL CONCEPT : TO BE OR NOT TO BE AN ATOLL ?

Darwin's deductive model of atoll genesis (1842) postulated that, as a subsiding volcanic island base disappeared below sea level, an atoll formed. Most atolls usually sink, as the sea floor cools and, consequently, sinks. However, tectonic displacements or eustatic changes preclude subsidence and atolls occasionally are elevated or emerge. Thus, numerous aspects of atoll history remain controversial, particulary the origin of the typical gross morphology showing a submergent ring around a broad, flattish lagoon. Earlier investigators (Forbes, 1893 ; Agassiz, 1903) then Hass (1962) and Menard (1964) suggested that such ring and lagoon were formed in many ways.

Arguments were advanced supporting the theory that such usual features resulted primarily from carbonate solution (Asano, 1942 ; Mc Neil, 1954 ; Purdy, 1974 ; Bourrouilh-Le Jan, 1977).

High coral islands all display a lot of similar characters : saucer-shaped gross morphology ; high peripheral rim with scattered residual hills ; pinnacled and deeply pitted surfaces ; single or multiple central depressions with isolated karstic towers ; outer and inner cliff walls.

However, long-term and presumably intensive solution alteration occurred in some places and not in others. Menard (1982) argued that one of the most important regional variables is the amount of rainfall. He demonstrated that the depth of atoll lagoons is largely a function of rainfall ; the depth generally increases with rainfall. Persistence of a number of Pacific elevated coral islands for millions of years can be ascribed to very low average annual rainfall (in cm per/year) : Makatea, 168 ; Ocean, 185 ; Mangaia, 191 ; Niue, 195 ; Nauru, 206. Two global factors which may be significant in terms of atoll morphology, are evaporation and climatic changes through time. The highly uplifted islands mentioned above are only in regions where evaporation exceeds rainfall. Moreover, regional variation in lagoon depth can result from a shift towards aridity during glacial periods. Consequently, elevated coral islands may be eroded very slowly in areas of low rainfall.

In brief, when tectonic or eustatic effects changed originally low reef islands into high islands, they were altered to a depth depended upon the amount of rainfall or the balance between rainfall and evaporation (Menard, 1982). The dominance of solution caused the top of the islands to be saucer-shaped. As sea level rose, the subaerially eroded surfaces may be progressively both colonized outward by builders or filled inward with unconsolidated skeletal sediments. As Bourrouilh-Le Jan (1977) and Scott and Rotondo (1983) concluded, the atoll concept must be mainly related to the recent eustatic and tectonic history of oceans. If, according to many authors, the term atoll refers to a Darwinian history of unceasing subsidence, Makatea and similar carbonate islands are not true atolls, but rather pseudo-atolls in the sense of Agassiz (1903 p. 105), i.e. ring-shaped reefs not formed by subsidence.

THE SEAWARD MARGIN : MEAN FEATURES

The survey of submarine features was limited to a few sites regarded as typical of the island, on the basis of mainland structure and exposure to wave action. The seaward reef margin of Makatea can be subdivided into three zones which are caused by differences in Recent morphologic evolution : an emerged, narrow reef flat zone of Late Holocene age (Montaggioni *et al.*, 1985 b), a shallower forereef zone whose lower limit is that of coral and calcareous green algal growth (about 60 m deep), and a deeper forereef zone which forms the upper parts of the island slope.

A. THE REEF FLAT ZONE

1. Morphology

Three fringing reef types can be distinguished on the basis of degree of evolution and exposition : apron reefs, high - energy and low energy reefs.

- Apron reef flats

At the base of the cliffs, at the extreme northern end and along the eastern coast of the island, living organic buildups occur as very narrow (3-10 m) pavements (Figure 4). The reef flat consists of a subhorizontal smooth-surfaced flagstone mainly made up by coralline algae (Figure 5).

- High energy fringing reef flats

Ranging in width from 70 to 90 m, these reefs are situated along the southwestern to southeastern shores. From sea landward two morphologic units have been described : outer reef front, reef flat.

The reef front is identified with the uppermost parts of outer organic spurs which emerge 0.40-0.50 m at low tide. Better coralline algal rims develop in higher wave energy. Thus a typical algal ridge is found on the southeastern reefs (Figure 6).

The reef flat resembles a deeply pitted and honeycombed flagstone. Just behind the algal ridge the substratum is furrowed with an outer moat parallel to the reef front , 10-20 m wide and 0.10 m deep. The surface becomes increasingly irregular and uneven : shallow erosional basins occur from place to place. In very exposed areas the reef flat topography is raised with conglomeratic crags, 2-10 m wide, 10-20 m long, oriented perpendicularly to reef front. Reaching 0.50 to 0.80 m above low tide level, these crags alternate with shallow (0.5 - 1 m) and narrow (1-2 m) grooves running across the reef flat zone from reef front shoreward. The crag-groove system tends to disappear towards the southern and southwestern areas, giving place to a common pitted flagstone. Generally the reef flat zone is separated from backreef sandy beaches by a narrow (5-10 m wide) and shallow (about 1 m deep) channel.

- Low-energy fringing reef flats.

Varying in width from 30 to 120 m, these reefs are found along the sheltered western coast and within Moumu Bay. Unlike that of the exposed reef tracts the reef front here is a subplanar platform (so-called *outer glacis*), a few metres in width. It is bounded shoreward by a microcliffed erosional step, 0.20-0.30 m high, spreading over 10 m and gently sloping towards the inner reef flat (Figures 7, 8).

The reef flat zone begins at the upper part of the microcliff; it consists of an organic planar, partly eroded flagstone exhibiting a number of shallow pools practically devoid of skeletal deposits. Behind this zone sand to pebble beaches or beach rock outcrops begin ; they gradually increase in width southward and eastward until they reach some 200 m wide at their widest part.

2. Ecological characteristics of benthic communities

- The outermost parts of the reef flat zone

In high-energy (eastern to southwestern) areas, construction is almost exclusively made by coralline algae (*Porolithon onkodes, P. craspedium*) which locally form a well-developed ridge. It reaches its maximum width (25 m) and thickness (0.15 m) along the southeastern area of the island. At the foot of the cliffs, in poorly developed reef areas, the algae *Porolithon* grow up to 1m high above mean sea level as vertical, thin veneers. The morphogenetic role of calcareous red algae progressively declines towards the more protected, southern, then southwestern shores. The front zone, therefore, grows richer in soft macroalgae typical of the reef edges of atolls, such as the brown algae *Lobophora variegata* and the green algae *Microdictyon, Neomeris, Halimeda, Caulerpa* and *Avrainvillea* . The coral fauna is very scattered or lacking; however some decimetre sized *Porites, Montastrea* and *Montipora* colonies and the hydrocoral *Millepora* were found. Consequently, except for the echinid *Colobocentrotus pedifer*, and a few crustaceans coming from the forereef zone, the fauna consists principally of molluscs. The dominant species are *Turbo setosus, Patella flexuosa, Drupa ricinus* and *D. morum.* Along the base of the exposed cliffs, *Thais aculeatus* assemblages occur up to 0.50 m above mean sea level ; this is successively replaced, at the height of 1.5 m, by a population of *Nerita plicata,* then, at the height of 2-2.5 m, by a population of *Littorina coccinea* (Figures 9, 10).

In low-energy (western to northeastern) areas, the reef front (so-called outer glacis) is characterized by a relative rich cover of coral communities in comparison with those from high-energy fronts. The dominant species is *Acropora rotumana* forming encrusting colonies. The subordinate forms consist of stunted *Porites sp., Leptastrea purpurea, Montipora sp., Montastrea curta* colonies, associated with scarce Faviidae. On the outer margin and in the outer part of the spurs, the hydrocoral *Millepora platyphylla* occur here and there. The amount of coral coverage ranges from 0 to 40%; it reaches maximum values at the outermost part of the glacis, while the top of the inner microcliffed step is totally devoid of corals. The algal cover fairly develops; coralline algae (*Lithophyllum sp.*) make up a skin-deep veneer only. Floristically speaking, the originality of the glacis lies mainly on the occurrence of an inner brown algal belt (*Lobophora variegata*).

Such an assemblage occurs wherever an erosional stepped reef front exists. In contrast, other Pheophyceae, and particularly *Turbinaria ornata* , are only observed at the vicinity of man-inhabited areas (Temao, Moumu); it is possible that the settlement of this brown alga may be a consequence of some human activity. The molluscan fauna is restricted to a few Muricids (*Drupa ricinus, D. morum, D. clathrata, Thais armigera, T. aculeatus, Mancinella tuberosa*) (Figures 11, 12).

- The inner parts of the reef flat zone

In exposed areas, just behind the algal ridge, the moat which parallels the reef front, is colonized by dense Rhodymenial or, locally, *Neomeris vanbosseae* turfs. Likewise this zone is rich in molluscs (*Thais aculeatus, Drupa ricinus, Tectarius grandinatus, Morula granulata, Bursa bufonia*); but it contains few corals. Directly landward of the outer moat, the reef flat grows richer in macroalgae. The brown alga *Lobophora variegata* becomes the dominating species whereas *Neomeris* is more or less absent. Three *Halimeda* species are present, in association with two other Chlorophyceae (*Caulerpa urvilliana, C. pickeringii*) and the red alga *Liagora ceranoïdes*
In the areas periodically subjected to exposure, the green alga *Cladophoroa* sp. flourishes. Molluscan communities are composed of *Tridacna maxima* (stunted shells), *Bursa bufonia, Thais armigera* and *Cypraea caputserpentis* . Locally, *in situ* dead *Chama iostoma* are found (Figures 9, 10). Corals are very scarce.

The crag-groove system is mainly colonized by molluscs (*Littorina coccinea, Thais aculeatus, Tectarius grandinatus, Morula granulata*). The bottom of pools and grooves are commonly occupied by cyanophytes (*Hassalia byssoïdea*), a few holothurids, crustaceans pagurids and molluscs neritids (*Clithon chlorostoma*). This zone also contains a few corals; colonies are stunted (mean diametre : 0.20 m) and form small clusters in ecologically favourable sites, i.e. along the margins of acting reef flat grooves. The most common forms are *Porites cf. compressa* and *Montastrea curta* ; the subordinate ones are *Pocillopora verrucosa, Favia stelligera, Leptastrea purpurea, Pavona clavus, P. varians* and *Psammocora contigua.*

In sheltered areas, at the top of the microcliff where the reef flat zone originates, a thin *Lithophyllum* rim occurs. Macrobenthic organisms are restricted to a soft algal turf (*Liagora ceranoïdes, Lobophora variegata*) inhabited by sparse molluscan populations (*Mancinella tuberosa, Thais aculeatus*). Shoreward of the microcliff, reef builders are almost absent.The coral fauna consists only of small-sized *Porites, Acropora* and *Leptastrea* colonies, and scattered calcareous algal crusts. This area consists mainly of an algal belt in which *Lobophora variegata* dominates along with various associated green algae (*Cladophora, Caulerpa, Halimeda*). Within pools, benthic communities are composed of the holothurid *Holothuria atra* and numerous molluscs (*Cypraea moneta, Morula granulata, Mitra litterata, M. pauperculata, Conus lividus*) most of which are carnivorous.

The inner limits of the low-energy reef flat are characterized by the presence of cyanophyte films (*Hassalia byssoïdea*, endolithic *Entophysalis granulosa*) associated with green algal populations (*Cladophora*). The macrofauna includes holothurids (*Holothuria*), grass-eating (*Puperita reticulata*) or carnivorous (*Cypraea moneta, C. depressa, Bursa bufonia, Morula granulata*) gastropods.

At the base of the cliffs and on the neighbouring beach-rock outcrops, irrespective of the areas considered, algal communities composed of *Hassalia* and *Entophysalis* are common. While echinoderms are sparse, molluscs constitue dense populations rich in neritids (*Nerita plicata, Clithon chlorostoma*) and littorinids (*Littorinea coccinea*) (Figure 11).

3. Unconsolidated sedimentary bodies

Modern skeletal sediments are mainly deposited as beaches.There are relatively well-developed along the southwestern and eastern margins of the island.

North of Temao the beach gradually narrows until it finally ends at the base of the cliffs. On the fringing reef flats and along the shallower fore-reef zone, loose skeletal deposits occur as thin and scattered layers and pockets. Figure 13 illustrates the textural and compositional characteristics of some typical sediment deposits.

- Texture

Two textural parameters (mean size Mz, sorting So; according to Folk and Ward, 1957) were graphically determined from the grain-size cumulative frequency curves.

Sediments from Moumu beach (eastern coast) are coarse to very coarse (Mz = 0.67-1.26 mm), well sorted (So= 0.77 - 1.41) sands. Those from Temao beach (western coast) consist chiefly of granules (Mz = 2.27 - 3.09 mm), generally poorly sorted (So = 1.15 - 1.79). Along the most exposed coastal areas the sands from the lower beach zone are very coarse-grained (Mz = 1.19 - 1.82 mm) and very well sorted (So = 0.58 - 0.87). In contrast, sediments trapped in erosional pools breaking the fringing reef surfaces, are of various types : well sorted (So = 0.80 - 0.87), coarse to very coarse sands (Mz = 0.66 - 1.71 mm); poorly sorted (So = 1.72) pebbles (Mz = 5.29 mm), or poorly sorted (So = 1.70) medium sands (Mz = 0.28 mm). Along the outer reef slopes, irrespective of the area considered the deposits consist mainly of very coarse (Mz = 1.23 - 1.31 mm), well sorted (So = 1.04 - 1.20) sands.

- Constituents

The constituent analysis data presented herein was processed in a manner similar to that defined by Gabrié and Montaggioni (1982). The grains counted were catalogued in 9 constituent categories (e.g. corals, coralline algae, *Halimeda* , molluscs, benthic foraminifers, crustaceans, bryozoans, serpulid worms and echinoderms); unidentified grains were left out from the statistical treatment since they are not quantitatively significant. In addition, the main foraminiferal genera were recognized.

The major sediment contributors are corals and calcareous algae (coralline forms and *Halimeda*). Foraminifers and molluscan elements are present in substantial content, whereas crustaceans, echinoderms, serpulids and bryozans play a minor sedimentogenetic role.

The coral component is the most ubiquitous in the whole reefal deposits; its abundance ranges between 20 to 38% of the total sediment particles. Amounts in coral grains increase rapidly seaward in the fore-reef zone (45-60%) as the cover rate of living corals increases. The abundance of coral material is originally due to the extensive development of forereef communities (herein), whose skeletal production partly supplies the inner reef areas during storm surges. Although coral elements are possibly widespread within all the size classes, they are best represented in coarse to medium-sized populations.

Likewise coralline algal detritus is widespread. It reaches levels of 22-37% on the fringing reef system as well as on the upper fore-reef zone. As could be expected the highest frequency of the coralline algal component is found in the high-energy reef areas where an algal ridge develops. Thus the occurrence of coralline algal grains in sediment can be considered a sensitive index of the close proximity of areas of high coralline algal productivity since their ability to be dispersed has been recognized to be particularly low (Maiklem, 1968. Montaggioni, 1978). This algal component is a significant contributor to sediment, chiefly in the size fractions greater than 1 mm.

Concerning *Halimeda* , the sediment production varies largely from place to place. The highest concentrations develop along the lower beach zones of the western and southwestern faces of the island (36%). In contrast, values are particularly low (4-5 %) along the northeastern margin and the whole shallow fore-reef zone (5-7 %). The distributional patterns of *Halimeda* seem to be controlled by sediment transport patterns rather than by the development and location of the living organisms. Indeed, along the fore-reef zone, *Halimeda* turfs reach rates of coverage up to 30% of the substrate, while they are practically lacking on the reef flat zones (herein). Owing to their great ability of movement, *Halimeda* plates are dispersed, from the outer slope and concentrate preferentially shoreward, i.e. in the more protected areas of the coastal margin. This is in accordance with previous investigations carried out in various reef provinces (Jindrich, 1969; Masse, 1970 ; Maxwell, 1973; Gabrié, 1982). The occurrence of *Halimeda* fragments is reasonably similar in all the size ranges.

Sediments contain relatively low amounts of molluscan particles which are appreciably equal for the whole environments (7-14 %). Higher values are found in Moumu bay (16%). These percentage data are possibly a reflection of the distributional pattern of molluscan populations since they are assumed to be relatively poor (herein). However these results may be also explained in terms of higher rate of dilution by other components as in some indopacific reef areas (Montaggioni, 1978; Gabrié, 1982). Molluscan grains are preferentially restricted to finer fractions.

Amounts of foraminiferal tests vary largely from reef front to beach (3-23%). The highest amounts develop in Moumu bay and the southern coast. Beyond the outer slopes, their abundance declines markedly so that the sediment contains 0.6 to 1.3% foraminifers. The most abundant forms belong to encrusting ones, such as Homotrematidae *(Miniacina alba, M. miniacea, Homotrema rubrum* : 0.2-7% of the total sediment grains ; *Carpenteria* : 0.2-4 %). The subordinate producers are Soritidae *(Sorites* : 0-3%) and Amphisteginidae *(Amphistegina* : 0-4%). The other types are rare : Planorbulinidae *(Planorbulina* = 0-0.5% ; *Gypsina* = 0-0.3%), Miliolidae (0-1%) and Cymbaloporidae (0-1%). The results obtained contrast strongly with the distributional pattern of foraminiferal populations in various indopacific reef areas where foraminifers are one of the major contributors to bioclasts (see, for instance, Cushman *et al.*, 1954;

Le Calvez *in* Guilcher *et al.*, 1965; Lewis, 1969; Masse, 1970; Coulbourn and Resig, 1975; Le Calvez and Salvat, 1980; Montaggioni, 1978, 1981; Venec-Peyré and Salvat, 1981; Gabrié, 1982). These data may be interpreted as indicating a lack of favourable environments for most types of foraminifers. While encrusting forms can easily find available substrates, epiphytic and free benthonic species do not flourish on Makatea reefs, as a consequence of lack of dense sea grass beds and wide subtidal sediment accumulations.

Although they never constitute an important sediment source, crustaceans (0.2-5%), serpulids (0.2-3 %) and echinoderms (0.2-2.9 %) contribute to present-day sedimentation in a wide spectrum of reef zones. These components seem to be closely related to corresponding fauna development and location. Bryozoan debris are uncommon; concentrations never exceed 0.5%. Such a low concentration is probably more function of their low contribution to reef framework than of their low ability to resist diminution by abrasion.

B. THE SHALLOWER FOREREEF ZONE

1. Morphology

Three shallower fore-reef types can be recognized in the fringing reef flat zones of Makatea. Development of physiography patterns appear to be controlled by antecedent topography and degree of water turbulence (Montaggioni *et al.,* 1985 b).

In poorly developed reef areas (apron reefs), the morphologic zonation is as follows, from the reef front seaward (Figure 5): upper drop-off, furrowed platform, zone of coral patches and lower drop-off . Below a depth of 4 m , the intertidal reef pavement changes abruptly into a subvertical (60°) escarpment (so-called upper drop-off) which may grade laterally into a typical spur-and-groove system where the best developed apron reefs occur. Deeper, an upper, markedly furrowed, gently dipping (20°) terrace is found between depths of 4 and 9 m . Then the zone of coral patches extends seaward for some thirty metres; it is a very gently sloping (5°) platform partly covered with skeletal sediments and elongate coral buildups, a few metres in diameter. This platform is bounded outward by a 1 - to - 2 m thick coral rim, having no grooves or distinctive relief feature. The latter is followed with a lower drop-off which exhibits two convex-upward breaks in slope at about 14 and 20 m , leading to a marked change in gradient (45-60°). At depths greater than 20 m, the margin slope has a linear talus of coarse-grained skeletal material, parallel to the reef front; these stable alignments of organism-encrusted, debris alternate with those formed by unconsolidated slumping material. No organism-built buttress is observable here.

Seaward of the high-energy fringing reef flats, the shallower fore-reef zone over 10 m deep has a relatively steep (20-30°) spur-and-groove system. Between 8 and 11 m deep, the slope increase abruptly (50-60°) and changes into a drop-off of low relief (Figure 6).

Seaward of the low-energy fringing reef flats, the spur-and-groove zone extends downward to depths greater than 10 m. Below 6 m deep, the slope is gentle (15-20°) and grooves are narrow (1-1.5 m) and deep (2.5 m). Deeper, the slope becomes steeper (60°-70°), while grooves change into wide channels for basinward transport of fore-reef material, and connect with a smooth-surfaced drop-off (Figure 7).

Locally, all along its edge, the coastal cliff is dissected by vertical extensional fracture networks roughly running perpendicular to the cliffline. These faults belong to the NNW-SSE trending system which dissects the whole island mass into several blocks (Montaggioni, 1985).

Fractures are locally infilled with consolidated, gravity-accumulated material consisting of pebbly to gravely reef limestone. They can extend seaward through the late Holocene reef tract, suggesting that tectonic extensional movements have occurred very recently. Underwater examination shows that the uppermost part of the forereef zone is morphologically fault-controlled. For example while breaks in slope (lower boundary of the spur-and-groove system) generally occur between depths of 6 and 11 m along the seaward margin of the island, they are found here at 20 m deep. Moreover, the spur-and-groove zone is replaced by a very uneven, steep platform littered with large erratic boulders (Figure 14). All this indicates that the upper part of the outer slope has recently slumped basinward.

2. Ecological characteristics of benthic communities

At the base of the cliffs, in reefless areas as well as in apron reef areas, the upper drop-off which extends to depths of 4 m , is colonized by an upper green-algal belt (*Microdictyon okumuraii, Neomeris vanbosseae, Halimeda taenicola, H. micronesica, Caulerpa urvilliana, C. seurati, Avrainvillea sp.*) and a lower dense population of boring echinids (*Echinometra mathaei).* At depths of 9-10 m , the zone of plurimetre-sized coral patches have a coral coverage ranging from 50 to 80% of the substrate surface, where *Pocillopora* colonies dominate. The coral rim, which marks the outer limit of the zone of patches, is formed by the species *Pocillopora verrucosa, P. eydouxi, Acropora spp., Astreopora myriophthalma, Porites sp..* their extent of cover reaches about 40%. Subordinate organisms are Chlorophyceae algae (*Halimeda, Microdictyon).* Along the lower drop-off, the coral cover declines rapidly; it reaches levels of about 10% at depths of 15-20 m, but it does not exceed 5% at 35 m . The main builders are *Astreopora, Pachyseris, Favia,* associated with *Montipora, Pocillopora* and *Dysticopora.* The algal flora is composed of *Caulerpa seurati, C. racemosa* and *Halimeda micronesica.* However encrusting forms (*Melobesieae*), which colonize the whole lower drop-off up to 40 m , display the highest degree of coverage (up to 60 %).

Along the forereef zone of the high-energy reefs, coralline algae (*Porolithon onkodes, Lithophyllum sp*) play the main building part. Scleractinian corals, such as *Pocillopora* and *Acropora,* and the hydrocoral *Millepora platyphylla* occupy about 25% of the surface available. The algal *Halimeda* are relatively abundant (cover = 10-15%). From 15 to 30 m , the margin slope (drop-off) is mainly colonized by the corals *Pocillopora, Astreopora* (cover = 15%) and the green algae *Halimeda* and *Caulerpa* (cover = 30-40%).

Seaward of the low-energy reefs, the degree of coral coverage of the spurs varies between 40 and 70% from sea surface to 6 m . Here *Pocillopora* and *Acropora* are dominating. From 6 to 15m, the coral fauna which is chiefly represented by *Porites* and *Synarea,* occupies 25 % of the substrate only.

C. THE DEEPER FOREREEF ZONE

The only sector selected for detailed bathymetric work is off Temao coast (Figure 15). It was mapped up to a depth of 450 m. The most prominent feature is that the margin ends abruptly in a drop of about 300 m; depths of 100 m generally occur less than 100-200m offshore. Along this steep fore-reef slope a few smooth grooves only are observable as indicated by local inflections of contour lines. However a narrow bench extends from depths of 40 to 60 m. With no noticable relief down to 290-310 m where a relatively abrupt ramp connects the upper part of the deeper fore-reef with the distal shelf slope. In marked contrast to its steepness and relatively smooth topography down to 310 m, the lower part of the deeper fore-reef at the depths of 310-450 m is characterized by a moderate gradient and noticeable relief.The contour patterns indicate well- developed hillocks and depressions on gently dipping (less than 20°) platforms. For instance, a bench extending from 310 to 340m exhibits a number of 15-20 m high hummocks and 8-10 m deep sinks; this bench is irregular in outline : wide amphitheatre-like cavities separate front cape-shaped lobes from another. An escarpment of some thirty metre high (340-345 to 370-375 m) grades into a large, very gently sloping area, broken by high-relief features (30-40 m) and deep basins (20-30 m).

Thus examination of sounding profiles clearly reveals the occurrence of two distinct insular slope zones delimited by the 300 m depth line. The latter may indicate two distinct superimposed reef buildups of Intermediate Tertiary age.

THE SEAWARD MARGIN : INTERPRETATIVE PATTERNS

A. EVOLUTIONARY PATTERN

Like most seaward margins of recent reef tracts, the reef margin of Makatea is steep. Summarizing the very earliest investigations on reefs, Darwin (1842) noted that reefs in many regions possess subvertical drop-offs just seaward. Subsequent profiles and soundings obtained notably from Pacific reefs (Marshall islands : Tracey *et al.*, 1948; Tuamotus : Newell, 1956; Chevalier *et al.*, 1969; Carolines : Tracey *et al.*, 1961) have recorded a "ten-fathom terrace", i.e. a sudden break in slope somewhere between 8-30 m, below which a submarine cliff occurs. The morphology of the upper fore-reef zone is usually as follows: the reef front extends slopeward as a spur-and-groove system to a gently dipping terrace the outer edge of which is at a depth averaging 10 m. The leading edge of this terrace is an abrupt change in slope and the bottom drops, beyond at an average slope of 45° or steeper (Figure 16).

As summarized by James and Ginsburg (1979, p. 153), the topographical features of the upper reef slopes were first regarded as resulting from shallow-water reef growth during subsidence, before Quaternary sea-level changes were known. David *et al.*, (1904) reported some evidence of coral growth on the seaward faces of reefs at depths below the limit of luxuriant coral development. With the subsequent knowledge of the extent of glacially-controlled Pleistocene sea level fluctuations, Daly (1910) postulated that the fore-reef zones are erosional relict features dating from a lower sea level. Likewise, although he did not agree with Daly entirely, Vaughan (1919) interpreted the reef wall as being the result of erosion during low sea stands. Recently, James and Ginsburg (op. cit.) studying the seaward margin of Belize barrier and atoll reefs extended the theory of discontinuous lateral accretion first suggested by David *et al.* , (1904). They concluded that this style of accretion is an universal phenomenon.

Investigations on some French Polynesian seaward margins furnished data indicating that this fundamental problem is less simplistic than was previously expected. Underwater observations and drilling through the outer rims of atolls and barrier reefs strongly support the fact that submerged terraces and the adjacent reef walls could either be an equilibrium feature related to the reef-building corals and wave and current action, or be erosional related to a lower sea level (Figure 17).

On the northern barrier reef face of Moorea island, the outer slope displays a well differentiated terrace about 20 m wide, at a depth of 15-16 m, below the upper spur-and-grooves system. This terrace is connected outward to a lower buttress system. A borehole which was positioned some 50 m behind the reef front, penetrated up to 20 m of unconsolidated to slightly cemented material of Holocene age, without reaching any unconformity surface, i.e. pre-Holocene constructional or erosional platform (Montaggioni and Delibrias, 1986). This demonstrates that this 15-16 m terrace is not erosional; it is a current induced feature as suggested by Jaubert *et al.* (1976), in accordance with the hydrodynamic model of Roberts *et al.* (1975). A similar conclusion arises from studies of nearby Tahitian outer reef slopes (Montaggioni, unpublished data). In these cases, the upper fore-reef zone appears to be the result of a significant upward and lateral accretion from a newly buried, preexisting reef surface, during the Holocene sea level rise.

On the atolls of Mataiva (Montaggioni, pers. observ.) and Mururoa (Chevalier *et al.*, 1969), the outer slopes are broken by an upper terrace lying respectively 6 and 8-11 m deep, which follows a small scarp 2-4 m high. The numerous holes drilled on these two sites (Mataiva : Pirazzoli and Montaggioni, 1986 ; Mururoa : Repellin, 1975; Buigues, 1983) give evidence that this terrace is the top of a former (Pleistocene or older) reef body in part subaerially eroded (equivalent to the Thurber solution disconformity of the limestone column). A similar origin is expected for the terraces at 6 and 12 m below sea level which have been reported respectively from Tikehau atoll (Faure, pers. comm.) and Takapoto atoll (Montaggioni, pers. observ.). In these cases, significant reef accretion seems to have been restricted to the upward growth of the upper spur-and-groove system, while the submerged platform and adjacent reef wall are partly eroded, coral-built relict reliefs on which recent corals have grown as thin veneers (Figure 18).

In conclusion, the present morphology of the outer reef margins in French Polynesia and consequently, in Makatea, is probably a reflection of both erosional and accretionary effects. The coincidence of the step in morphology at depths of 6-16 m reflects either the upper level of reef growth during former sea level high stands prior to subaerial exposure and alteration, or an interaction of current with morphology during reef growth. The variability of the depth at which the submarine terraces are at present recorded, is chiefly a function of the local tectonic history prior to the Holocene marine transgression. For instance, in the northwestern Tuamotu region, the late Pleistocene reef surfaces lie between a few metres above present sea level and about ten metres below, while, in the Society high volcanic islands, they lie at depths over to 30 m. The first ones belong to a relatively uplifting area, while the second are affected by an active subsidence, caused by thermal contraction of the underlying crust.

B. DISTRIBUTIONAL PATTERN OF BENTHIC COMMUNITIES

1. Flora

Generally the uppermost parts of the reef margin are preferentially colonized by encrusting coralline algae (*Porolithon, Lithophyllum*). According to wave energy, these algae make up either a thin veneer (sheltered areas) or a well-developed ridge (exposed areas) similar to those classically described from other Polynesian atolls (Denizot, 1969). At the base of the cliffs, beside Rhodophyceae, a number of other algae (*Microdictyon, Neomeris, Caulerpa, Halimeda, Avrainvillea*) typical of the reef edges of atolls (Chevalier *et al.,* 1969; Denizot, 1969, 1972) occur widely. Along the high-energy fore-reef zone to 10 m, the coralline algal surface coverage reaches up to 60%, while that of *Halimeda* species does not exceed 15%. From 10 to 40 m , *Halimeda* and *Caulerpa* flourish (40% of the substrate).

The outer parts of the reef flat zone exhibit highly variable specific diversity. The total algal cover can reach up to 80%, but the related populations only form a very close-cropped turf. The brown alga *Lobophora variegata* forms a continuous peripheral belt. The other floristic elements (*Giffordia sp., Liagora ceranoïdes, Hassalia byssoïdes, Halimeda opuntia, H. taenicola, Caulerpa cupressoïdes, C. urvilliana, Dictyospheria favulosa,* Rhodymenials) are subordinate, colonizing the substrates here and there. Coralline algae are still present. Among soft algae, the most common forms belong to the following genera : *Halimeda, Caulerpa, Microdictyon, Amphiroa* and *Turbinaria*.

In contrast, the inner parts of the reef flat zone display more monotonous floristic communities. The substrate is widely occupied by turfs of *Cladophora* whose coverage increase with confined conditions. Locally, in exposed areas, cyanophyte films develop. Thus all the substrates which undergo long periods of emergence (beach-rocks) are colonized by the blue-green algae *Hassalia* and *Entophysalis*. However no stromatolite-like feature has been observed at Makatea, while protostromatolitic deposits occur on several Polynesian atolls (Rangiroa, Mataiva, Mururoa,...) (Bourrouilh-Le Jan, 1977 ; Montaggioni, pers. observ.; Trichet, pers. com.; Defarge, 1983). This may be ascribed both to the unevenness of the reef flat surfaces and the coarseness of reef flat sediments. In some areas four species of brown algae (*Turbinaria ornata, Chnoospora minima, Ectocarpus breviarticulatus, Hydroclathrus clathratus*) produce high biomasses. This is a confusing particularity of Makatea since the brown algae and these two species of *Turbinaria* and *Chnoospora* are very uncommon on the other Tuamotu atolls (Seurat, 1934; Doty, 1954; Denizot, 1971, 1972).

2. Fauna

The reef-building scleractinians and hydrocorals reported from Makatea belong to about 15 genera and more than 35 species; they are the same as those described in the majority of Tuamotu atolls (Chevalier, 1979). The reef flat zone has a very low coverage (less than 5%) and only show stunted colonies. The dominant forms are *Acropora rotumana* in sheltered areas, *Porites cf. compressa* and *Montastrea curta* in exposed areas. In contrast, coral communities flourish along the forereef zone; their distributional patterns are dependent upon water energy and/or depth. At a depth of 10 m, in higher energy zones, coral cover does not exceed 25%, while it can reach 40-70% in lower energy slopes. The dominant species is *Pocillopora verrucosa,* associated with several species of *Acropora, Porites* and, locally, *Millepora platyphylla.* The 10-25 m zone is dominated by *Pocillopora verrucosa* and *P. eydouxi.* The lower parts of the shollower fore-reef zone studied (25-40 m deep) are characterized by high amount of *Astreopora myriophthalma* and high degrees of coral coverage (higher than 80%).

The composition of the molluscan fauna of Makatea is relatively similar to those mentioned from various Tuamotu islands (Salvat, 1979; Richard, 1982). On the algal ridges and reef fronts, the dominant species are *Patella flexuosa, Turbo setosus, Drupa morum* and *D. ricinus.* The reef flat zone is inhabited by dense populations of molluscs mainly including *Mitra litterata, M. pauperculata, M. granulata, Drupa cancellata, Conus sponsalis, C. lividus, Puperita reticulata, Bursa bufonia, Tridacna maxima, Thais armigera, Cypraea moneta, C. caput-serpentis.* Emerged beach-rocks are colonized by *Nerita plicata, Tectarius grandinatus, Thais aculeatus* and *Littorina coccinea.* Along the poorly developed reef areas, the zonation of molluscs reminds successively of those of the algal ridges and beach-rocks; from the upper parts of the outer slopes to the cliffwalls, *Haliotis pulcherrima, Drupa ricinus, D. morum, Turbo setosus, Patelloida conoidalis, Thais aculeatus, Nerita plicata* and *Littorina coccinea* can be found.

At Makatea, as on the majority of the Tuamotu reefs, the specific diversity is higher in the sheltered areas, but the highest amounts in individuals occur in the most exposed areas. The families showing the highest specific richness are omnivorous (Cypraeidae : 20 species) or carnivorous (Muricidae : 15), but those showing the highest concentration in individuals (Littorinidae, Cerithiidae) are grass-eating.

With 121 species collected, the molluscan fauna is here assumed to be relatively poor, by comparison with those described from the outer rims of the other Tuamotu atolls.

On the whole flat reef zone, echinoderms are not very common, except for the echinid *Echinometra mathaei* and the holothurid *Holothuria atra*. Moreover, the echinid *Colobocentrotus pedifer* is highly frequent, locally associated with *Heterocentrotus mamillatus* in the high energy zones of this island, whereas it is generally scarce in the Tuamotu archipelago (Richard and Salvat, pers. obs.).

CONCLUSIONS

Makatea island has a singular submarine morphology whose major features have been controlled by global and regional events (eustasy, climate and uplifting) mostly during Quaternary times .

The main ecological characteristics of the seaward margin are the monotony and paucity of fauna and the wide-spreading of fleshy brown algae.

The algal flora has to be regarded as a mixture of species typical of high volcanic islands (*Pheophyceae*) and species typical of low carbonate islands (*Chlorophyceae*).

While the coral colonies living on reef flats are sparce, a large part of the shallower forereef zone is characterized by the richness and vitality of coral communities. The associated macrofauna (molluscs, echinoderms) is poorer than those commonly observed along the outer margins of Polynesian atolls. This may be due to the reduction of available biotopes and the long-term exposure of some reef flat areas.

Makatea seems to be a very special island within the Tuamotu archipelago and although its main biological features of which cannot be used as a model for nearby Polynesian islands, it is a geologically very interesting experimental field since it retains about 25 millions year-long history of Pacific near surface waters. Future research on Makatea island will have to focus on Miocene reef deposits : nature and distribution of main builders, reef growth and global changes, early diagenesis and phosphatogenesis.

ACKNOWLEDGEMENTS

Gratitude is due to the Service de l'Equipement and Administration Civile des Iles Tuamotus (Tahiti, Papeete) for their assistance and logistic support. The field help of natives was greatly appreciated.

Special thanks are extended to Dr MacIntyre for reviewing this manuscript.

DEDICATION

This work is dedicated to our colleague and friend Marie-Hélène SACHET, formerly Curator of the Botanical Department, who died in July 1986

REFERENCES

Agassiz A. 1903. The coral reefs of the tropical Pacific. *Mem. Mus. Comp. Zool. Harvard,* 28, I-XXXIII : 1-410.

Asano D. 1942. Coral reefs on the South Sea islands. *Tokoku Imp. Univ. Geol. and Paleont. Inst., Rep. 39* : 1-19.

Bourrouilh-Le Jan F. 1977. Géomorphologie de quelques atolls dits "soulevés" du Pacifique Ouest et Sud-Ouest ; origine et évolution des formes récifales actuelles. *Mem. B.R.G.M.,* 89 : 419-439.

Buiges D. 1983. Sédimentation et diagénèse des formations carbonatées de l'atoll de Mururoa (Polynésie Française). *Unpubl. Thesis, Univ. Paris XI,* 2 vol. : 309 p.

Chevalier J.P. 1973. Geomorphology and geology of coral reefs in French Polynesia. *In* : Jones 0.A. and Endean R. (ed.). *Biology and geology of coral reefs,* vol. I, Geol. I, Academic Press, New-York : 113-141.

Chevalier J.P. 1979. La faune corallienne (Scléractiniaires et Hydrocoralliaires) de la Polynésie Française. *Cah. Indopacif.,* 1(2) : 129-151.

Chevalier J.P., Denizot M., Mougin J.L ., Plessis Y., Salvat B. 1969. Etude géomorphologique et bionomique de l'atoll de Mururoa (Tuamotu). *Cah. Pacif.,* 12 : 1-144.

Clague D.A. 1981. Linear island and seamount chains, aseismic ridges and intraplate volcanism : results from DSDP. *Soc. Econ. Paleontolog. Mineralog., Spec. Publ.,* 32 : 7-22.

Coulbourn W.T. and Resig J.M. 1975. On the use of benthic foraminifera as sediment tracers in a Hawaïan bay. *Pacif. Sci.,* 29 : 99-115.

Cushman J.A., Todd R. and Post R.J. 1954. Recent foraminifera of the Marshall islands. *U.S. Geol. Surv., Prof. Papers,* 260 H : 319-384.

Daly P.A. 1910. Pleistocene glaciation and the coral reef problem. *Amer. Jour. Sci.,* 30 : 297-310.

Darwin C. 1842. On the structure and distribution of coral reefs. *Ward Lock, London.*

David T.W.E., Halligan G.H. and Finckh A.E. 1904. Report on dredging at Funafuti. *In* : *The atoll of Funafuti,* sect. VII, *Roy. Soc. London* : 151-159.

Defarge C. 1983. Contribution à l'étude géochimique et pétrologique des formations protostromatolitiques de Polynésie. Application à la connaissance des mécanismes de la précipitation des carbonates de calcium au sein des matières organiques sédimentaires. *Unpubl. Thesis,* Univ. Orléans, 2 vol.: 169 p.

Denizot M. 1969. Introduction de quelques algues en Polynésie et variations saisonnières. *Bull. Soc. Phycol. France,* 13-14 : 33-35.

Denizot M. 1971. La végétation terrestre et sous-marine des atolls. *Bull. Soc. Hort. Hist. Nat. Hérault,* 3(4) : 133-136.

Denizot M. 1972. Sur le rôle constructeur des algues dans les récifs de Polynésie Française. *Proc. Symp. Corals and Coral Reefs, Mandapan Camp,* 1969, *Mar. Biol. Ass. India* : 497-505.

Doty M.S. 1954. Floristic and ecological notes on Raroia. *Atoll. Res. Bull,* 33 : 1-54.

Doumenge F. 1963. L'île de Makatea et ses problèmes (Polynésie française). *Cah. Pacif.,* 5 : 41-68

Duncan R.A. and Mc Dougall I. 1976. Linear volcanism in French Polynesia. *J. Volc. Geotherm. Res.,* I : 197-227.

Emery K.O., Tracey J.I. J r. and Ladd H.S. 1954. Geology of Bikini and nearby atolls. I. Geology. *U.S. Geol. Survey, Prof. Pap.,* 260-A : 1-265.

Farrar E. and Dixon J. 1981. Early Tertiary rupture of the Pacific plate : 1 700 km of destral offset along the Emperor through-Line island lineament. *Earth Planet Sci. Lett.,* 53 : 307-322.

Folk R.L. and Ward W.C. 1957. Brazos river bars : a study of the significance of grainsize parameters. *J. Sedim. Petrol.,* 27 : 3-26.

Forbes H.O. 1893. The Great Barrier reef of Australia. *Geog. Jour.,* 2 : 540-546.

Gabrié C. 1982. Sédimentologie de quelques récifs coralliens frangeants de la Mer Rouge et de l'Océan Indien Occidental. Traitement mathématique des données. *Unpubl. Thesis,* Univ. Marseille II : 128 p.

Gabrié C. and Montaggioni L.F. 1982. Sediments from fringing reefs of Reunion island, Indian Ocean. *Sedim. Geol.,* 31 : 281-301.

Guilcher A., Berthois L;, Le Calvez Y., Battistini R. and Crosnier A. 1965. Les récifs coralliens et le lagon de l'île Mayotte (Archipel des Comores, Océan Indien). *Mem. O.R.S.T.O.M.,* 8 : 1-210.

Hass H. 1962. Central subsidence : a new theory of atoll formation. *Atoll Res. Bull.,* 91 : 1-4.

Hays J.D. and others. 1972. *Initial Reports of Deep sea Drilling Project,* 9 : 21-42.

Heezen B.C., Mac Gregor I.D., Foreman H.P., Forristal G., Hekel H., Hesse R., Hoskins R.H., Jones J.W., Kaneps A., Krasheninnikov U.A., Okada H. and Ruef M.H. 1973. Diachronous deposits : a kinetic interpretation of the post-Jurassic sedimentary sequence on the Pacific plate. *Nature,* 241 : 25-32.

Jackson E.D. and Schlanger S.O. 1976. Regional syntheses, Line Islands chain, Tuamotu Island chain and Maniki Plateau, Central Pacific Ocean. *Initial Reports of Deep Sea Drilling Projects,* 33 : 915-927.

James N.P. and Ginsburg R.N. 1979. The seaward margin of Belize Barrier and atoll reefs. *Intern. Ass. Sedimentologists, Spec. Publ. 3, Blackwell Sci. Publ., Oxford,* 1-191.

Jarrard R.D. and Turner D.L. 1979. Comments on "Lithospheric flexure and uplifted atolls" by Mc Nutt M. and Menard H.W. *J. Geophys. Res.,* 84 : 5691-5694.

Jaubert J. Thomassin B. and Vasseur P. 1976. Morphologie et étude bionomique préliminaire de la pente externe du récif de Tiahura, île de Moorea, Polynésie Française. *Cah. Pacif.,* 19 : 299-324.

Jindrich V. 1969. Recent sedimentation by tidal currents in lower Florida keys. *J. Sedim. Petrol.,* 39 : 351-553.

Lambeck K. 1981. Flexure of the ocean lithosphere from island uplift, bathymetry and geoid height observations : the Society islands. *Geophys. J. R. Astr. Soc.,* 67 : 91-114.

Le Calvez Y. and Salvat B. 1980. Foraminifères des récifs et lagons coralliens de Mooréa, Ile de la Société. *Cah. Micropaleontol.,* 4 : 1-15.

Lewis M.S. 1969. Sedimentary environments and unconsolidated carbonate sediments of the fringing coral reefs of Mahé, Seychelles. *Mar. Geol.,* 7(2) : 95-128.

Maiklem W.R. 1968. Some hydraulic properties of bioclastic carbonate grains. *Sedimentology,* 10(2) : 101-110.

Mammerickx J., Anderson R.N., Menard H.W. and Stuart H.W. 1975. Morphology and tectonic evolution of the East-central Pacific. *Geol. Soc. Am. Bull.,* 86 : 111-118.

Masse J.P. 1970. Contribution à l'étude des sédiments bioclastiques actuels du complexe récifal de l'île de Nossi-Bé (NW de Madagascar). *Rec. Trav. Sta. Mar. Endoume,* hors sér., 10 : 229-251.

Maxwell W.H.G. 1973. Sediments of the Great Barrier reef Province. *In* : Jones O.A. and Endean R. (eds) *Biology and geology of coral reefs,* vol. I, Academic Press, New-York : 299-346.

Mc Neil F.S. 1954. The shape of atolls : an inheritance from subaerial erosion forms. *Amer. Jour. Sci.,* 252 : 402-427.

Mc Nutt M.K. and Menard H.W. 1978. Lithospheric flexure and uplifted atolls. *J. Geophys. Res.,* 83 : 1206-1212.

Menard H.W. 1964. Marine geology of the Pacific. *Mc Graw-Hill,* New-York, 271 p.

Menard H.W. 1973. Depth anomalies and the bobbing motion of drifting islands. *J. Geophys. Res.,* 78 : 5128-5137.

Menard H.W. 1982. Influence of rainfull upon the morphology and distribution of atolls. *In* : Scrutton R.A. and Talwani M. (ed.). *The ocean floor,* John Wiley and Sons, Chichester : 305-311.

Menard H.W. and Mc Nutt M.K. 1982. Evidence for and consequences of thermal rejevenation. *J. Geophys. Res.,* 87 : 8570-8580.

Montaggioni L.F. 1978. Recherches géologiques sur les complexes récifaux de l'archipel des Mascareignes, Océan Indien occidental. *Unpubl. D. Sci. Thesis, Univ. Marseille II,* 2 vol. : 524 p.

Montaggioni L.F. 1981. Les associations de foraminifères dans les sédiments récifaux de l'archipel des Mascareignes (Océan Indien). *Ann. Inst. Océanogr., Paris,* 57 (1) : 41-62.

Montaggioni L.F. and Pirazzoli P.A. 1984. The significance of exposed coral conglomerates from French Polynesia (Pacific Ocean) as indicators of recent relative sea-level changes. *Coral Reefs,* 3(1) : 29-42.

Montaggioni L.F., Lauriat-Rage A., Von Rusel R., Dolin L., Le Calvez Y., Merle D., Roman J. and Venec-Peyré M. Th. 1985a. Depositional environments and paleoecology of an Early Miocene atoll-like reef plateform (Makatea island, Central Pacifique). *Proc. 5th Intern. Coral Reef Congr., Tahiti,* vol. 6 : 575-580.

Montaggioni L.F., Richard G., Gabrié C., Monteforte M., Naim O., Payri C. and Salvat B. 1985b. Les récifs coralliens de l'île de Makatea, archipel des Tuamotus, Pacifique central : géomorphologie et répartition des peuplements. *Ann. Inst. Océanogr., Paris,* 61(1) : 1-25.

Montaggioni L.F. 1985. Makatea island, Tuamotu archipelago. *Proc. 5th Intern. Coral Reef Congr., Tahiti,* vol. 1 : 103-157.

Montaggioni L.F. and Delibrias G. 1986. Holocene reef growth, Moorea and Tahiti islands, Central Pacific. *12th Intern. Sediment. Congress, Camberra, Abstr.* : 215.

Monti S. 1974. Carte bathymétrique - Pacifique du Sud- échelle 1 : 1 000 000. *Centre Océanol. Bretagne, C.N.E.X.O., Ed.*

Newell N.D. 1956. Geological reconnaissance of Raroia (Kon Tiki) Atoll, Tuamotu archipelago. *Bull. Amer. Mus. Nat. Hist.,* 109 : 312-372.

Pirazzoli P.A. and Montaggioni L.F. 1985. Lithospheric deformation in French Polynesia (Ocean Pacific) as deduced from Quaternary shorelines. *Proc. 5th Intern. Coral Reef Congr., Tahiti,* vol. 6 : 195-200.

Pirazzoli P.A. and Montaggioni L.F. 1986. Late Holocene sea level changes in the Northwest Tuamotu islands, French Polynesia, Pacific ocean. *Quatern. Res.,* 25 : 350-368.

Purdy E.G. 1974. Reef configurations, cause and effect. *In* : Laporte L.F. (ed.). *Reefs in time and space. Soc. Econ. Paleont. Mineral, Spec. Pap.* 18 : 9 - 76.

Repellin P. 1975. Contribution à l'étude pétrologique d'un récif corallien : le sondage Colette, atoll de Mururoa (Polynésie Française). *Unpubl. Thesis, Univ. Paris VI,* 203 p.

Richard G. 1982. Mollusques lagunaires et récifaux de Polynésie Française : inventaire faunistique, bionomie, bilan quantitatif, croissance, production. *Unpubl. D. Sci. Thesis, Univ. Paris VI,* 2 vol. : 313 p.

Roberts H.H., Murray S.L., Suhayda J.N. 1975. Physical processes on a fringing reef system. *J. Mar. Res.,* 33(2) : 223-260.

Salvat B. 1979. Etudes quantitatives sur les mollusques récifaux de l'atoll de Fangataufa (Tuamotu, Polynésie). *Cah. Pacif.,* 14 : 1-57.

Salvat B. and Venec-Peyré M.T. 1981. The living foraminifera in the Scilly atoll lagoon. *Proc.4th Intern. Coral Reef Symp., Manila,* vol. 2 : 767-774.

Schlanger S.O., 1981. Shallow-water limestones in oceanic basins as tectonic and paleoceanographic indicators. *Soc. Econ. Paleontol. Mineralog., Spec. Publ.,* 32 : 209-226.

Schlanger S.O., Jackson E.D. and others. 1976. *Initial reports of the Deep sea Drilling Project,* 33.

Schlanger S.O., Garcia M.O., Keating B.H., Naughton J.J., Sager W.W., Haggerty J.A.and Philpotts J.A. 1984. Geology and geochronology of Line islands. *Journ. Geophys. Res.,* 89 : 11.261 - 11.272.

Scott G.A.J. and Rotondo G.M. 1983. A model to explain the differences between Pacific plate island-atoll types. *Coral Reefs,* 1 : 139-150.

Seurat L.G. 1934. La faune et le peuplement de la Polynésie Française. *Mem. Soc. Biogeogr., Paris,* IV : 41-74.

Tracey J.I.Jr., Ladd H.S. and Hoffmeister J.E. 1948. Reefs of Bikini, Marshall islands. *Amer. Geol. Soc. Bull.,* 59 : 861-878.

Tracey J.I. Jr., Abbott D.P. and Arnow T. 1961. Natural history of Ifaluk atoll ; physical environment. *Bull. Bernice P. Bishop mus.,* 222 : 1-75.

Vaughan T.W. 1919. Fossil corals from central America and Puerto Rico, with an account of the American Tertiary, Pleistocene and Recent coral reefs. *Bull. U.S. Nat. Mus.,* 103 : 189-524.

Veeh H.H. 1966. Th^{230}/U^{238} and U^{234}/U^{238} ages of Pleistocene high sea level stands. *J. Geophys. Res.,* 71 : 3379-3386.

Venec-Peyré M.T. and Salvat B., 1981. Les Foraminifères de l'atoll de Scilly (archipel de la Société) : étude comparée de la biocénose et de la thanatocénose. *Ann. Inst. Océan.*, Paris, 57 (2) : 79-110

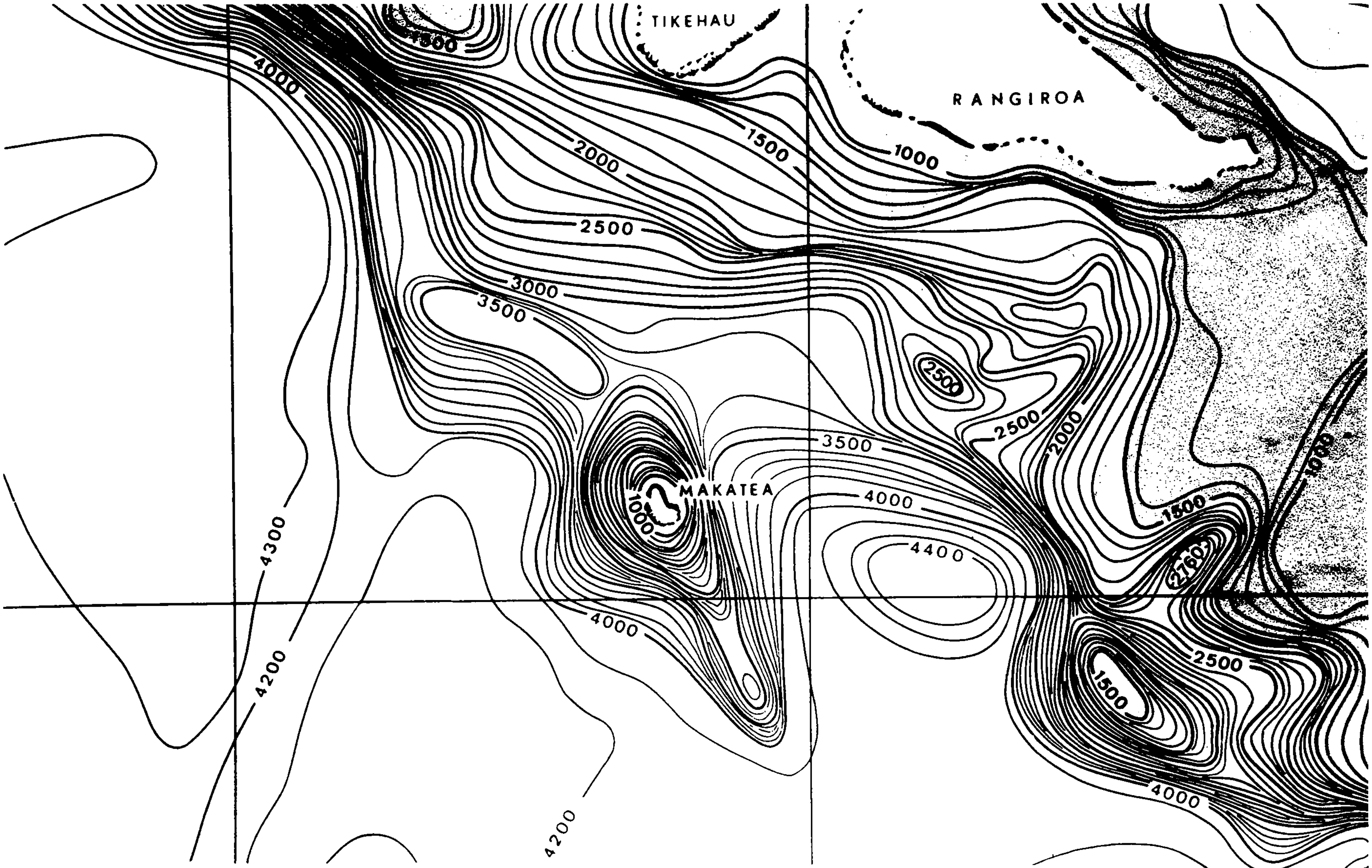


Figure 1 .- Bathymetric chart of the northwestern part of the Tuamotu archipelago with the area of Makatea island (depth contours in metres) (after Monti, 1974).

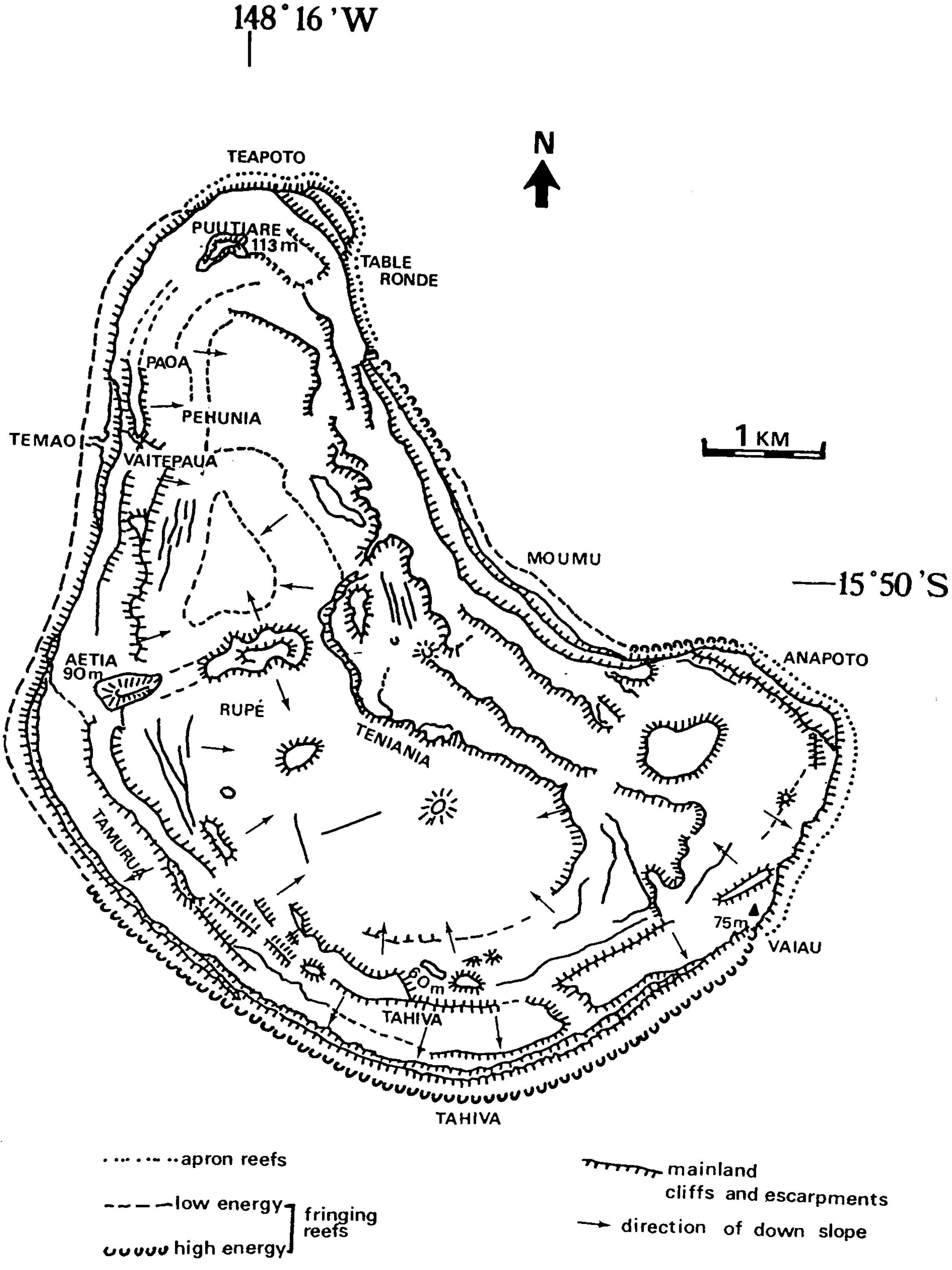


Figure 2 .- A schematic map illustrating the main geomorphologic characteristics of Makatea island (modified from Bourrouilh-Le Jan, 1977, and Montaggioni *et al.,* 1985 b).

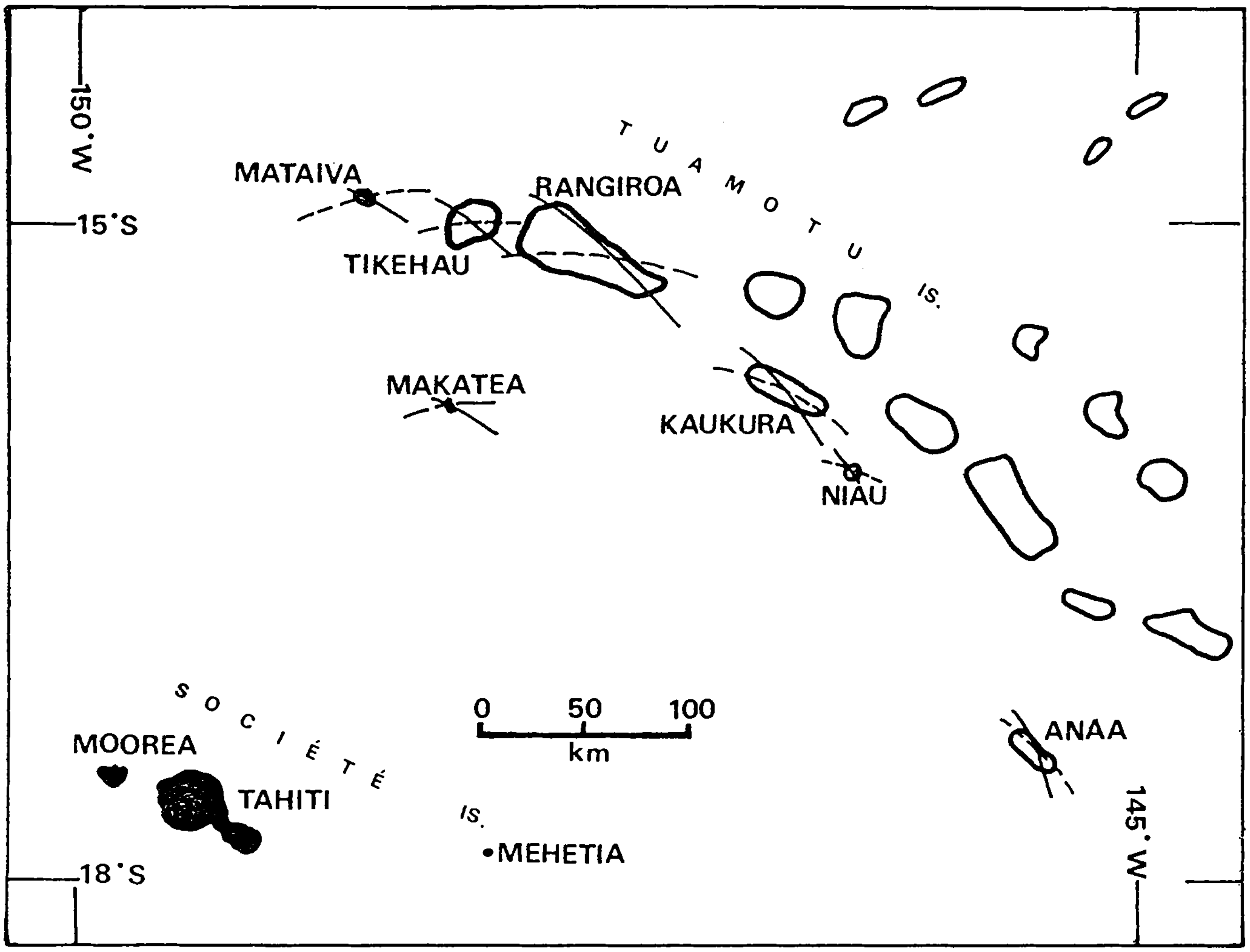


Figure 3 .- Atoll uplift in the nortwestern Tuamotu area. Uplift contours drawn through atolls correspond to the flexure from loading by Tahiti (solid arcs) and Mehetia (dashed arcs).
Simplified from Mc Nutt and Menard (1978).

Figure 4 - General view of the northeastern cliff bounded by narrow apron reefs and beaches (photo L. Montaggioni)

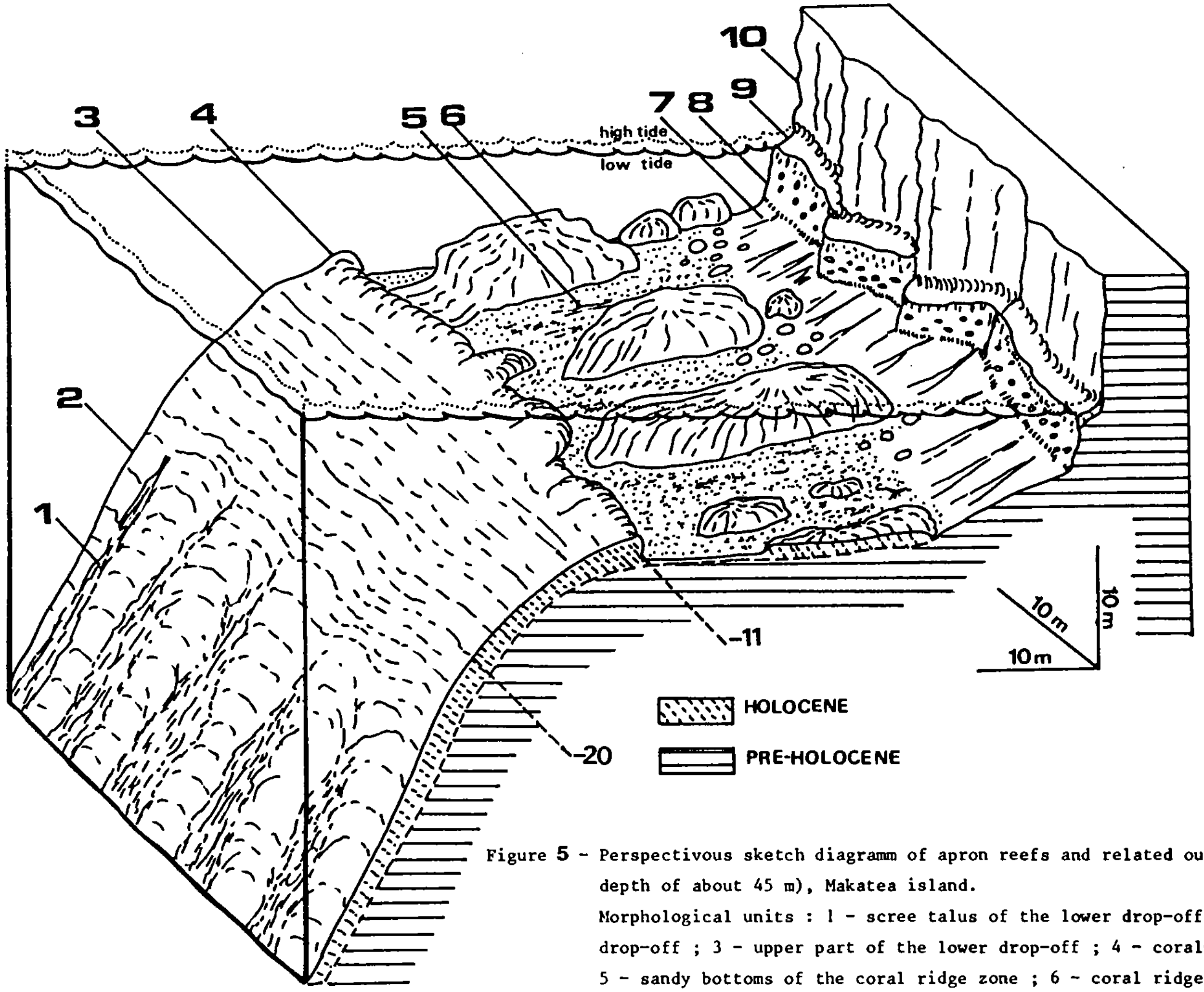


Figure **5** - Perspectivous sketch diagramm of apron reefs and related outer slopes (to the depth of about 45 m), Makatea island.
Morphological units : 1 - scree talus of the lower drop-off ; 2 - coral-built drop-off ; 3 - upper part of the lower drop-off ; 4 - coral-built step ; 5 - sandy bottoms of the coral ridge zone ; 6 - coral ridge ; 7 - furrowed platform ; 8 - upper drop-off ; 9 - apron reef flat ; 10 - cliff.
The depth of 11 m indicates the position of the break in slope.

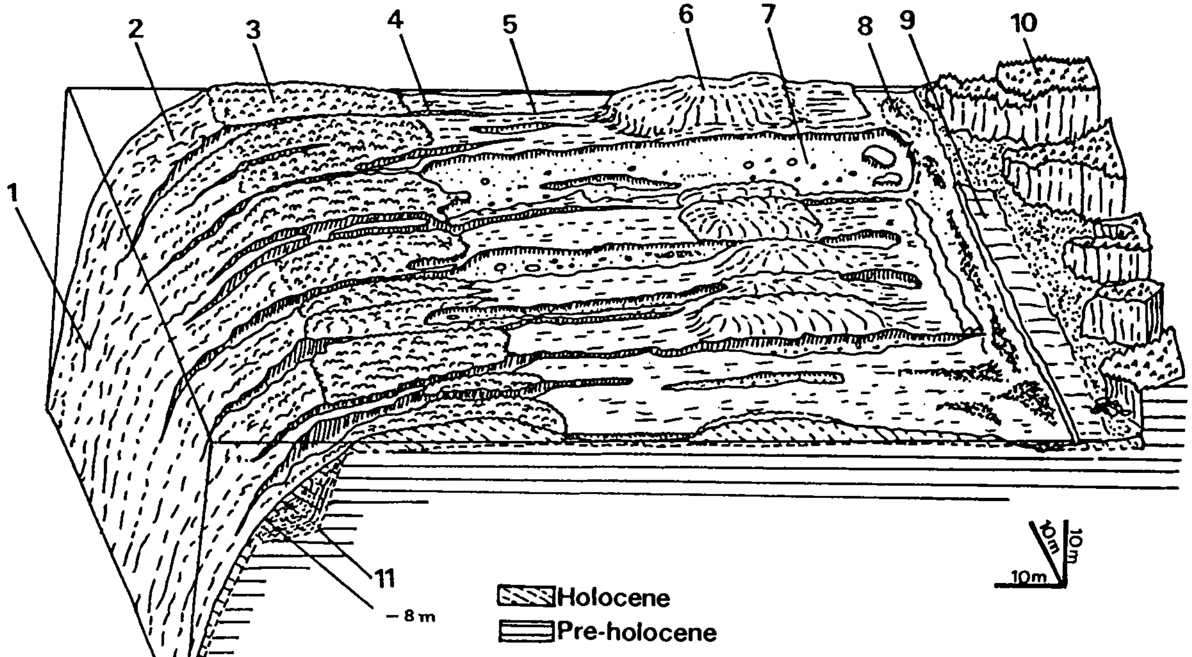


Figure 6 Perspectivous sketch diagramm of an high-energy fringing reef (to the depth of about 30 m), Makatea island.

Morphological units : 1 - outer drop-off ; 2 - spur-and-groove system ; 3 - algal ridge ; 4 - reef flat groove ; 5 - reef flat flagstone ; 6 - conglomeratic crag ; 7 - erosional basin from the reef flat flagstone ; 8 - backreef channel ; 9 - beach-rocks ; 10 - cliff ; 11 - hypothetic submarine platform of Pleistocene age. The depth of 8 m indicates the position of the break in slope.

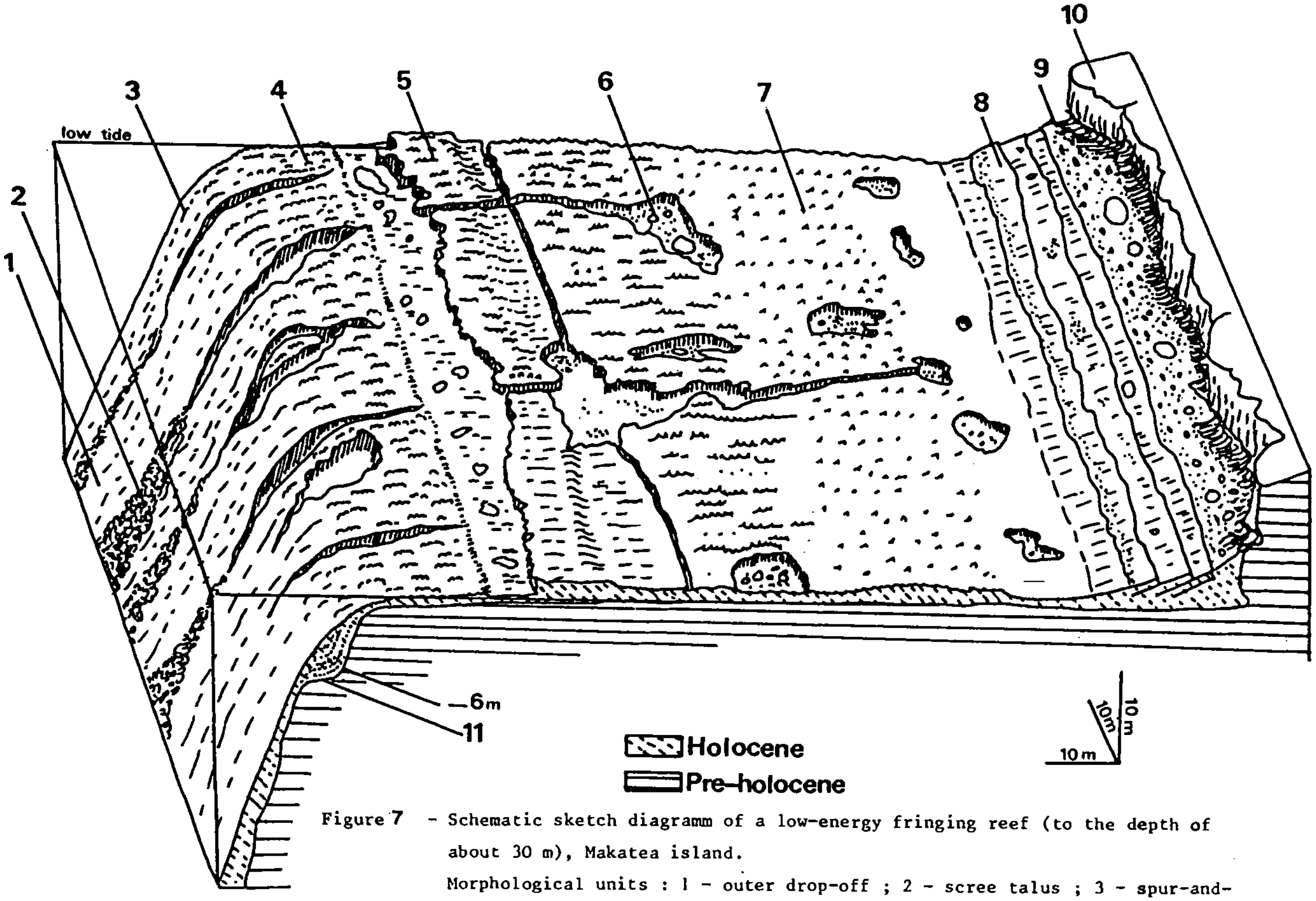


Figure 7 - Schematic sketch diagramm of a low-energy fringing reef (to the depth of about 30 m), Makatea island.
Morphological units : 1 - outer drop-off ; 2 - scree talus ; 3 - spur-and-groove system ; 4 - outer glacis ; 5 - micro cliff and erosional step ; 6 - erosional basin from the reef flat flagstone ; 7 - reef flat flagstone ; 8 - exposed beach-rocks ; 9 - gravel-and-sand-grained beach ; 10 - cliff ; 11 - hypothetic submarine platform of Pleistocene age. The depth of 6 m indicates the position of the break in slope.

Figure 8 - General view of the northwestern margin with a low-energy reef flat zone (photo L. Montaggioni)

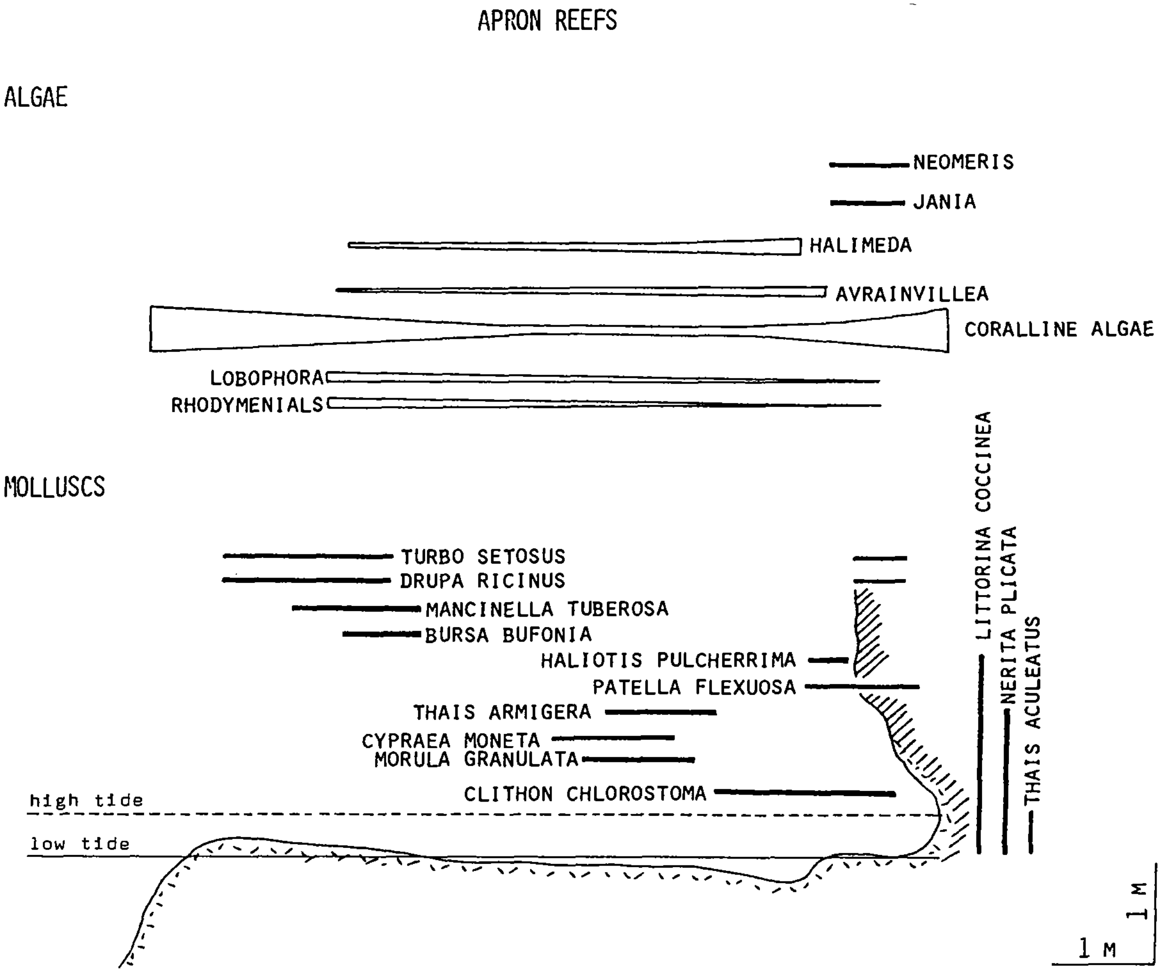


FIGURE 9 - DISTRIBUTIONAL PATTERNS OF THE MAIN ALGAL GENERA OR FAMILIES AND MOLLUSCAN SPECIES ON THE APRON REEFS OF MAKATEA ISLAND

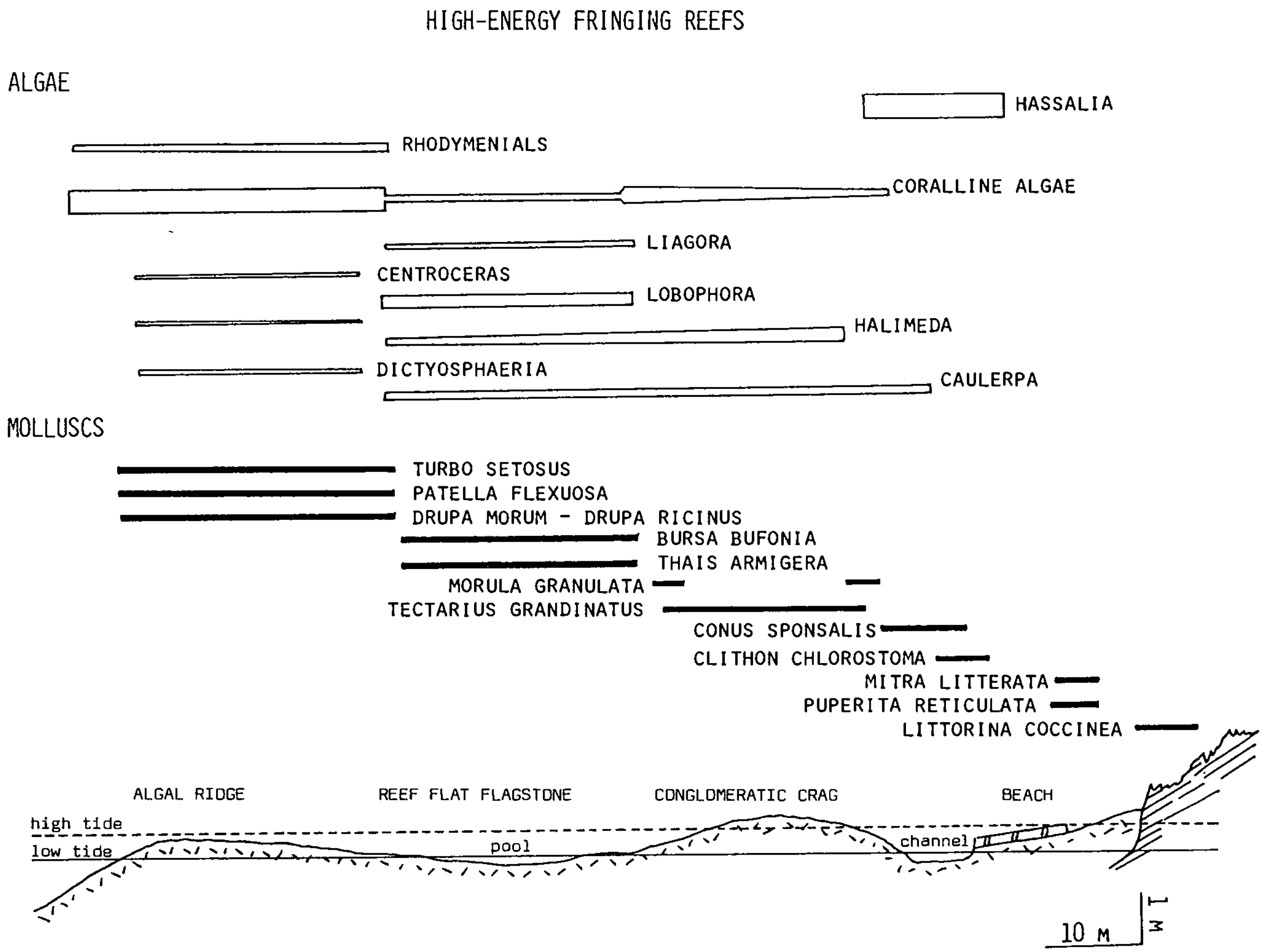


FIGURE **10** - DISTRIBUTIONAL PATTERNS OF THE MAIN ALGAL GENERA OR FAMILIES AND MOLLUSCAN SPECIES ON THE HIGH-ENERGY FRINGING REEFS OF MAKATEA ISLAND

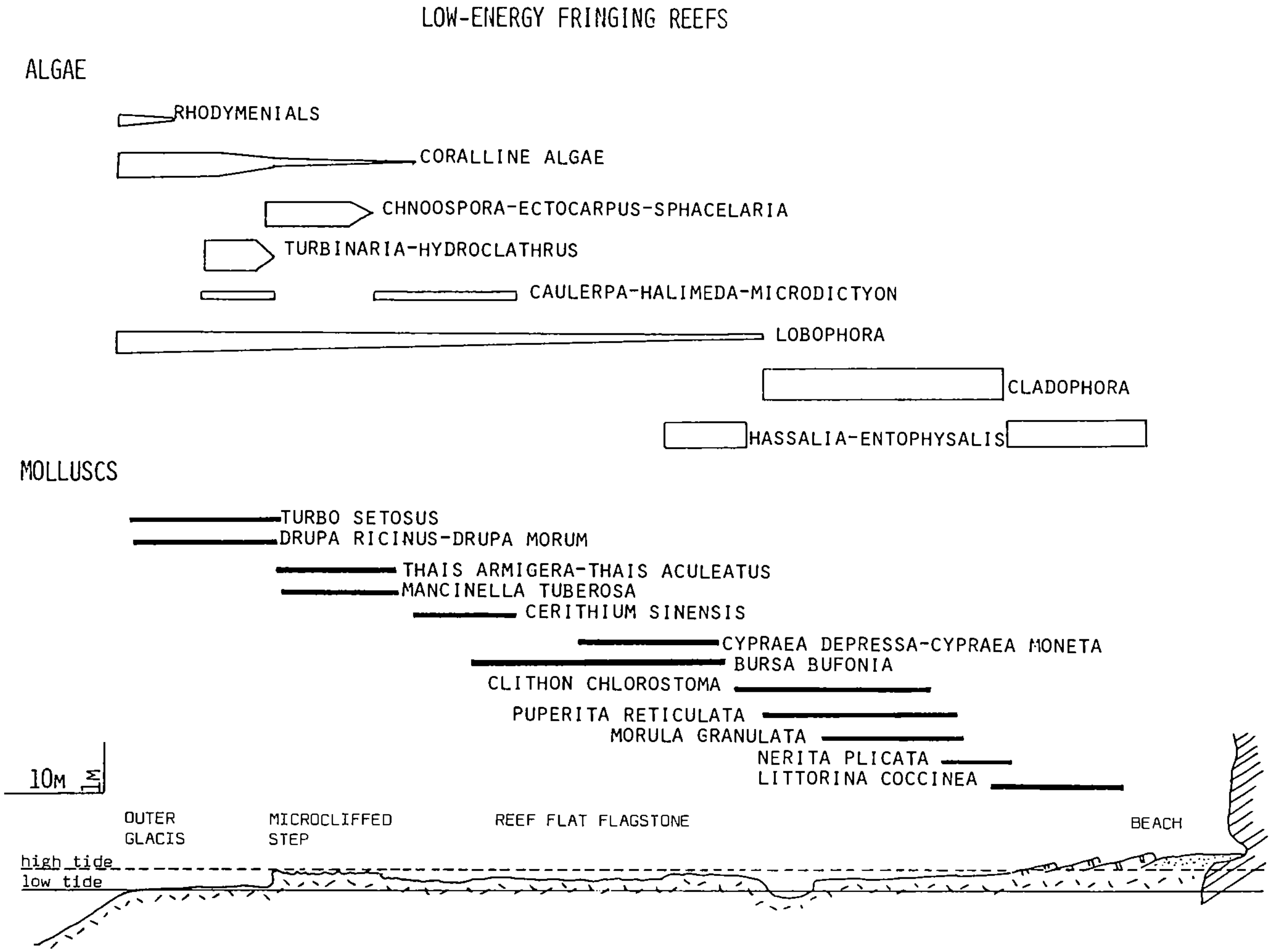
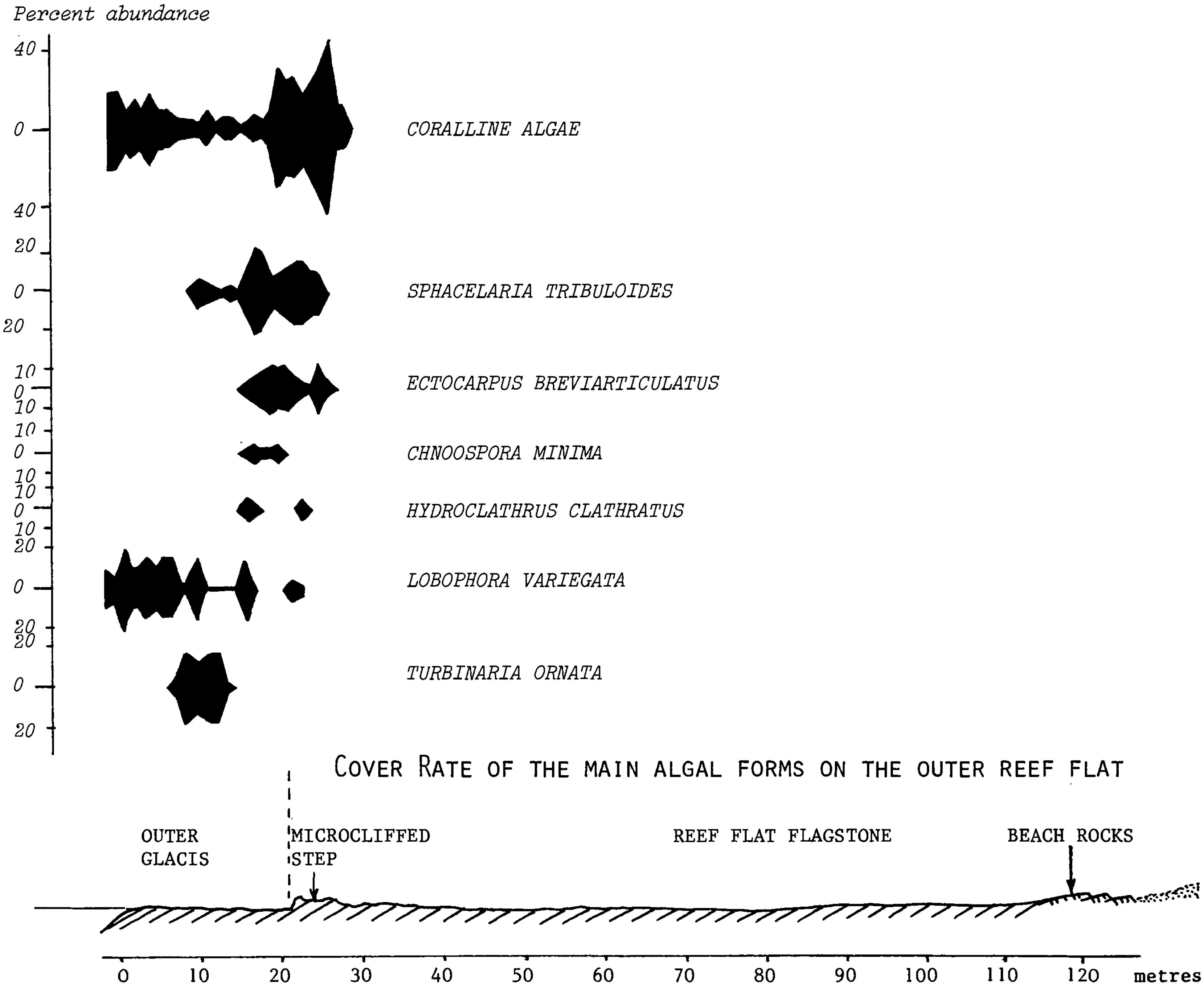


FIGURE **11** - DISTRIBUTIONAL PATTERNS OF THE MAIN ALGAL GENERA OR FAMILIES AND MOLLUSCAN SPECIES ON THE LOW-ENERGY FRINGING REEFS OF MAKATEA ISLAND



COVER RATE OF THE MAIN ALGAL FORMS ON THE OUTER REEF FLAT

FIGURE 12

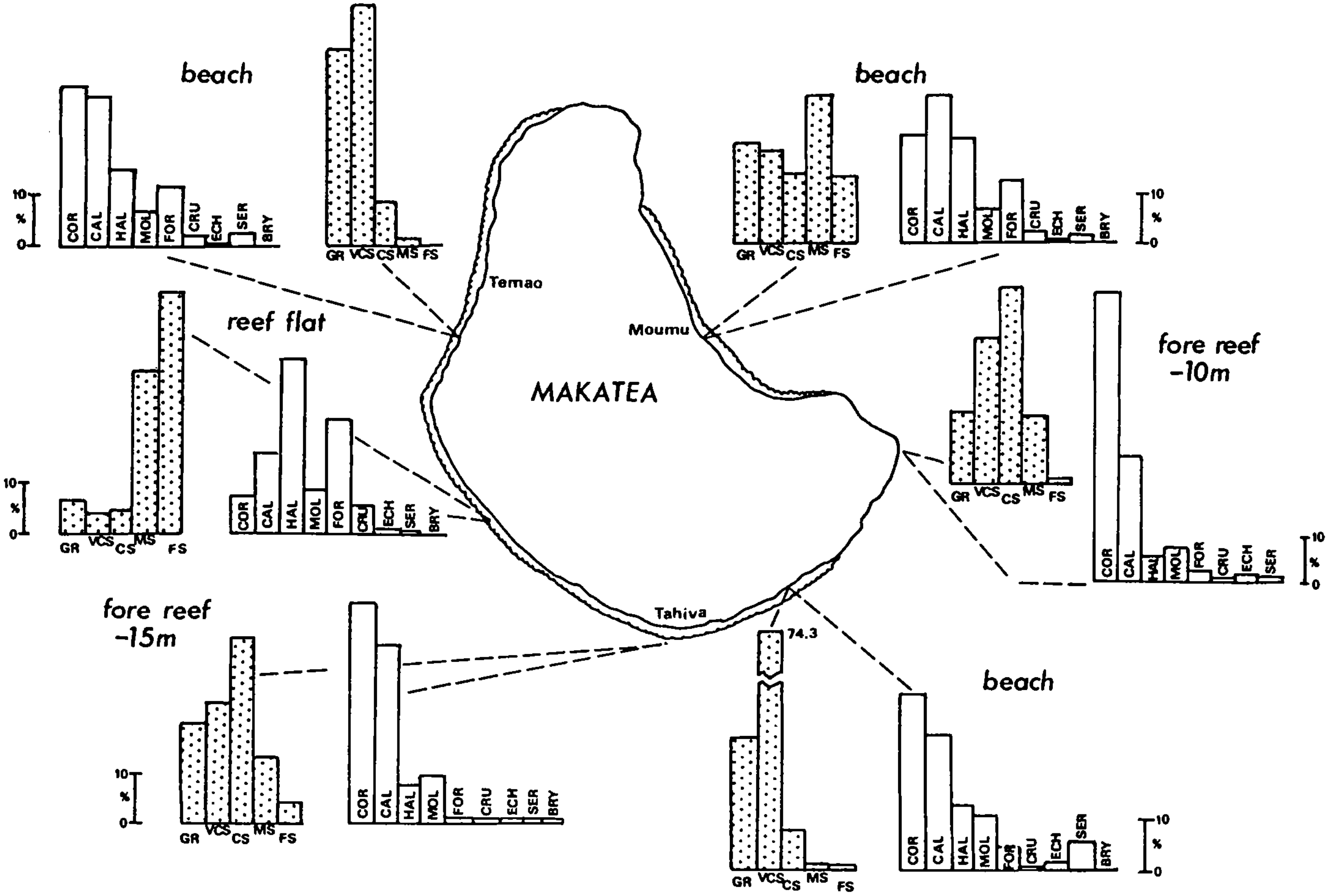


Figure **13**- Frequency histograms of selected sediment types illustrating the occurrence of distinct size classes (GR = granules ; VCS = very coarse sands ; CS = coarse sands ; MZ = medium sands ; FS = fine and very fine sands) and of constituent categories (COR = corals ; CAL = coralline algae ; HAL = *Halimeda* ; MOL = molluscs ; FOR = foraminifers ; CRU = crustaceans ; ECH = echinoderms ; SER = Serpulids ; BRY = bryozoans), from various reefal unconsolidated bodies of Makatea island.

SHALLOWER FOREREEF PROFILE IN A FAULT-CONTROLLED AREA

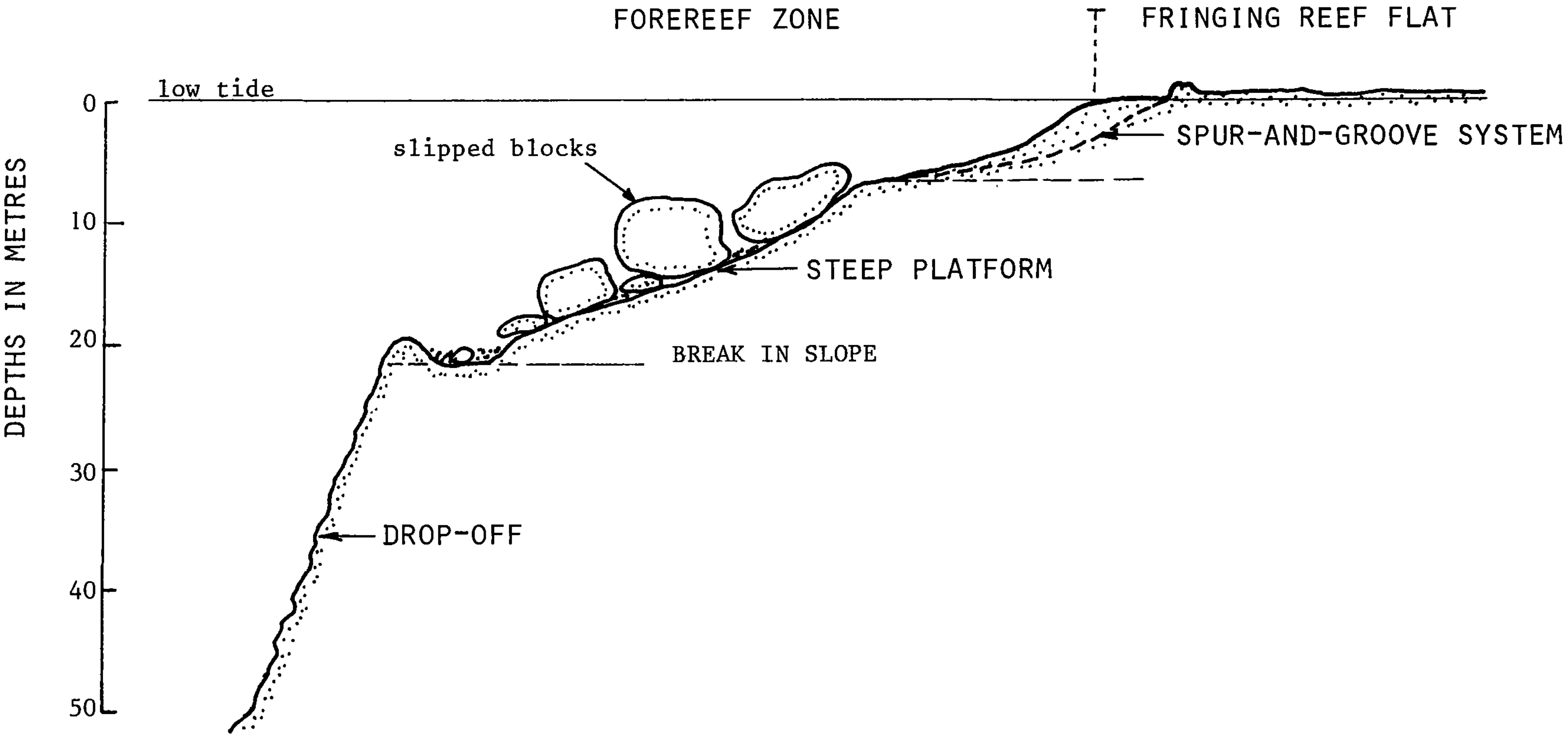


FIGURE **14**

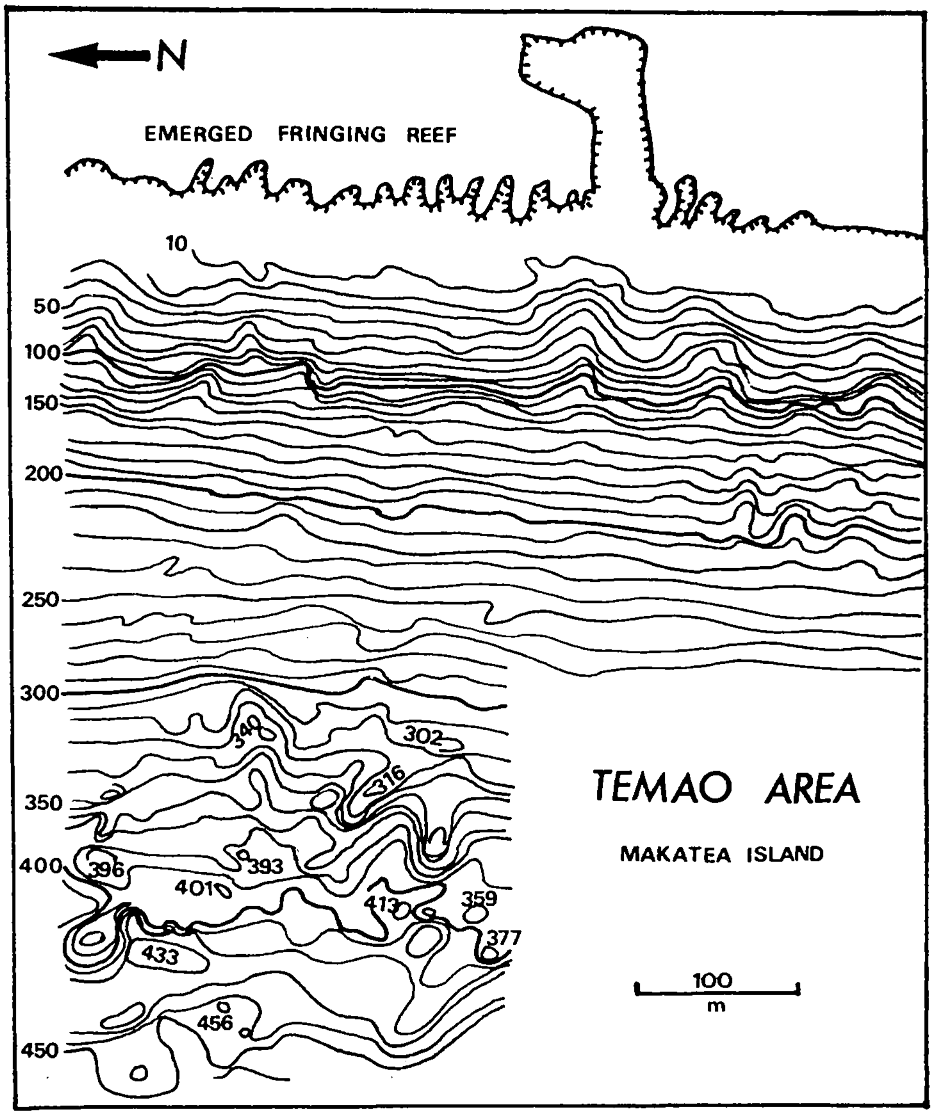


Figure 15 .- A bathymetric chart of the western seaward margin of Makatea island, Temao area (After Doumenge, 1963).

REPRESENTATIVE PROFILES ACROSS THE SEAWARD MARGIN AT MAKATEA, MATAIVA, MURUROA AND BIKINI, CONSTRUCTED FROM DEPTH SOUNDINGS (MAKATEA: DOUMENGE, 1963; MATAIVA: DELESALLE, PERS. COMM.; MURUROA: CHEVALIER ET AL., 1969; BIKINI: EMERY *ET AL.*, 1954)

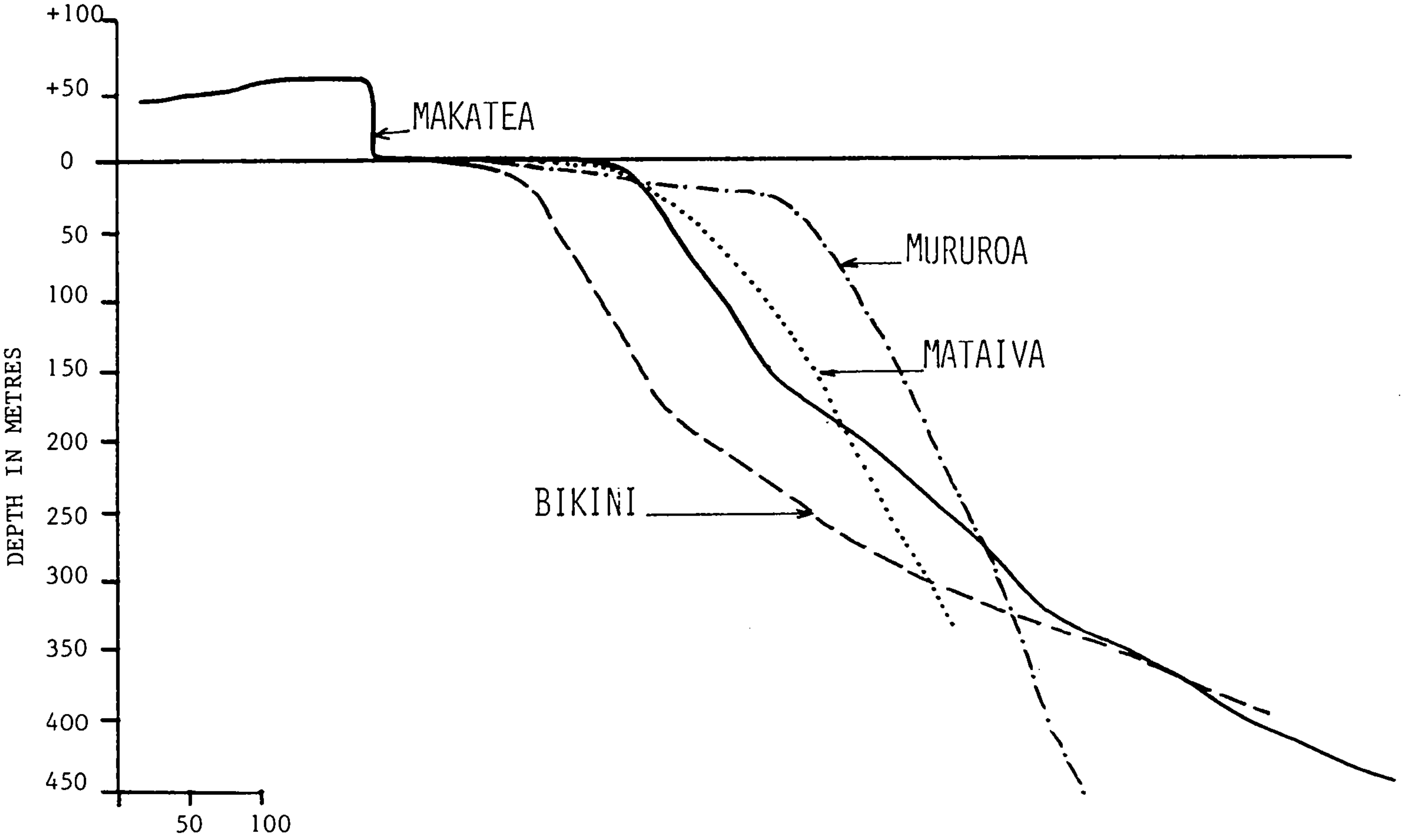


FIGURE **16**

REPRESENTATIVE PROFILES ACROSS THE UPPER PARTS OF THE SEAWARD MARGINS FROM A NUMBER OF FRENCH POLYNESIAN ATOLLS AND REEFS , CONSTRUCTED FROM UNDERWATER OBSERVATIONS (MAKATEA: MONTAGGIONI *ET AL.*, 1984; TAKAPOTO, MOOREA, MATAIVA: MONTAGGIONI, PERS. OBSV.; TIKEHAU: FAURE, PERS. COMM.; MURUROA: CHEVALIER *ET AL.*, 1969)

T terrace BS break in slope

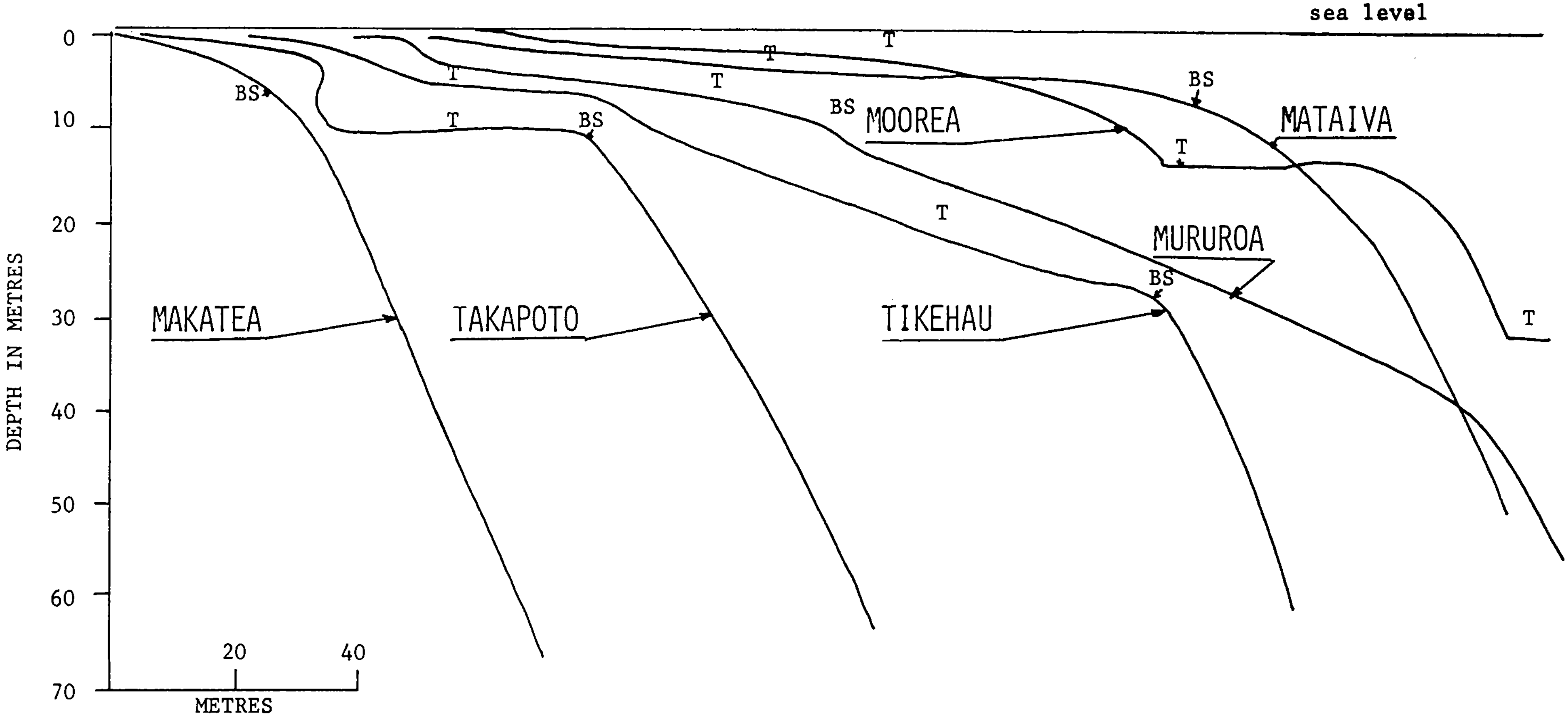
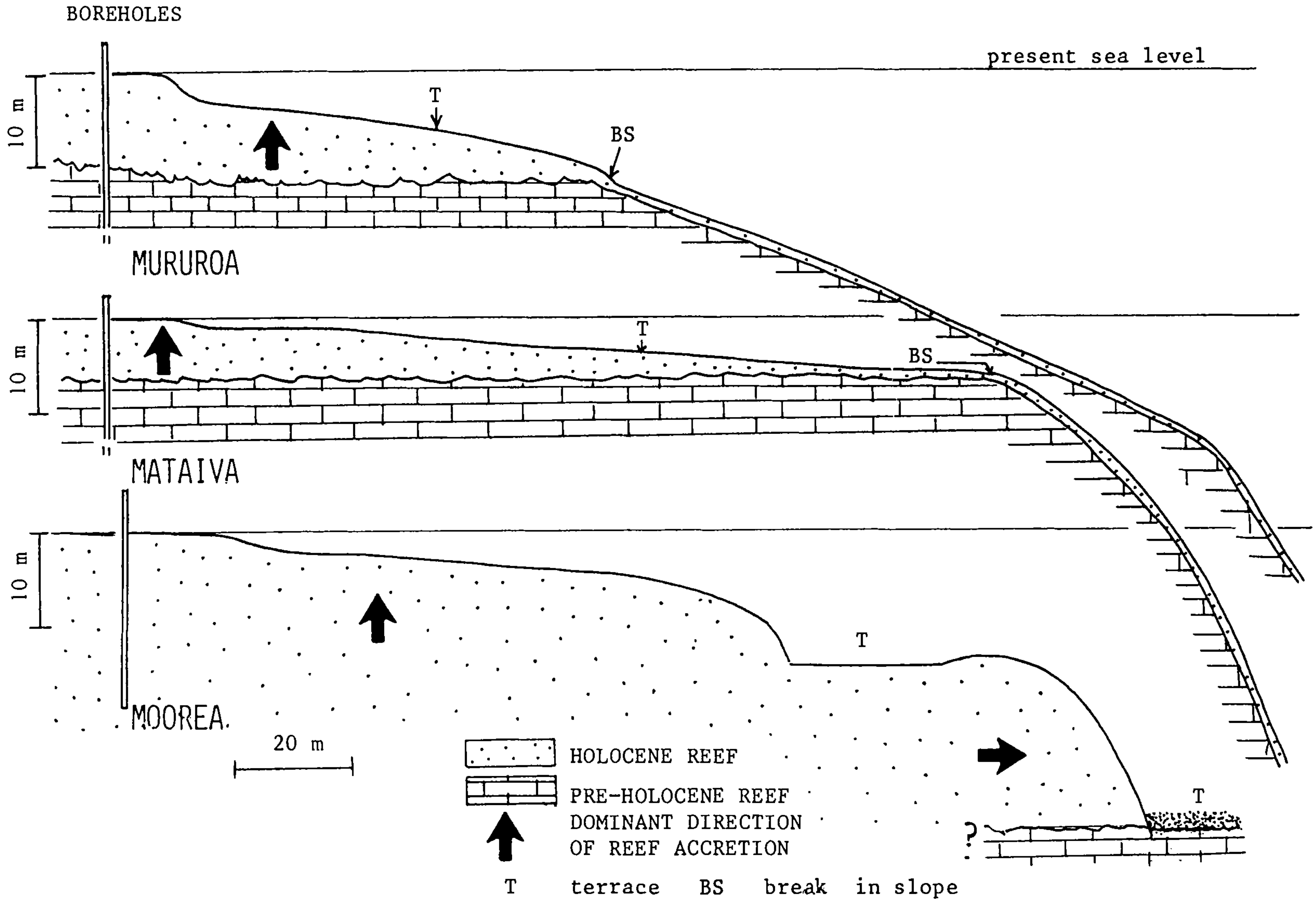


FIGURE **17**



INTERPRETATIVE CROSS-SECTION OF THE UPPER PARTS OF THE SEAWARD MARGINS, FRENCH POLYNESIA REEFS, CONSTRUCTED FROM UNDERWATER OBSERVATIONS AND DRILLING

FIGURE **18**