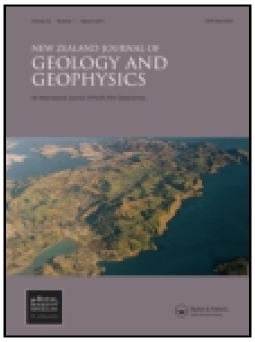

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Late Holocene sea level, Gilbert and Ellice Islands, west central Pacific Ocean

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LATE HOLOCENE SEA LEVEL, GILBERT AND ELLICE ISLANDS, WEST CENTRAL PACIFIC OCEAN

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ABSTRACT

Four coastal deposits are recognised: two intertidal and/or supratidal—calm-weather and stormy-weather beach breccia and conglomerate; and two subtidal—back-reef breccia and biohermal reef rock. High-level outcrops of the subtidal facies provide evidence for six second-order transgressions of Late Holocene age. Most of these have been radiocarbon dated from *Tridacna* shells. Where *Tridacna* samples were available instead, all coral dates were rejected because of secondary aragonite contamination. The ages of the second-order transgressions correlate well with transgressions recorded from New Zealand and fall on a curve representing the first-order Flandrian Transgression and subsequent regression which in these islands reached a maximum of about +2·4 m 2760 radiocarbon years B.P. This maximum is about 1250 years younger than the +2·1 m maximum recorded for the northern part of New Zealand, and thus fits a predicted difference in timing of the Flandrian Transgression maxima caused by oceanic salinity changes.

The net fall in sea level of 2·4 m from the Flandrian Transgression maximum has been of major importance in the development of atoll islets, which, mainly, if not wholly, as a result of this fall, have been built from sand taken from the shallow margins of the lagoonal floor. It may be no coincidence that the earliest Micronesian and Polynesian settlements date from about the period of the transgression maximum.

INTRODUCTION

Newman (1968) summarised two schools of thought on the subject of a postglacial rise in sea level—"the North Atlantic–Gulf Coast school . . . who find that sea level has risen to its present position only during the last few millennia, and the Indo-Pacific school . . . who believe that sea level rose to its present level some 5000–6000 years ago and has since fluctuated within 3 metres of its present level, including one or more conspicuous stands at [+] 2–3 metres". The Scripps Institute of Oceanography CARMARSEL Expedition "was organised in an attempt to resolve this late Quaternary sea level controversy" (Curray *et al.* 1970). A study of the Caroline and Marshall Islands was chosen because it was believed "that they had a greater probability of relative stability throughout the period of time considered than is true of the islands and atolls that are associated with tectonically and volcanically active trenches and island arcs". The members of the Expedition concluded "that there was no higher than present Holocene stand of sea level in the Caroline and Marshall Islands we visited but that sea level was at least near to present level at the time of formation of the rubble ridges", i.e., 2500 to 3000 years B.P.

Nor did Guilcher (1967) find at Tarawa and Abemama (atolls within the Gilbert Islands) "aucun indice de récif ancien actuellement émergé et hors

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de sa position de croissance". He added, however, "soit qu'il n'y en ait jamais eu, soit qu'il ait été entièrement détruit par corrosion au-dessus du niveau d'édification actuelle. Toutefois, avant de l'affirmer, il faudrait parcourir les îles des atolls de façon plus détaillée que nous l'avons fait."

On the other hand, David & Sweet (1904), Sollas (1908), and Cloud (1952) described undated, high-level, biohermal reef-rock and subtidal breccias in the Gilbert and Ellice Islands that indicate sea levels of at least 2·4 m above today's level.

Suggate (1968) suggested that sea level change, as distinct from crustal uplift and subsidence, could have different histories in different parts of the world, thus both schools of thought may be correct. I am sympathetic towards this view and suggested (Schofield 1967) that changes in ocean salinity, because of rapid ice melting, could have led to isostatic imbalance of oceanic water columns which would have promoted a greater rise of the sea in higher latitudes than in more tropical regions. If the change to the present-day salinity pattern was slow enough this could have led to the maximum postglacial rise being not only different in magnitude but occurring at different times in different parts of the world. This is compatible with, but not necessarily a confirmation of, the conclusions of the CARMARSEL Expedition. The present study is of five atolls in the Gilbert and Ellice Islands, which lie close to the Caroline and Marshall Islands and could be expected to have had similar histories as far as crustal movements are concerned, as all lie in the aseismic western Pacific (Gutenberg & Richter 1941), east of the Andesite Line and in latitudes 0–10° (Fig. 1).

ATOLL COAST DEPOSITS—THEIR RELATION TO SEA LEVEL

Although geomorphology (Fig. 2) is a major tool, the study of the coastal rocks is of equal, if not greater, importance in determining past sea levels. Facies important to this study include "calm-weather" beach sediments, "stormy-weather" beach sediments, back-reef breccia, and biohermal reef-rock.

Calm-Weather Beach Sediment

A typical, well developed, lagoonal beach at Funafuti has slopes that change from horizontal in the low-tide platform to about 2° just above low tide, to 7° just above mean sea level, and to 12° just above high-tide level. The lagoonal beach sediments change from well sorted coarse sand at low tide to rounded 0·15–0·30 m boulders at storm-ridge level. Non-cemented beach deposits on the ocean side of the windward islands of all atolls visited differ from those on the lagoonal beaches in being coarser in their upper part, and in being commonly limited to deposition above high-tide level; below this level cemented, carbonate rock, usually fossil beach conglomerate, crops out. The surface slope on the ocean beach deposits, immediately above high-tide level, can be as low as 8° but is commonly about 12° and steepens rapidly to angles greater than 15° in the higher parts of the profile.

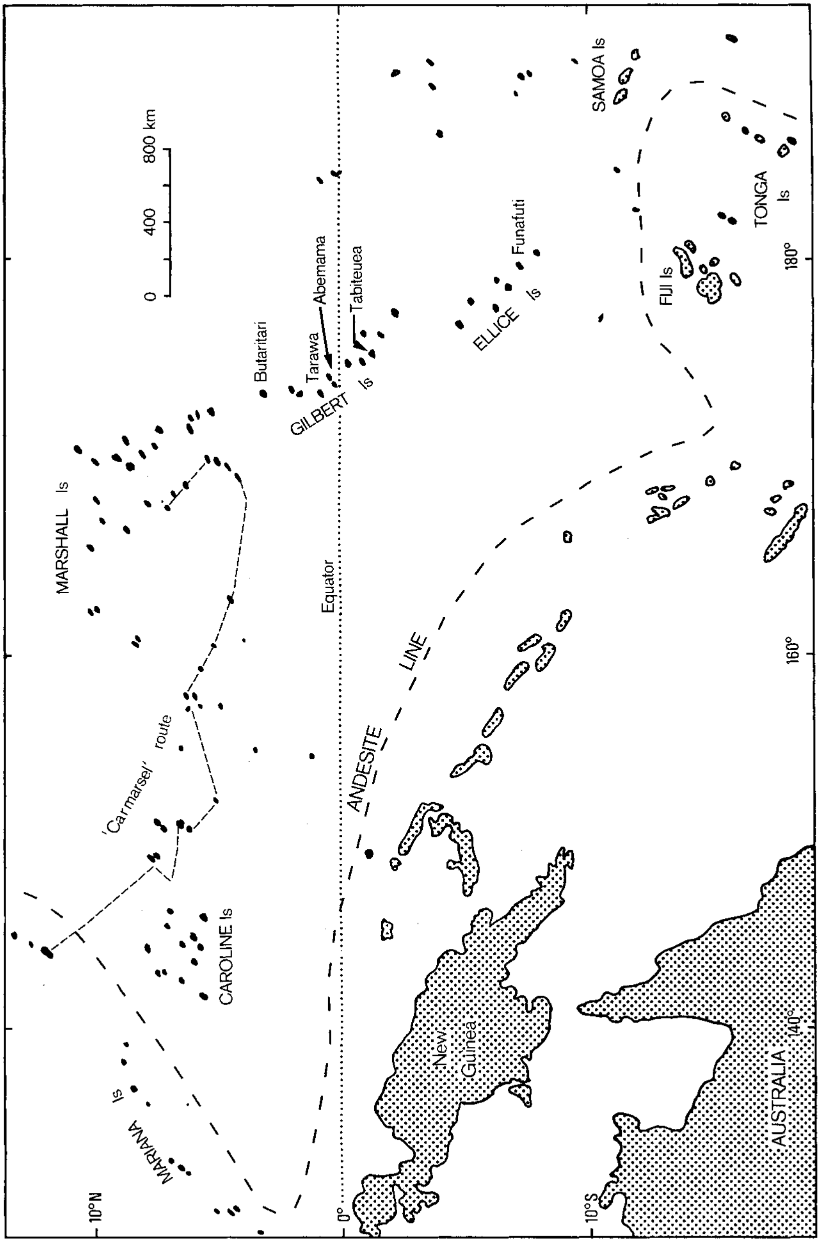


FIG. 1—Locality map showing atolls visited (Butaritari, Tarawa, Abemama, Tabiteuea and Funafuti) and the route of the CARMARSEL Expedition.

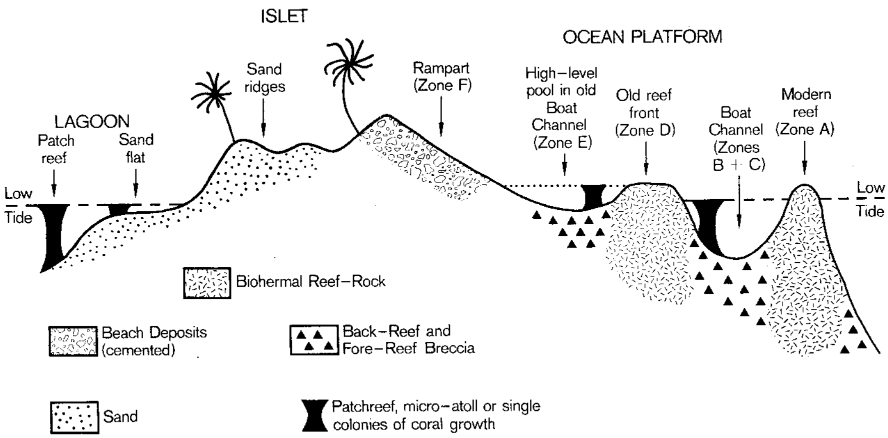


FIG. 2—Diagrammatic representation of coastal deposits as related to some important reef zones. These may not always be present or, if present, may not always be readily discernible. This applies particularly to zones B, C, D, and E. Probably B, C, and E often seem absent through being completely in-filled with back-reef breccia. For zone descriptions see Schofield (1977).

Lagoonal and ocean beach calm-weather sediments are similar in that high-tide and supra-high-tide boulder deposits are generally well rounded and free of matrix down to depths of 0·75 m. Below this matrix-free zone the interstices between the boulders are packed with small pebbles. An important feature of both environments is the development of imbrication, the flatter boulders sloping towards the lagoon on the lagoonal beaches and towards the ocean on the ocean beaches. Also, as noted by McKee (1959), calm-weather sediments are characterised by good sorting. Finally, any bedding developed dips parallel to that part of the beach profile in which the deposit was formed.

Stormy-Weather Beach Deposits

A storm-derived gravel sheet, deposited on the island's surface above high tide level, is structurally a single layer with minor imbrication (McKee 1959). Sand and other fine matrix is absent but the depth to which the matrix-free nature of these high-level gravel sheets extends is not mentioned by McKee (1959). Stoddart (1963) notes that although such high-level rubble carpets are present, those best developed on the British Honduras Reefs were along the old reef crest where they rarely emerged as low ridges and terminated lagoonwards in steep faces. Stoddart (1963) also recognised the formation of a lag deposit at Colson Cay, where a ridge formed by the hurricane is "now being destroyed by wave action, flushing out the fine material" leaving a lag of larger slabs.

A new coastal gravel ridge, formed at Funafuti Atoll during the October 1972 hurricane, provides interesting lithological data. Its morphology has been described in some detail by Baines *et al.* (1974) and Maragos *et al.* (1973). It is about 4 m high and up to 40 m wide, piled onto the low-tide platform just inside the algal ridge, and in most places is separated by a trough from the old shore. The inner part is the least disturbed portion, as is shown by the medium to dark-grey stain on the undisturbed material. The outer part is being constantly reworked, as is shown by the clean, creamy-white colour of the boulders.

The inner edge of the least disturbed sediment is very steep and shows some rudimentary bedding into coarse and finer boulders, perhaps because of subsequent periods of wash-over during shoreward migration of the ridge (Baines & McLean 1976). There are no fines smaller than pebbles about 25 mm in diameter, nor is there any surface imbrication. With extremely rare exceptions, the coral clasts are highly angular with rough, unabraded surface textures. In contrast, the reworked clasts show good surface imbrication, mainly towards the ocean, but with some towards the land where slabs have slid down the ridge on the landward side. There has been a remarkable rounding within two years—most surface textures have been abraded, and in some cases completely worn away, producing well rounded clasts. There are also examples of well developed sphericity but this could have been the original form of the unworn clast.

It appears, therefore, that the deposition of stormy-weather beach deposits is commonly followed by reworking of at least part of the deposit into a calm-weather lag. Thus a composite unit is formed in which the upper layer is a calm-weather deposit and the lower part is a stormy-weather sediment. Cemented examples of these units are common, and are particularly well exposed along the windward side of Funafuti Atoll. In many places they have a dip of up to 8° (Fig. 3). The upper stratum of each unit consists of well sorted, matrix-free, angular to rounded (commonly well rounded) conglomerate or breccia-conglomerate (0·15–0·30 m maximum boulder size) with well developed imbrication. The thickness of this lag is nearly always close to the length of the largest boulder present. This upper bed grades downwards into a lower stratum of poorly sorted, unbedded, cemented, mostly angular rubble (some rounded fragments were found only in column F9-L, Fig. 4) with rare, poorly developed imbrication at the base. The base of the complete unit is sharp and in two places (columns F2-L and F8-L, Fig. 4) is irregular as a result of erosion of the underlying material.

Back-Reef Breccia

MacNeil (1954) divided detrital reef-rock into back-reef debris and fore-reef clastics. Back-reef debris is almost certainly synonymous with "The Breccia", a facies recognised by David & Sweet (1904) as being quite distinct from beach deposits. Back-reef breccia is similar to stormy-weather breccia in that the material is angular, non-sorted, and non-imbricated (Figs. 5A and 5B). The two breccias are also similar in that there is bedding, but whereas the bedding in stormy-weather breccias is well defined as a result of subsequent sorting in its upper part and commonly has a dip, back-reef breccia bedding is always sub-horizontal and ill-defined. More important, there is a complete absence of lag material in back-reef breccia.

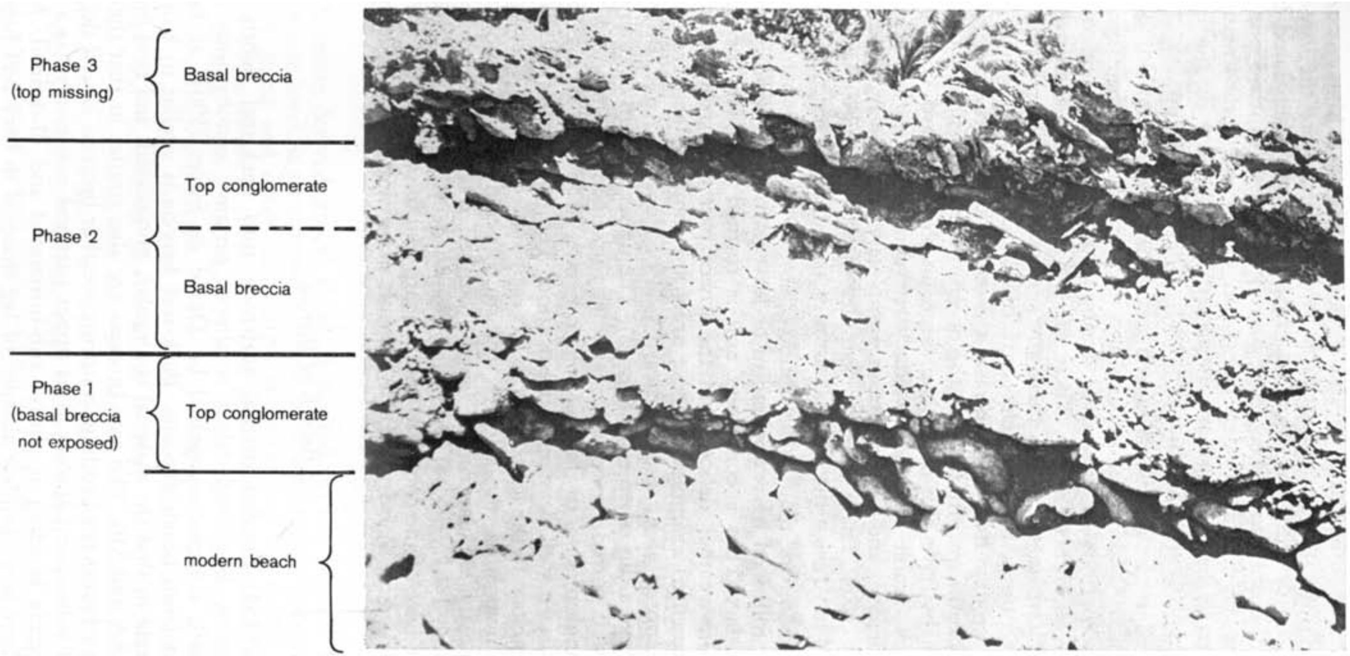


FIG. 3—Cemented beach sediments, lagoonal beach, southern end of Funafuti Island, Funafuti Atoll—stratigraphic column, F9-L in Fig. 4. More than one phase of deposition is present. Each phase consists of an upper, well sorted lag formed during "calm-weather" conditions and a lower, non-sorted beach breccia deposited during "storm-weather" conditions.

David & Sweet (1904) concluded that as "The Breccia" is cemented by *Lithothamnion* and *Polytrema planum* it "has been formed below water, mostly at or below low tide, probably the latter".

Immediately inland of the algal ridge there is commonly a channel below the low spring tide level—the so-called "boat channel". In areas where the "boat channel" is absent it has presumably been completely in-filled by back-reef breccia or perhaps by finer sediments, depending on local conditions. If this is the environment of deposition, some corals in position of growth should be expected within the fossil breccia but it is difficult to be certain that a few corals in such a position are not purely random in orientation. However, corals in position of growth are far more commonly recognised on the surface of a back-reef breccia than in any other type of facies, except the biohermal reef. For example, at the southern end of the Lua Motu Islet, Funafuti Atoll, *Porites* ex gr. *lobata*, *Heliastraea* sp. and *Acropora* sp. were recognised as being in position of growth on top of back-reef breccia (Fig. 5A) by Dr E. V. Krasnov, Institute of Biology, Laboratory of Paleoecology, Vladivostok. Such surface corals in position of growth are rarely preserved, all observed being at the inner edge of the coast where loose, protective, islet sediments had been recently removed by erosion.

Another facies associated with back-reef breccia consists of a non-sorted, non-imbricated breccia with some rounded boulders and common non-*in situ Tridacna* that, where present, always appears as a bed 0·3 m thick at the top of the back-reef breccia. The basal contact is commonly slightly wavy. It is not found at Funafuti, but is common in the Gilberts where an abraded reef flat is much wider and on which little understood "stone patches" (see Transgression Gilbert-VI below) have developed. Fossil *Tridacna* beds could represent "stone patches" but have a greater number of *Tridacna* present. However, there could be environmental reasons, including man-made ones, for this comparative absence of *Tridacna* in modern "stone patches". On the other hand, as the back-reef breccia was built up towards low tide, the change in environment may have encouraged the introduction of *Tridacna*.

Back-reef breccia is thus an angular, non-sorted, non-imbricated, subtidal breccia with rare, crudely developed, subhorizontal bedding. It contains no lag conglomerate. In many places *Tridacna* is concentrated near the top where corals in position of growth are also more commonly recognised than in other facies, excepting biohermal reef rock.

Biohermal Reef Rock

MacNeil (1954) recognised biohermal reef rock as a latticework of corals in position of growth. McKee (1956) used the term "frame work limestone" and described how

> "Attempts were made . . . to determine the lithographic character and structural features of the framework limestone through studies of material exposed in cracks below the pavement . . . . The investigation was hampered by the extreme difficulty of digging into the rock reef . . . . In many specimens, the reef rock appears aphanitic, but in others the relict structures of corals are clearly preserved. The framework limestone as a whole seems to be very cavernous, although small masses and hand specimens commonly have a relatively low apparent porosity."

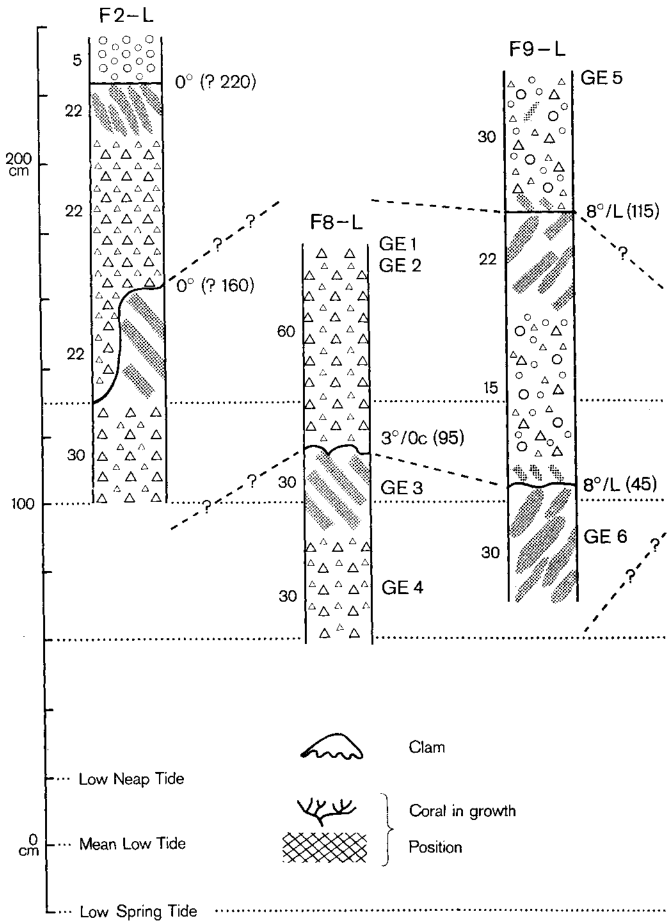
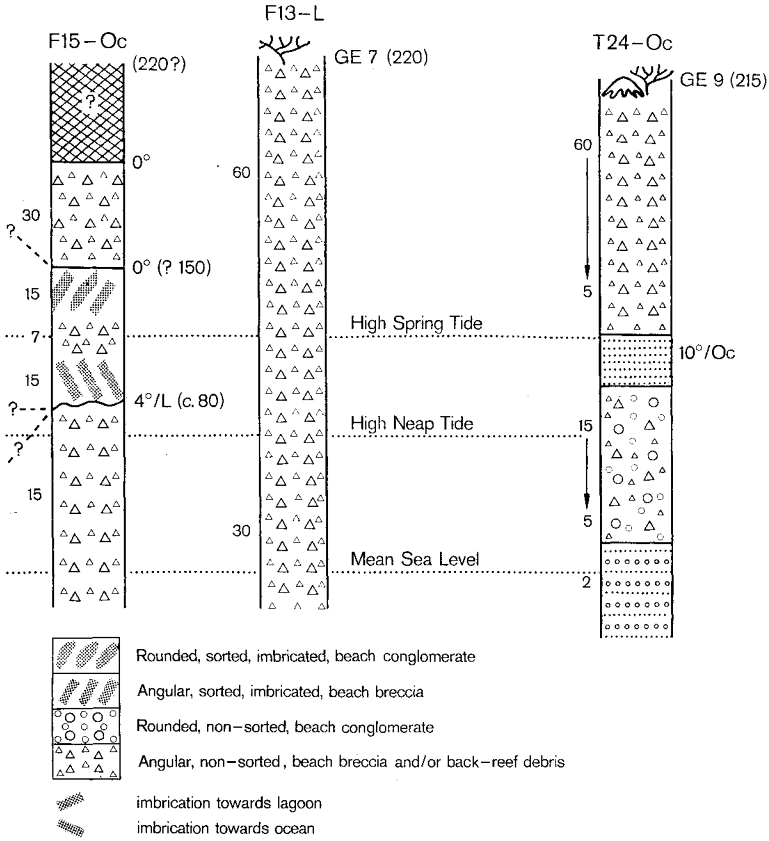


FIG. 4—Stratigraphic sections. F2, F8, etc., refer to localities on Funafuti Atoll and T24 to a locality on Tarawa. "L" and "Oc" refer to lagoonal or ocean side respectively. Numbers prefixed GE refer to samples collected for radiocarbon dating. Numbers on left side of column refer to maximum diameter of clasts in cm. Dips are given in degrees on right side of column and are shown dipping either lagoonward (L) or oceanward (Oc) except where strata are horizontal (0°). Numbers in brackets refer to estimated level of sea in cm above the present at the



time the deposit was formed—based on dip of lag conglomerate relative to dip on present coastal lag deposits. In longitude and latitude the localities are: F2, 179° 12′ 40″ E, 8° 30′ 35″ S; F8, 179° 11′ 20″ E, 8° 32′ 23″ S; F9, 179° 11′ 30″ E, 8° 32′ 18″ S; F13, 178° 6′ 43″ E, 8° 36′ 36″ S; F15, 179° 6′ 50″ E, 8° 37′ 20″ S; and T24, 173° 7′ 20″ E, 1° 21′ 33″ N. Sections from which samples GE11–GE20 were obtained are described in the text.

FIG. 5—A—Platform remnants 2·3 m above low spring tide, lagoon side at south end of Lua Motu Island, Funafuti Atoll; underlain by back-reef breccia. Corals in position of growth on the platform surface (radiocarbon samples GE7 and GE10) came from an area immediately oceanward of the foreground.
B—Close-up view of back-reef breccia.

Large blocks (Fig. 6A) of biohermal reef rock are thrown onto the reef platform during hurricanes. As a result, remnants of a biohermal reef formed during some previous high sea level could be misinterpreted as hurricane blocks. (For further discussion see Discussion below).

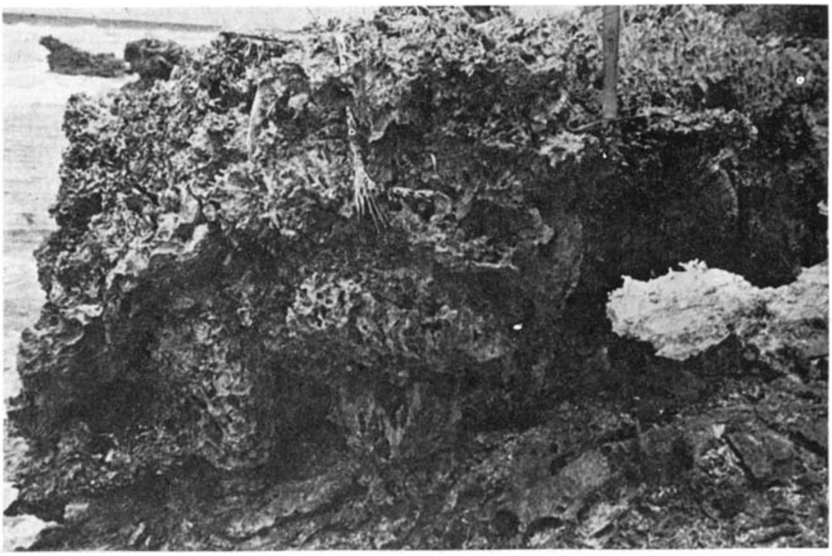
Insufficient studies have been made to determine the percentage of coral that remains in the position of growth within a biohermal reef. In the more cavernous varieties it may be high, being reduced when the interstices become filled with coral debris. However, even in the cavernous varieties there may be a substantial percentage of displaced coral.

Almost certainly there is also rock that is intermediate between biohermal reef rock and back-reef facies, but, because of the absence of beach conglomerates, biohermal reef rock is readily differentiated from beach deposits.

LATE HOLOCENE SEA LEVELS

During the investigations of the Gilbert and Ellice Islands it was found that coral samples were invariably contaminated, usually by secondary aragonite (Grant-Taylor, Schofield, and Wodzicki; "Secondary aragonite and other dating impurities in coral", in prep.). As this is impossible to eradicate, their radiocarbon dates are too young by an unknown amount, and hence coral dates are of little use. Instead, the dates for almost all the sea-level transgressions recorded at the Gilbert Islands were obtained from *Tridacna* shell, a very massive and impervious material. The only way in which contamination of *Tridacna* is likely to occur is the introduction of easily recognised and removed sediment in fine borings. All dates given (Table 1) are "with respect to the Seawater (9° S) Std" adopted by the N.Z. Institute of Nuclear Sciences dating laboratory; are in terms of ^{14}C half life of 5730 years, and have not been corrected for secular effect.

Before the following evidence is accepted as evidence for a postglacial sea level of $+2{\cdot}4$ m and not a crustal rise of the same order, some consideration must be given to the possible direction and rate of crustal movement. In fact, instead of being a region that is rising, the Gilbert, Ellice, and Marshall Islands lie within an area which is slowly subsiding. The rate of this subsidence during the Cenozoic is approximately shown by the ages of shallow-water reef limestone in drillholes at Bikini and Eniwetok within the Marshall Islands (Ladd *et al.* 1953; Emery *et al.* 1954). From the dates of the ending of the different Cenozoic periods the average rate of sinking has been about 0·025 m per 1000 years, with a possible increase to about twice this value in the last 5 million years. These rates are insignificant compared with the 15 m per 1000 years rate of sea-level rise during its major period of postglacial transgression, or even compared to the present rate of sea-level rise which has a world-wide average of about 1 m per 1000 years. Furthermore, the region is currently aseismic and there is no evidence for differential uplift or subsidence. Thus the effects of any geologically recent sea-level change, both major and minor, far outweigh the effect of local crustal movement.



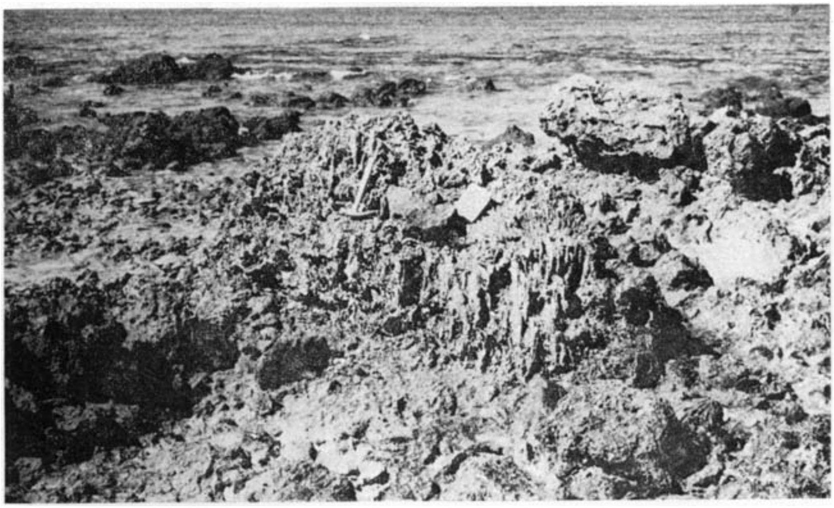


FIG. 6—A—Boulder of biohermal reef-rock, Funafuti Atoll, Funafara Island, ocean beach, 179° 6′ 54″ E, 8° 37′ 28″ S. Note abrupt, probably non-cemented contact with underlying breccia. Note also close-fit at contact brought about by pressure solution at point contacts and/or abrasion through rocking movements of the boulder.
B—Hammer on remnant of biohermal reef-rock, Butaritari Atoll, ocean coast, 2 km north of Ukiangana Pt. Note absence of an abrupt contact at base.

TABLE 1—Radiocarbon samples

Field No.	Lab.No.	Age($T_{½}$ 5730)	Material	Secondary/ aragonite	Locality	Stratigraphy	Sea level
GE1	NZ1595	1200±60	Coral boulder	slight	See Fig. 3	See Fig. 3	*c.* +1 m
GE2	NZ1596	2120±65	Coral boulder	rare to high	As for GE1	As for GE1	*c.* +1 m
GE3	NZ1597	1670±65	Coral boulder	slight	As for GE1	See Fig. 3	*c.* +0.5 to +1.0 m
GE4	NZ1598	2180±65	Coral boulder	rare to high	As for GE1	See Fig. 3	*c.* +0.5 to +1.0 m
GE5	NZ1599	1950±50	Coral boulder	very common	See Fig. 3	See Fig. 3	unknown
GE6	NZ1600	1590±60	Coral boulder	very common	As for GE5	See Fig. 3	correlated with GE3
GE7	NZ1601	1615±60	Coral in growth position *Heliastraea* sp.	very common	See Fig. 3	See Fig. 3	+2.3 m
GE8	NZ1602	1335±60	Coral in growth position *Porites* ex gr *lobata*	varies	Funafara Island†		+0.5 to +1.5 m
GE9	NZ1603	2760±70	*Tridacna*	-	See Fig. 3	See Fig. 3	+2.25 m
GE10	NZ1688	1150±60	Coral in growth position *Acropora* sp.	Some	As for GE7	As for GE7	+2.3 m
GE10*	NZ3213	1040±90	Coral in growth position *Acropora* sp.	Some*	As for GE7	As for GE7	+2.3 m
GE11	NZ3316	1570±50	*Tridacna*	-	See "Transgression Gilbert V" in text		
GE12	NZ3317	3520±60	*Tridacna*	-	See "Transgression Gilbert II" in text		
GE13	NZ3318	3980±70	Coral boulder	slight	See "Transgression Gilbert I" in text		
GE14	NZ3320	2400±70	*Tridacna*	-	See "Transgression Gilbert IV" in text		
GE15	NZ3321	2230±70	*Tridacna*	-	As for GE14 (from same bed)		
GE16	NZ3336	1320±50	*Heliopora* in growth position	very slight	See "Transgression Gilbert V" in text		
GE17	NZ3337	2890±40	Coral boulder	Some	Tabiteuea Atoll§	As for GE18	+1 m
GE18	NZ3339	1740±50	*Tridacna*	-	Tabiteuea Atoll¶	See "Transgression Gilbert VI" in text	
GE19	NZ3340	2190±50	*Porites* central 3-6 cm	rare to common	Butaritari AtollΨ	Biohermal reef	+2.4 m
GE20	NZ3341	2140±40	As for GE19 outer 50-55 cm	rare to common	Butaritari AtollΨ	Biohermal reef	+2.4 m

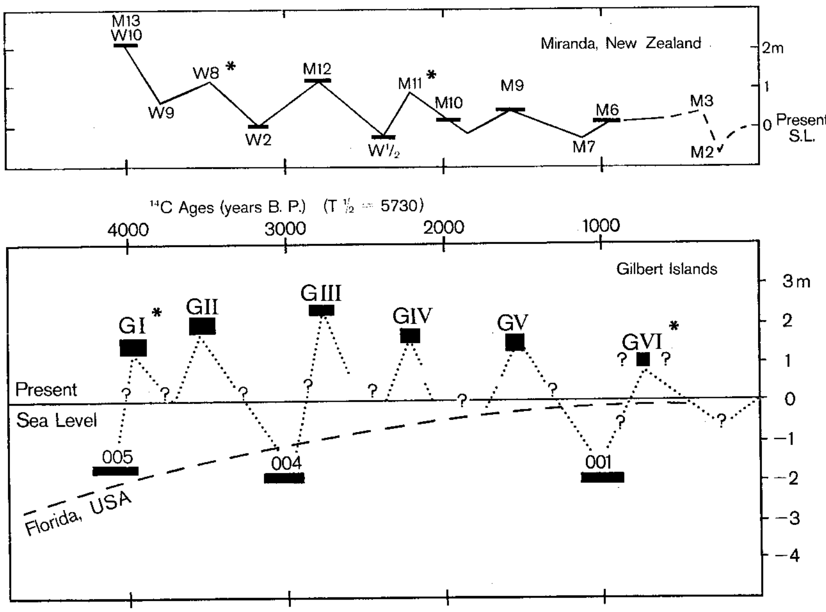
*Same as sample GE10, except that more massive portions were removed.

†Lagoonal coast of Funafara Island, 250 m from north end of island, Funafuti Atoll. A Russian dated sample MGU-190 taken from the same coral yielded a date of 880±50 (Agadzanin *et al.* 1973; P. Kaplin pers. comm.).

§Tabiteuea Atoll, ocean coast 2 km south of Government Resthouse.

¶Tabiteuea Atoll, ocean coast, east of southern end of airstrip.

ΨButaritari Atoll, ocean coast, 2 km north of Ukiangang Point.



CORRECTION: *For* 001, *read* 011.

FIG. 7—Correlation of dated sea levels recorded in the Gilbert and Ellice Islands with second-order transgressions recorded from New Zealand (in radiocarbon years based on $T\frac{1}{2} = 5730$; not $T\frac{1}{2} = 5568$ as originally used (Schofield 1960). The GI to GVI rectangles denote approximate limits of accuracy. An asterisk denotes some uncertainty: GI is almost certainly the oldest transgression recorded from the Gilbert Islands but, unlike GII, GIII, GIV, and GV, is not dated from *Tridacna* but from untrustworthy coral; GVI platform remnants associated with GVI are much better preserved that those associated with older transgressions but the only *Tridacna* sample yielded an age that was obviously too old; both W8 and M11 in the New Zealand curve have not been radiocarbon dated but are dated within known limits from their relative positions in prograded sequences (for original Miranda (M) and Whakatiwai (W) curves see Schofield 1960, 1973). Also shown is the possible relationship of Bloom's (1970) peat dates, 004, 005 and 011, from the Caroline Islands, with the Gilbert transgressions.

Transgressions

Strictly, as no evidence for periods of minor regressions in the Gilbert and Ellice Islands has yet been recognised, the second-order sea levels (Fig. 7) should not be interpreted as peak periods of minor transgressions. Nevertheless, the proposed correlations of the Gilbert and Ellice relative sea-level data with New Zealand transgressive peaks (see below) suggest that the former are also transgressive maxima. Furthermore, the dated sea-level evidence from these islands most likely represents transgressive maxima because on the ocean coasts of the atolls, to which the present studies have been mainly confined, the building up of a coral reef to a new level during transgressions is likely to provide the only datable material of significance.

Six second-order transgressive maxima are thus recognised (Fig. 7) and here named Gilbert I, II, III, IV, V, and VI. Four are dated by *Tridacna* samples from layers of concentrated *Tridacna*; one has only a coral date; and the sixth, the youngest, has no acceptable local date. Most maxima are based on a consistent stratigraphic sequence leading up to an associated high-level platform remnant which lies at different levels for the different transgressive periods and which is almost certainly a high-level analogue of the modern wave-cut platform (see Discussion). At its base the stratigraphic sequence consists of a cemented, highly angular, non-sorted, non-imbricated breccia, with some indistinct, undulating, sub-horizontal bedding, but no evidence of the re-sorting that produces the better-bedded, imbricated, rounded, beach conglomerate. Almost invariably non-*in-situ* *Tridacna* shells appear near or at the top of the sequence—in a concentration that is not in the form of a beach conglomerate. The *Tridacna* bed and the absence of beach conglomerate show that this facies is not a normal beach facies of either calm-weather or storm origin. With the possible exception of the *Tridacna* bed at the top of the sequence it is almost certainly a back-reef facies that was formed up to low-tide level and is referred to as such in the evidence presented below for many of the transgressions. The *Tridacna* layer is commonly 0·3 m thick and could be equivalent to the modern "stone patches" that form up to 0·3 m above low tide (see Gilbert-VI below).

GILBERT-I (+1·2 to +1·5 m)

Evidence for the earliest Gilbert and Ellice Islands sea-level transgression is scarce. Along the oceanic coast of Eanikari Island, Tabiteuea Atoll, exposures of old beach conglomerate strike at an angle to the present coast, and have been planed across, forming an old platform that is 1·2 m above the present local low-tide platform and 1·5 m above low tide. Younger cemented beach gravels have been welded on top of this surface (Fig. 8A). No *Tridacna* could be found in the old conglomerate and of the two coral samples collected, only one had a reasonably small amount of secondary aragonite. This sample, GE13 (Table 1) is dated as 3980 ± 70 years B.P. The acceptance of this age for Gilbert-I is in doubt for two reasons: the age could be too young because of contamination with younger carbon, or too old because the sample is probably a boulder.

GILBERT-II (+1·8 to +2·1 m)

Platform remnants at 1·8 m above the present low-tide platform and 2·1 m above low tide are underlain by back-reef breccia. *Tridacna*, GE12, from the typical *Tridacna* layer at the top of the breccia was dated as 3520 ± 60 (sample from Abemama Atoll, 0·6 km south of Kariatebike). If the *Tridacna* bed represents the top of a back-reef facies, i.e., formed up to low-tide level, this section shows that the sea has been 2·1 m above its present level. If, however, the *Tridacna* bed represents a "stone patch" then the sea would have been about 1·8 m higher than its present level.

GILBERT-III (+2·25 to 2·4 m)

Evidence for this transgression is widespread. Well preserved platform remnants cut on back-reef breccia are exposed at the lagoonal coast at the south end of Lua Motu Island, Funafuti Atoll, where they are 2·3 m above

FIG. 8—A—Horizontal contact (half way up the scarp) on top of truncated beach conglomerates represents the 1·2 m surface developed during the Gilbert-I transgression. Ocean coast, North Tabiteuea, 0·8 km south of Government Resthouse.

B—Platform remnants of Gilbert-V 1·65 m above local low-tide platform. Site of radiocarbon sample GE11. Ocean coast, Abemama Atoll, 2 km south of Government Resthouse.

FIG 8—*continued*

C—Platform remnants of Gilbert-VI, 1 m above low tide, ocean coast, North Tabiteue Atoll, 2 km south of Government Resthouse.

low spring tide (Fig. 5); and the lagoonal and ocean coasts of Bikenibeu Island, Tarawa Atoll, 1240 m west of Otintau Hotel, where they are 2·25 m above low spring tide. Corals in probable position of growth are found on both these high-level platform remnants. A *Tridacna* from the Tarawa site, GE9, yielded a radiocarbon date of 2760 ± 70 years B.P.

Biohermal reef, probably *in situ*, at 2·4 m above its modern counterpart, on the lee side of Butaritari Atoll (see 'Evidence for high-level biohermal reef rock' below) could be of the same age (Fig. 6B). Coral radiocarbon dates from the latter and from corals in position of growth on the 2·3 m platform at Funafuti were all younger than the *Tridacna* date from Tarawa, and because of contamination by younger carbon are not accepted as reliable.

David & Sweet (1904) record that similarly, on the lee side of Funafuti Atoll,

> "numerous *Porites* heads ... are in many cases over a foot, some ... 4 feet above high water [about 2·3 to 2·6 m above low spring tide]. These immense heads [up to 2·4 m in diameter and 1.5 m high] could not have grown in land-locked reef pools, but must have flourished under the most favourable conditions, such as free access to food-bringing currents, etc. [The] peculiar circular masses of coral raised mound-like in the centre, with concentric and rudely radiating joint-like markings, have the appearance, at first sight, of having been hurricane stranded. These are *Porites* blocks tilted slightly to the sea as they grew, and embedded in the breccia mass, as though set in concrete. The latter contains only an occasional fragment of *Porites*, and, except for these broken pieces, most of the *Porites* masses are *in situ*."

Obviously, careful consideration had been given before concluding that most of the *Porites* are *in situ*. Nevertheless, David & Sweet record that two other members of the party, Halligan (government hydrographer) and Finckh (biologist) "consider that these blocks are not *in situ*".

GILBERT-IV (+1·5 to +1·8 m)

At 1·7 km south-east of the Government Resthouse, along the eastern ocean coast of Eanikari Island, Tabiteuea Atoll, the typical back-reef breccia, complete with a *Tridacna* bed at the top, underlies platform remnants at 1·5 m above the local modern low-tide platform and about 1·8 m above low tide. Samples from two *Tridacna* shells showed no significant difference in age (2400 ± 40 yrs B.P., GE14; 2230 ± 40 yrs B.P., GE15).

Correlated with the development of this back-reef breccia is the extensive *Heliopora* reef flat at Onotoa Atoll, the next atoll in the Gilbert chain to the south-east of Tabiteuea Atoll. Cloud (1952) records that this *Heliopora* reef lies from 1·5 to 1·8 m above its living counterpart. No date is available.

GILBERT-V (+1·3 to +1·65 m)

High-level platform remnants, 1·65 m above their local modern counterpart and about 1·95 m above low tide, are exposed along the eastern ocean coast of Abemama Atoll, 2 km south of Karitebike (Fig. 8B). They are underlain by a typical back-reef facies complete with *Tridacna* at the top. A *Tridacna* sample, GE11, yielded a radiocarbon date of 1570 ± 50 years B.P.

An extensive *Heliopora* reef-flat on the ocean side of Eanikari Island, Tabiteuea Atoll, 10 km north-west of the Government Resthouse, has remnants at 1·3 m above low tide. There is no sign of any barrier that could have ponded an area in which this reef could have grown to some level above low tide. Thus it is considered to represent a +1·3 m sea level. *Heliopora* sample GE16 yielded a radiocarbon age of 1320 ± 50 years B.P. but slight contamination could make this age too young.

Additional evidence for a youthful sea level of about +1·35 m is provided by Hedley (1896), David & Sweet (1904), and Sollas (1904, 1908). They described an inner depression known as the Mangrove Swamp at Funafuti which, unfortunately, has since been largely filled to form the runway for the Funafuti aerodrome. The Mangrove Swamp was formed behind a storm-built rampart and, like the areas dammed behind the recently built rampart at Funafuti, there was free movement of water in and out of the swamp during tidal changes. Thus a dammed intertidal pool could not explain the well preserved, stranded, biohermal reef within the Mangrove Swamp. Fortunately, this evidence is well documented, including a beautifully prepared diagram of *Porites* that had grown amongst *Heliopora* over an area of 360 m² (David & Sweet 1904, plate 18). Sollas (1904) described two instrumental surveys that established that the summit of this reef lay 1·35 m above low water at spring tide or 1·1 m above low water at neap tide.

The evidence from all of these localities suggests that Transgression Gilbert-V was up to possibly +1·65 m but more likely about +1·3 m above present sea level at about 1570 years B.P.

GILBERT-VI (+0·6 to +0·8 m)

Transgression Gilbert-VI is represented by widespread, strikingly well preserved, relatively low-level, horizontal platform remnants (Fig. 8C). A *Tridacna* date, GE18, of 1740 ± 50 years B.P. is incompatible with their state of morphological preservation, which makes them clearly younger than the platform remnants left by the older transgressions. Whereas the latter invariably parallel the coast, and are narrow and poorly preserved, these youngest and lowest-level remnants differ markedly in forming long tongue-like projections at right angles to the coast, commonly from headlands. In longitudinal section their surface is horizontal but in cross section they have a slight slope in both directions from their crest. Their surface, solution-pitted and not abraded, lies at 0·9 to 1·1 m above the local low-tide platform. They are underlain by cemented, non-sorted, angular to subrounded rubble, commonly with a crude horizontal bedding plane about 0·3 m below their surface. Poorly developed imbrication is rare and in one example, along the coast east of the southern end of the North Takiteuea air strip, dips outwards along both longitudinal sides and ocean end of the remnant that extended at right angles to the coast. In others, imbrication dips outwards on one longitudinal side only. Some have a capping of vegetated, non-cemented sand and gravel. Their margins consist of vertically eroded, sometimes slightly undercut faces.

It seems almost certain that they are eroded remnants of "stone patches" that were built up to about 0·3 m on top of a high-level platform, the contact being the horizontal bedding plane 0·3 m below the surface of the remnants. Stone patches on the present low-tide flat are, as yet, little understood. They consist of non-sorted, angular to partly rounded, generally non-imbricated rubble up to 0·3 m thick, the maximum size of the boulders present. They are usually non-cemented; however, the central part was cemented in one example, suggesting that accretion had taken place along both sides. It seems that the high-level fossil "stone patches", being at a higher level than the surrounding low-tide platform, protected the underlying platform from erosion once sea level began to fall. However, lateral erosion has cut back their margins, exposing the contact between the overlying "stone patch" and underlying platform. A similar type of protection of a high-level platform from erosion has been demonstrated by MacNeil (1950), who found Tertiary limestone boulders perched on pedestals of Quaternary reef limestone standing 2 m high above the surrounding modern low-tide platform. This interpretation means that these remnants, 0·9 to 1·1 m above the present platform (i.e., approximately 1·2 to 1·4 m above low tide level), represent a sea level of about +0·6 m to 0·8 m.

These fossil "stone patches" seem to be restricted to the inland side of the fossil reef front preserved within Zone D (Schofield 1977) of the present low-tide platform. As discussed by Schofield (1977), this fossil reef probably represents a sea level more than 0·3 m above the present. It may well have been contemporaneous with these fossil patches.

Correlation

Other *Tridacna* dates from high-level reef remnants in the south-west Pacific region seem to be restricted to those recorded by Curray *et al.* (1970). In their table 2, under the heading of 'Significance' for Sample No. CRS600, they record a *Tridacna* date of 3400 ± 250 years from Guam for an "emerged reef implying sea level 1·4 to 1·8 m above present". Both level and date are close to Gilbert-II of +1·8 to +2·1 m, 3520 years B.P.

Curray *et al.* (1970) also record a *Tridacna* (CRS643) "firmly cemented to flat upper surface of platform, but not in growth position", its elevation being 0·7 m above mean sea level, i.e., 1·5 m above low tide level. This sample came from Ailinglapalap Atoll of the Marshall Islands and was dated as 2785 ± 100 years B.P. Another *Tridacna* from Ebon Atoll, Marshall Islands, CRS629, seems to have been identically situated and is dated as 2920 years B.P. Both these ages are very close to the age of 2760 years B.P. given to Gilbert III, but the actual sea level seems to have been about 0·75 m less in the more northern Marshall Islands, than it was in the equatorial Gilberts.

Recent, non-*Tridacna* evidence, has been summarised for the Enewetak (Eniwetok) Atoll of the Marshall Islands by Buddemeir *et al.* (1975). They wrote that these "studies show a history of:

(1) rapid reef growth until 3500 to 3000 yr ago;

(2) a sea level that reached the present height no later than 4000 yr B.P. and was significantly more than 1 m above present height from about 3500 to about 2000 yr B.P.; and

(3) a drop to present sea level, accompanied by extensive reef erosion, in the period 2000 to 1000 B.P.". This agrees with the first-order sea level trend determined here for the Gilbert and Ellice Islands (Fig. 7).

Figure 7 shows a reasonable correlation of the Gilbert and Ellice Islands second-order transgressive peaks with those recorded from shelly beach ridges on a chenier plain at Miranda and at other localities in the almost stable northern part of New Zealand (Schofield 1960, 1973). These minor sea-level fluctuations are superimposed upon the first-order Flandrian Transgression and subsequent regression. The Flandrian Transgression reached a maximum in the Gilbert Islands at about the period of Gilbert-III, i.e., about 2760 radiocarbon years B.P. This differs from the time its maximum was reached in New Zealand, which was at about the time when beach ridges M13 and W10 were formed, 4015 radiocarbon years B.P. There is thus a difference of about 1255 years between the maxima of the Flandrian Transgression in these two areas.

Evidence given by Schofield (1967) and Pisias *et al.* (1975) strongly suggests that several thousands of years are required to completely mix low-saline, glacial melt with high-saline, ocean water. Because of this factor, it was predicted (Schofield 1967) that sea level "changes in the equatorial regions are likely to be later than those in the higher latitudes". Although not clearly stated, this predicted difference was meant to apply mainly to the maximum of the Flandrian Transgression, and the discussion that followed suggested that perhaps the Flandrian Transgression had not yet reached its maximum in some tropical regions. Although it now seems that the prediction was essentially correct, the present evidence suggests that the delay was much less than that previously considered.

DISCUSSION

The recognition of a subtidal coastal facies, first named by David & Sweet (1904) as The Breccia and later by MacNeil (1954) as a back-reef facies, together with high-level biohermal reef remnants, allows estimates of the heights of a number of sea levels that are almost certainly transgressive peaks. Their correlation through radiocarbon dates with similar sea level peaks in New Zealand must lie beyond the possibilities of coincidence (Fig. 7). These peaks are of second-order importance and fall on the first-order Flandrian Transgression (and subsequent regression) that in the Gilbert and Ellice Islands reached a maximum of about +2·4 m, 2760 radiocarbon years B.P. This conclusion is at variance with that reached by the CARMARSEL Expedition (Curray *et al.* 1970; Bloom 1970) from their studies of the nearby Caroline and Marshall Islands, their conclusion being that there had been no Holocene sea level higher than the present level. As it is almost certain that all these islands will have had closely similar eustatic and crustal-movement histories closer examination of their conclusion is warranted. Especially to be considered are:

(1) evidence for high-level biohermal reef rock;
(2) the formation of high-level platform remnants; and
(3) the reliability of peat as a sea level indicator.

Two other factors have also been considered elsewhere, namely the effect of late postglacial, first-order, sea-level regression on atoll islet development (Schofield 1977) and the effect of a Pacific sea level high, 1000 years B.C., on Polynesian migration (Green & Schofield; "Relative sea-level change as a factor in Polynesian migration," in prep.; see conclusion 6 below).

Evidence For High-Level Biohermal Reef Rock

Biohermal reef rock is formed mainly along the exposed oceanic coast, as patches in pools on the reef flat, and as patches within the lagoon. The coastal reef, killed by a fall in sea level, would be the most exposed of all coastal facies to abrasive erosion and hence would be the least likely to survive. The less exposed reef patches, besides being comparatively rare, are less welded by algae and could also be comparatively easily eroded. Thus it is not surprising that most examples of high-level remnants of biohermal reefs are found in special conditions of protection such as the lee side of atolls, or in a coastal lagoon formed and protected by a later-formed hurricane rampart.

The rare examples of high-level biohermal reef facies were discounted by the CARMARSEL Expedition members as evidence for high sea levels; instead, as the examples in the Gilbert and Ellice Islands and at Bikini in the Marshalls are within intertidal limits, it was considered that these "could have developed in tide pools that subsequently drained".

At issue is the height of living coral growth. The maximum recorded by David & Sweet (1904) was 0·6+ m "above low water", but I found no living coral in tidal pools more than 0·35 m above corals living at low tide. Thus from height considerations alone it seems highly unlikely that the *Heliopora* reef flat at 1·5 to 1·8 m above the present living *Heliopora* reef at Onotoa Atoll within the Gilberts (Cloud 1952) has been formed in an intertidal pool. A similar *Heliopora* reef at Tabiteuea, up to 1·3 m above low tide, is widespread and there are no remnants of structures that could have ponded it.

Of special interest are the large blocks of biohermal reef which can be torn off the reef edge during hurricanes and transported on to the reef flat (Fig. 6A). Some of these may have been interpreted as evidence for past high sea levels, but it is misleading to dismiss all high-level biohermal reef remnants as stranded blocks without a very close scrutiny of their contact with the underlying reef flat (cf. Fig. 6A with Fig. 6B).

Gardiner (1931) commented on the constant rocking of blocks which inhibit welding. Newell (1956) also believed that "present erosion processes are now so effective that erratic blocks are moved or destroyed before they can become welded to the reef flat"; but, in addition, wrote, "Under more stable conditions preceding the present epoch, reef blocks were rigidly cemented to the reef flat". Could these, in fact, be high-level biohermal reef remnants *in situ*?

Welding of hurricane blocks may be possible, but such inorganic welding should be distinguishable from the organic.

Both Kuenen (1950) and Spender (1930) noted that blocks are commonly on the lee side of an atoll, where they could be derived, during rare storms, by the snapping off of "unwieldy knobs" and "mushroom shape" coral colonies that are also more common on the lee side. Nevertheless, Kuenen (1950) also believed that some blocks are reef remnants *in situ*. The evidence for *in situ* remnants of biohermal reef rock on the lee side of Butaritari Atoll is that although each remnant is not too large to be transported during a hurricane, they do not form isolated blocks but are clustered together in the form of remnants of a reef with its top about 2·4 m above its modern analogue. Undercutting is more prevalent in offshore positions as is shown by mushroom-shaped remnants which are ultimately broken to form true blocks that are transported and concentrated in the inner shore. Non-undercut reef remnants are common in the intermediate zone (Fig. 6B), and form sea-stacks identical in appearance to those formed from cemented breccias and conglomerates. Their basal contact does not seem to form a clear break, as is often found between boulders and matrix in welded breccia and conglomerate, but careful observation is required because the clarity of a contact is affected by algal coating and surface pitting.

Formation of High-Level Platform Remnants

Members of the CARMARSEL Expedition concluded that "high-level remnants with flat tops may reflect from cementation up to the level of high tide and erosion by storm waves above that level" (Shepard *et al.* 1967). However, the same authors commented that "indications of bevelling by erosion . . . may possibly indicate slightly higher stands" of sea level and that "major unsolved problems emphasized by our investigations include the cluster of dates, from flat-topped cemented rubble terraces, between 2500 and 3000 years ago, and the firm cementation of this rubble up to approximately the present level of high tide". The following discussion examines these problems more closely.

FLAT-TOPPED NATURE

Newell & Bloom (1970) found that the highest beach rock lies near the level of high spring tides. Their test trenches "generally indicate that the underlying beach rock continues at this level for a few metres landward before dropping in elevation and giving way to uncemented sand and gravel of the interior". Thus, if the unconsolidated sediment were removed by storm waves an undulating surface should be left, its height depending on previous sea-level changes and rates of progradation. Furthermore, in freshly exposed, recently cemented beach sediments each bed dips seawards, commonly in the form of a cuesta, its scarp facing inland (Newell 1956; also seen by me). These cuestas are absent from the flat-topped remnants. That abrasion of cemented beach sediments during the formation of flat-topped remnants has been an important factor is not denied by the members of the CARMARSEL Expedition, but the time of this abrasion raises many questions. Was it at about low tide level during some higher sea level (low tide being a common level to which present wave-cut platforms are formed), or is it taking place at today's high tide level as is believed by Newell & Bloom? If these remnants are being formed at today's high tide level, they ought to be more continuous and the surface smoothed by abrasion rather than being sharply pitted and delicately pinnacled by solution. The much simpler explanation is that these remnants are parts of once more extensive platforms formed near low tide during periods of higher sea level. As well as being downwasted by solution, the remaining sea-stacks are still being eroded by lateral abrasion and corrosion into a new platform not far above present low tide level.

FUNCTION OF TIDAL RANGE

It is probably more than a coincidence that, during the CARMARSEL Expedition, it was only in the Marshalls, where the tidal range is about 1·5 m that the +1·5 m level was found, whereas in the western Carolines, where the tidal range is 0·5 m to 1 m, rubble levels were found at +0·5 and +1 m. These lower levels are not recorded from the Marshalls by the members of the CARMARSEL Expedition. However, there is an 0·6 m level at Bikini Atoll in the Marshalls (Emery *et al.* 1954) and there are several levels from 0·6 m to 2·4 m in the Gilbert and Ellice Islands (where tides are also 1·5 m). Furthermore, there are wave-cut notches at 1·3 and 2·4 m in volcanic rocks in the Carolines (Curray *et al.* 1970). These examples all show the ubiquity of a much wider range of platform levels than is suggested by the CARMARSEL restriction of a 1·5 m level to the Marshalls and 0·5 to 1·0 m levels to the Carolines. Nevertheless, it seems equally likely that because of intertidal cementation a high-level platform remnant is favoured by a local high tide of the same level. Furthermore, solution downwasting may be retarded at some optimum level close to high tide by renewal of cement in the intertidal zone.

Reliability of Peat as a Sea-Level Indicator

Bloom (1970) concluded that there is a "close correspondence of the Florida and Eastern Carolines submergence curves". This conclusion is interesting for two reasons. Firstly, it suggests that postglacial sea level has not been higher than at present within the western Pacific, which is contrary to much of the evidence discussed above. Secondly, the Caroline Islands sea-level curve depends solely on buried peats.

Bloom (1970) remarked that the paludal stratigraphy of the three volcanic island groups investigated in the Caroline Islands is "remarkably uniform". He described in some detail an example from Moen which "illustrates most of the stratigraphic relationships that were encountered". Here, a freshwater or near freshwater swamp, flooded to about high tide level, is dammed back by mangrove-coated coral reef. Although the freshwater swamp consists in the main of peat overlying estuarine mud, there is one area of "floating mats of vegetation in deep pools".

None of the Caroline Islands peat samples (Bloom 1970) has been shown to have come necessarily from a transgressive sequence such as that in Florida where supratidal, freshwater, calcitic muds, and peat are overlain by mangrove peat, which is in turn overlain by marine deposits (Scholl & Stuiver 1967). Instead, the Caroline sequences consist of freshwater or mangrove peats over volcanic bedrock or various types of marine sediments and could equally well be regressive. As "floating mats" of vegetation could have settled in deep pools at levels well below high tide level, the absence of a reliably attested transgressive sequence is critical, and the assumption that each sample represents the initial transgression over land is suspect.

The freshwater peat sample numbered .011 (Fig. 7) is a hindrance to Bloom's (1970) attempted fit with the Florida sea-level curve. He considered that this discrepancy was caused by the smallness of the sample and the probable presence of modern roots, but it could be equally explained by settling of floating vegetation. This possibility may also apply to samples 005 and 004 (Fig. 7), and thus I am unable to agree that the results "are best interpreted at this time as the result of slow submergence totalling somewhat less than 2 m in the last 4000 years" (Bloom 1970).

The question of contamination by modern roots must make all radiocarbon peat ages suspect. It is one thing to identify and clean a sample of modern roots, but how many peats are contaminated with post-depositional roots that have in turn been peatified and are not readily recognisable as contaminants? If such contamination is general, then the tendency would be to erroneously shift the main postglacial transgressive curve forward in time. Scholl & Stuiver (1967) agree that "peat dates cannot be entirely free of age-reducing root contamination" and their fig. 6 shows that known contamination samples of Late Holocene age are commonly 700 years and as much as almost 1000 years too young.

Assuming little contamination, Bloom's Caroline Islands peats may record periods of low sea level, for their dates lie between transgressive peaks (Fig. 7). If this were true, the maximum Late Holocene, local sea level fluctuations would be about 4·5 m which is no more than some of those recorded from France (Ters 1973).

CONCLUSIONS

(1) Four coastal facies are recognised, three of which are formed mainly of coral rubble, the fourth being biohermal reef rock. The three sediments include a massive, cemented, subtidal, back-reef breccia which is important in preserving evidence of past sea levels—more important than the more

easily eroded biohermal reef rock. The back-reef breccia is different from the intertidal and supratidal stormy-weather breccia, with which it could be confused, in that (a) lag conglomerate is absent, (b) crude bedding is sub-horizontal (never with a dip that develops in intertidal situations), (c) algal cement is reportedly present, (d) a *Tridacna* bed (not a lag deposit) is common at the top of back-reef breccia sequences, and (e) corals in apparent position of growth are more commonly observed on remnants of its surface than elsewhere.

(2) Some high-level biohermal reef-rock remnants are hurricane blocks but others are most likely in position of growth. Careful observation is needed of the nature of the basal contact of such remnants, for if hurricane blocks are subsequently welded at their base (there is, however, some evidence that rocking may prevent such welding) such a weld should differ from the organic contact of a biohermal reef remnant in position of growth.

(3) Because of secondary aragonite crystallisation, coral is not suitable for radiocarbon dating. Consequently the six second-order transgressive peaks recorded from the Gilbert and Ellice islands have been dated mainly from *Tridacna* shells.

(4) The second-order transgressions show good correlation with equivalent transgressions recorded from New Zealand. They fall on the first-order Flandrian Transgression and subsequent regression.

(5) Locally the Flandrian Transgression reached its maximum of +2·4 m, 2760 radiocarbon years B.P. This is 1250 radiocarbon years younger than the +2·1 m maximum found in New Zealand. Salinity changes may be the main cause of these differences in the age of the Flandrian Transgression maxima but oceanic currents and possibly changes in such currents are likely to be important.

(6) Sand studies show that islets have been formed from sand drawn from shallow lagoonal margins (Schofield 1977) almost certainly in response to the 2·4 m fall in sea level in the last 3000 years, since sea-level fall promotes progradation. Before then there may have been no permanently established islets. Thus it may be no coincidence that the earliest known Micronesian and Polynesian settlements date from about the local Flandrian Transgression maximum.

(7) The CARMARSEL Expedition conclusion that postglacial sea level has not been above the present level is based on scarcity of high-level, biohermal reef-rock remnants; coincidence of some high-level platform remnants with local high spring tide levels; and ages and depths of buried peats within the Caroline Islands. However, CARMARSEL failed to recognise a subtidal back-reef breccia. CARMARSEL also failed to take into account the fact that high-level, reef-platform remnants are being downwasted by solution pitting and cannot therefore be simultaneously formed by abrasion at high tide levels. Finally, buried peats, particularly those from the Caroline Islands, may not be reliable indicators of either age or sea level.

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