URANIUM-SERIES DATING OF CORALS FROM THE SOUTHWEST PACIFIC

by

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Statement

The analytical data and conclusions presented in this thesis are my own, unless otherwise acknowledged in the text

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Abstract

The uranium-series technique is based on the observation that carbonates precipitating in nature, in particular corals and oolites, show an initial disequilibrium between Th^{230} and its parent U^{238}. The amount of Th^{230} initially present in a coral is negligible in comparison to that subsequently generated by the radioactive decay of uranium. If the system remains closed then the ratio of Th^{230} to U^{238} is a simple function of time. Because there is a 15 percent excess of U^{234} to U^{238} in sea water this has to be taken into account when determining the age.

Corals from New Guinea, the Loyalty Islands, and the east coast of Australia were provided for dating. The New Guinea corals, from the Huon Peninsula, had been dated previously, and so they provided a check on the reliability of the techniques used in this study. With one exception the ages from this study are within the error limits placed on the original ages. The one sample that does not agree is shown to have a high proportion of void-filling low-Mg calcite cement.

Corals from the Capricorn Group and Hayman Island within the Great Barrier Reef province show relatively young ages. One coral recovered by drilling at a depth of 17m on the Hayman Island reef indicates that the time of recolonization of the reef towards the end of the Holocene transgression is about 8,300 yr B.P. Coral samples below a marked discontinuity at a depth of about 20m are extensively recrystallized.

Ages of corals from the Inner Barrier of New South Wales show that this feature formed during the last interglacial at about 120,000 yr B.P. The ages suggest that there were two periods of high sea level at about this time.

Ages from reef terraces 2-6m above present sea level from three islands of the Loyalty Archipelago show the varying degrees of uplift of these islands. Corals from +2m on Beautemps-Beaupre are older than 200,000 yr B.P., while a coral at +6.5m from Ouvea gave an age of 117,000 ± 6,000 yr B.P. Ages from the +2m terrace on Lifou support the interpretation of a relatively high sea level at about 180,000 yr B.P.

Ages of corals from a slightly raised fringing reef around Mud Island, Moreton Bay indicate a sea level about one metre higher than present during the interval 4,000 - 6,000 yrs B.P. This slightly higher sea level could have been the result of a changing tidal regime within the bay.

Contents

List of Tables

List of Figures

Chapter 1 - Introduction

1.1 Development of the Uranium-Series Technique

The development of dating methods based on the radioactive decay of the uranium-series commenced when Joly (1908) observed that deep-sea sediments have a higher radium content than their terrestrial counterparts. Pettersson (1937) suggested that the high radium content was the result of precipitation of Th^{230} from ocean water. This was confirmed by Koczy *et al.*(1957) and Sackett *et al.* (1958), who discovered that the amount of thorium in deep-sea waters was less than one percent of the amount required for secular equilibrium with the uranium content. Therefore, recently deposited sediments tend to be rich in thorium, and if there is no exchange between the layers, then the decay of Th^{230} to secular equilibrium can be used for dating each individual layer.

Conversely, because of the deficiency of Th^{230} with respect to its parent, U^{238}, in ocean waters, carbonates precipitating in nature would be expected to show an initial disequilibrium in the U^{238} series. Therefore, the amount of Th^{230} initially present in any fossil carbonate could be considered negligible in comparison with that subsequently generated by the radioactive decay of uranium. If this is the case, and providing that the system remained closed to the addition or losses of U^{238} and its daughter products, then the ratio of Th^{230} to U^{238} in the carbonate would be a simple function of time.

This was confirmed by Barnes *et al*. (1956) from core samples of coral limestone on Eniwetok Atoll in the Pacific Ocean. It was found that while the uranium content remained nearly constant (2·9 to 5·5ppm variation) the amount of Th^{230} increased with depth, and that the activity ratio of Th^{230} to U^{238} changed more or less regularly from nearly zero for recent coral until it approximated the equilibrium ratio ($Th^{230}/U^{238} \simeq 1$) at depths beyond 30m. This discovery suggested that absolute age determinations could be made for Pleistocene marine carbonates up to 300,000 years old.

Cherdyntzev (1955) showed that the activity ratio of U^{234} to U^{238} in nature often differed from secular equilibrium. Thurber (1962) confirmed this anomaly, and suggested that there is a 15% excess of U^{234} to U^{238} in the present-day ocean. This made it necessary to revise the relationship between the activity ratio (Th^{230}/U^{238}) of the sample and its age. However, this disequilibrium meant that it could also be used as a dating technique itself, based on the disappearance of the initial excess of U^{234} in the sample. The age limit is about one million years.

Since these early discoveries attempts have been made to date various materials using the uranium-series disequilibrium method. Marine carbonates have been extensively studied (e.g. Thurber *et al*., 1965; Kaufman and Broecker, 1965; Ku, 1965; Veeh, 1966; Lalou *et al*., 1966; Blanchard *et al*., 1967; Mesolella *et al*., 1969; Veeh and Chappell, 1970; Konishi *et al*., 1970; Ku *et al*., 1974; and Bloom *et al*., 1974). Reliable uranium-series ages have been detmined for unrecrystallized corals and oölites, but the reliability of dating molluscs has been seriously questioned. Studies by Kaufman *et al.* (1971) on an extensive suite of molluscs have indicated that isotopic and/or chemical migration takes place. Inorganically precipitated carbonates, such as cave deposits and marls have been dated (e.g. Duplessy *et al.*, 1970; Kaufman, 1971; Thompson and Lumsden, 1973; and Thompson *et al.*, 1975). Dating of vertebrate fossils (Szabo *et al.*, 1969; Hansen and Begg, 1970; and Szabo *et al.*, 1973) has had some success, although migration of uranium and daughter elements has occurred in many of the specimens. Marine phosphorites have also been dated by the uranium-series method (Baturin *et al.*, 1972; Veeh *et al.*, 1973; Burnett, 1974). Because of the uncertainties that arise from dating molluscs and other materials, only unrecrystallized corals have been used in the present study.

1.2 Theory

The general equation for determining the age of a sample from the activity ratios U^{234}/U^{238} and Th^{230}/U^{234} is given in Kaufman and Broecker (1965), and it is reproduced below. The equation assumes that the sample has remained a closed system, i.e. there is no initial Th^{230}, and that there is an initial 15 percent excess of U^{234} to U^{238} that disappears at a rate determined by the decay constant of U^{234}.

$$\frac{Th^{230}}{U^{234}} = \frac{U^{238}}{U^{234}} \left[1 - e^{-\lambda_o t} \right] + \left[1 - \frac{U^{238}}{U^{234}} \right] \cdot \left[\frac{\lambda_o}{\lambda_o - \lambda_1} \right] \cdot \left[1 - e^{-(\lambda_o - \lambda_1)t} \right]$$

Where: (i) U^{234}/U^{238} and Th^{230}/U^{234} are the measured activity ratios

(ii) λ_o and λ_1 are the decay constants for Th^{230} and U^{234} respectively (half-lives used in this study are $7{\cdot}52 \times 10^4$ yr for Th^{230} and $2{\cdot}48 \times 10^5$ yr for U^{234}; $\lambda_o = 9{\cdot}21738 \times 10^{-6}$ yr^{-1} $\lambda_1 = 2{\cdot}79495 \times 10^{-6}$ yr^{-1})

A direct solution for t is impossible but ages can be determined using standard graphs, such as those reproduced by Kaufman and Broecker (1965) and Gustavsson and Högberg (1972), and by iterative convergence.

In order to determine whether or not a particular Th^{230} age is reliable, Thurber *et al.* (1965) used the following criteria:

(1) The sample should contain less than a few percent calcite. The recry stallization of aragonite to calcite, or introduction of calcite cement is likely to lead to a violation of the closed-system assumption. In the present study corals with a calcite content in excess of 5 percent were rejected for

dating.

(2) The uranium concentration in the sample should be 2 to 3ppm. Gvirtzman *et al.* (1973) on the basis of fission-track analysis indicated that modern scleractinian corals have a concentration of about 2ppm uranium, and that the presence of aragonite or high-magnesium calcite cement raises this concentration to about 3ppm. However, uranium analyses carried out during uranium-series dating indicate that the normal values are 2-3ppm. *Acropora* species commonly have a uranium concentration of about 4ppm, and although they generally give reliable ages (e.g. Broecker *et al.* 1968) some doubt has been cast on their reliability (e.g. Sample number 6 of Bloom *et al.*, 1974).

(3) The U^{234}/U^{238} ratio, corrected for age should be $1{\cdot}15 \pm 0{\cdot}03$.

(4) The Ra^{226}/Th^{230} ratio should be consistent with the age of the sample. Samples with ages greater than 70,000 years should yield ratios of unity within the experimental error. No Ra^{226} values were determined during this study, and most recent workers no longer apply this criterion.

(5) The Th^{230}/Th^{232} ratio in the sample should exceed 20. The presence of Th^{232} in fossil

corals may be taken as evidence of secondary addition.

(6) The Th^{230}/U^{234} age of the sample should be consistent with its C^{14} age (where available).

(7) The Th^{230}/U^{234} age should be consistent with stratigraphic data.

1.3 Sample Preparation and Analytical Techniques

Each sample was first cleaned using an ultrasonic vibrator to remove soil or any lightly adhered material. After this initial shaking, the sample was examined in hand specimen for any visual signs of calcite cleavage which may indicate recrystallization. The sample was then broken up into small pieces and any external crust or remains of encrusting organisms were removed with a vibratool and a dentist drill. Particular attention was paid to the presence of any borings, as these are often the site of secondary carbonate cements. If borings were present then they were usually drilled out, or, if the frequency of borings was high, the sample was rejected for dating. After treatment with the vibratool and dentist drill, the sample was cleaned once more in the ultrasonic vibrator to remove carbonate dust and any previously unremoved soil. The sample was then air dried for six hours in an oven set at 50°C.

A representative split of the dried sample was ground to a grainsize less than 65μm, and analysed by X-ray diffraction. The diffractometer was set to scan between 25° and 31° 2θ, and the areas under the secondary aragonite peak at

27.2° 2θ and any calcite peak present (usually at 29.4° 2θ for low-Mg calcite) were integrated. This was repeated three more times, and a mean value for the areas was calculated and compared with those of prepared standards of known mixtures of aragonite and calcite. In this way the amount of recrystallization could be determined to within less than one percent, for samples containing up to ten percent calcite. If the sample contained more than five percent calcite it was rejected for dating.

In some cases thin sections of corals were prepared in order to determine if aragonite and calcite cement were present, and to delineate the sites of the cement. The corals were impregnated with epoxy resin and both transverse and longitudinal sections were cut for each coral. In this way any samples which have a high aragonite cement content were detected; these would have ordinarily been passed for dating if only X-ray diffraction methods were used.

The sample was then ground in an agate mortar to a fine grainsize and weighed. Normally about 20gm of ground coral was used if available, but in some cases there was insufficient material. The minimum amount of material used was 5gm.

U^{232} and Th^{234} tracers were added to the coral for chemical-yield determinations. The U^{232} spike, of known activity (7.860±0.065 dpm/gm), was added in such proportions as to approximate an activity ratio of about 1.0 with respect to U^{238} and U^{234}. Usually about 1gm of spike was added for every 4gm of coral. The U^{232} spike had been previously calibrated against a gravimetric uranium standard by α-particle spectrometry. 100λ (0·1c.c.) of Th^{234} yield tracer, of known activity, was pipetted into the beaker containing the coral. The Th^{234} tracer was prepared by a procedure similar to that described by Goldberg and Koide (1962); the procedure is outlined in Appendix 3. To this 4-5 drops of an iron carrier were added (the preparation of the iron carrier is outlined in Appendix 1).

Concentrated HNO_3 was added dropwise until all the coral had dissolved. The sides of the beaker were rinsed with concentrated HNO_3, and the solution was heated to promote oxidation of organic material. In some cases a few drops of concentrated $HClO_4$ were added to the solution to effect complete oxidation. After the solution had digested for several hours, it was allowed to cool. If any insoluble material still remained it was removed by centrifuging, and the residue was treated with a concentrated $HF/HClO_4$ mixture, and heated until it had completely decomposed. The remaining HF and $HClO_4$ were evaporated, and the residue was dissolved in dilute HNO_3 and returned to the original solution.

Ammonia gas was bubbled through the solution until a pH of 6·5-7·0 was reached. This results in the precipitation of ferric hydroxide which acts as a carrier for U and Th. The ferric hydroxide was centrifuged, washed and then dissolved in concentrated HCl. The ferric hydroxide was precipitated once more with NH_3, centrifuged, and washed three times with distilled water.

The ferric hydroxide precipitate was dissolved in distilled 10N HCl and put through an anion exchange column. The anion column (8mm internal diameter) was packed with Bio-Rad AG1-X8, 200-400 mesh, anion exchange resin to a height of 10-12cm, and washed and rinsed thoroughly with 8N HCl, prior to adding the solution. Both Fe and U are retained on the column, while Th passes through it. The resin was washed with one column volume of 8N HCl to completely remove any thorium.

After removal of the thorium the anion column was given two further column volume rinses of 8N HCl. Fe was removed from the column with two column volume rinses of 0·25N $(NH_4)_2SO_4$ solution saturated with SO_2 (see Appendix 2 for preparation). After all Fe was removed, the column was rinsed with three column volumes of 8N HCl to remove $(NH_4)_2SO_4$. Finally U was eluted with three column volume rinses of 3N HBr, and evaporated to dryness.

The thorium eluate was evaporated and reduced in volume to about 2ml. The sides of the beaker were rinsed with 3ml of distilled water, and the volume taken up to 15ml with 4N HCl. The Th-bearing solution was warmed slightly to ensure complete dissolution, cooled, and put through a cation exchange column. The column (5mm internal diameter) was packed with Bio-Rad AG 50W-X8, 100-200 mesh, cation exchange resin to a height of about 8cm; the column had been thoroughly washed and rinsed with 4N HCl before adding the Th solution. Th remained on the resin while other elements passed through. The resin was rinsed with one column volume of 4N HCl, and Th eluted with two column volumes of 0·75N oxalic acid. The eluate was evaporated until crystals of oxalic acid formed. The oxalic acid was destroyed by evaporating to dryness twice with concentrated $HClO_4$, and once with 4N HCl.

Both U and Th were electroplated separately onto stainless steel planchets. The plating solution consisted of 2N NH_4Cl acidified to pH 2·5. The plating time for U was 30 minutes at 10 volts, while for Th it was 90 minutes at 6 volts. After plating the planchets were flamed to red heat over a Bunsen Burner to completely oxidise any residue.

After electroplating, the Th-bearing planchet was allowed to stand for five minutes so that any Pa^{234} ($t\frac{1}{2}$= 1·2m) present had decayed. The activity of the Th^{234} was then measured on a Nuclear Chicago gas flow beta counter. Th^{234} served as a yield tracer for thorium. The Th^{234} was counted for a total of 10,000 counts, a background correction was applied, and the activity determined as counts per minute (cpm). This activity was compared with the known activity of the Th^{234} tracer, and the thorium yield was expressed as a percentage. Chemical yields for thorium varied between 10 and 40 percent.

Th^{230}, Th^{232}, U^{234}, and U^{238} activities were determined by α-particle spectrometry. The counting system consisted of two Ortec surface barrier detectors, each connected to an Ortec 101-201 amplifier system, which in turn were connected to a Nuclear Chicago multi-channel pulse-height analyzer. The multi-channel analyzer has a capacity of 400 channels, 200 channels for each system. Counts were usually stored in the multi-channel analyzer for twenty four hours, and then printed out. The counts were erased, and counting continued for another twenty four hours. The total counting time varied, depending on the chemical yields. U isotopes were normally counted for about 10,000 counts, i.e. until the U^{234}/U^{238} activity ratio could be determined to within ±0·01 (at one standard deviation). In some cases where the sample size or yield was low, counting times in excess of 10,000 minutes had to be used. However, most counting times were less than 8,000 minutes. Th isotopes were usually counted until the total number of Th^{230} counts was about 6,000. If the Th^{230} activity was low, then the sample was counted for about 8,000 minutes.

The separation between the peaks was good. U isotopes were integrated for a total of 19 channels, and the separation between the maximum count for each isotope was of the order of 40 channels. Figure 1.1a shows a typical spectrum for U isotopes. There was complete separation between the U^{238}, U^{234} and U^{232} peaks, and no correction was needed for U^{235} interference. Th isotopes were integrated over 11 channels, and separation between the maximum count for Th^{232}, Th^{230} and Th^{228} was again of the order of 40 channels (Fig.1.1b). Both U and Th peaks had low energy tails, and so more channels were counted on the low energy side than on the high energy side. Very little drift in the detector was experienced during operation. If drift

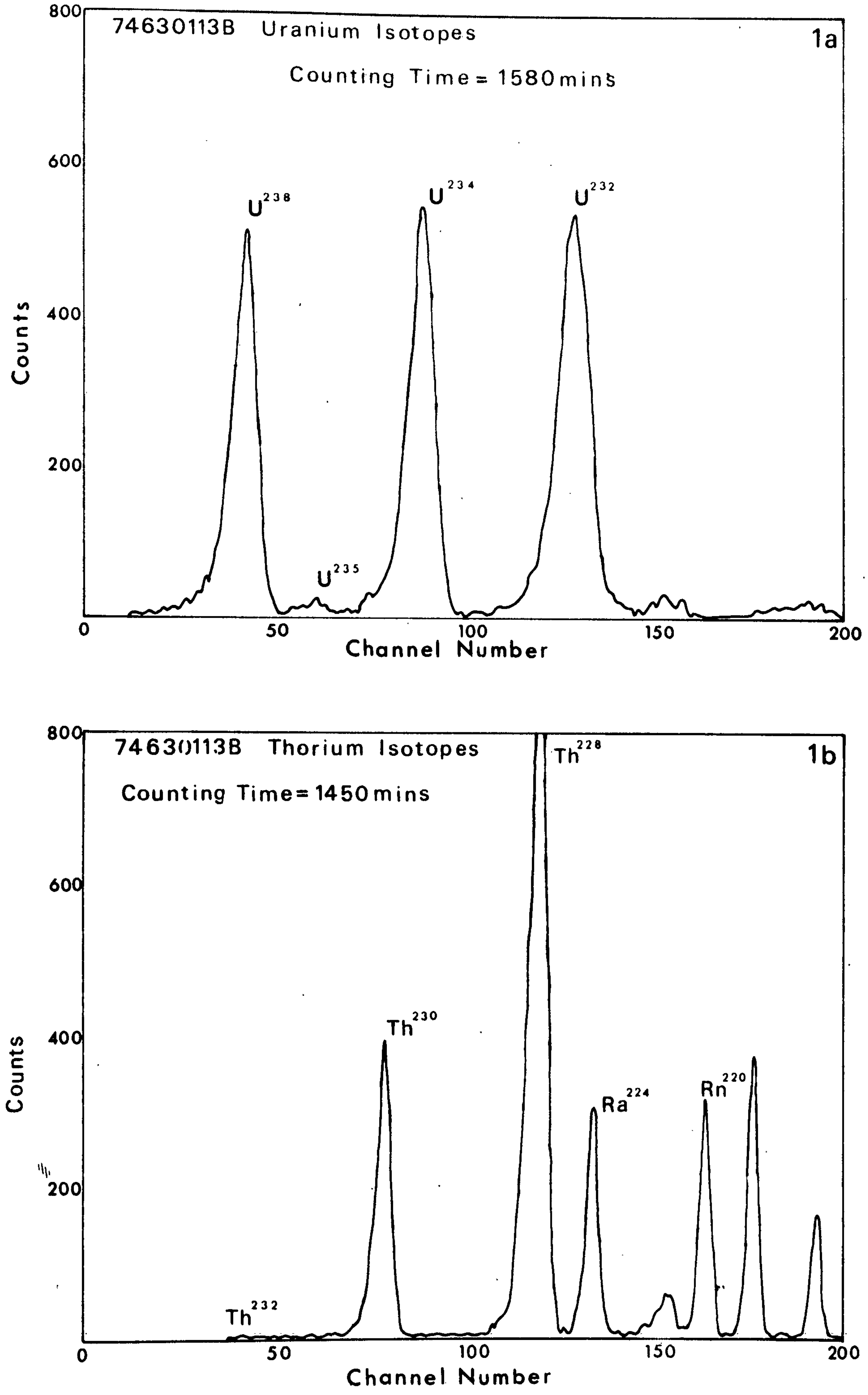


Figure 1.1 Alpha spectra of coral sample 74630113B

(a) Uranium isotopes

(b) Thorium isotopes

started to occur it usually indicated some electrical fault in the amplifier.

U^{234} and U^{238} activities were calculated from the calibrated U^{232} spike. Th^{232} and Th^{230} activities were calculated from the chemical yield, as determined by the Th^{234} tracer, and the efficiency of the detector (the efficiency of each detector was calibrated using a gravimetric Th^{232} standard). Blanks composed of all the reagents and tracers were treated in the same manner as the sample runs, and analyzed for U and Th isotopes. The measured activities for the blanks were subtracted for each isotope to give the final result. A small correction was made for Th^{230} present in the Th^{234} yield tracer. As U^{234} and U^{238} were counted on the same planchet, their activity ratio was calculated directly from the total number of counts for each isotope, after the counter background had been subtracted. The Th^{230}/U^{234} activity ratio was determined from their respective, corrected activities. Total uranium values, expressed as parts per million (ppm), were determined from the activity of U^{238} and the specific activity of U^{238}. The specific activity of U^{238} was calculated as 0.7462 dpm/μg using the new half-life of 4.4683×10^9yr. (Jaffey, *et al.*, 1971).

Chapter 2 - Th^{230}/U^{234} Ages from the Huon Peninsula, New Guinea

2.1 Introduction

Before absolute dating of new material commenced, it was considered essential to attempt to date corals of known ages, so that the degree of reliability of the techniques and the counting equipment used in this study could be determined. For this purpose a suite of corals was provided by J. Chappell of the Department of Geography, Australian National University, from the Huon Peninsula, New Guinea. The corals come from a series of raised coral terraces which extend along the northeast coast of the Huon Peninsula (Chappell, 1974a). These corals had previously been dated at the laboratories of the Lamont-Doherty Geological Observatory, New York by W.S. Broecker, and the ages were reported in Bloom *et al.* (1974).

The raised terraces consist of over twenty reef complexes, and age estimates for the lower half have been made by C^{14} and Th^{230}/U^{234} methods (Polach *et al.*, 1969; Veeh and Chappell, 1970; Bloom *et al.*, 1974). Chappell (1974a) has numbered the dated reef complexes from 0 to XII; reef complex 0 represents the modern reef, which is less than 500 years old while reef complex XII has been dated as >250,000 yr B.P. The major reef complexes give ages of 5,000-9,000 yr (reef complex I), 29,000 yr (reef complex II), 41,000 yr (reef complex III), 61,000 yr (reef complex IV), 85,000 yr (reef complex V), 107,000 yr (reef complex VI), and 118,000-142,000 yr (reef complex VII).

Each age for a particular reef complex has been substantiated by a number of dates, and they agree with dated uplifted reefs from other areas, such as Barbados (Broecker *et al*, 1968; Mesolella *et al*., 1969) and the Ryukyu Islands (Konishi *et al*., 1970; Konishi *et al*., 1974).

2.2 Ages of Selected Corals from the Huon Peninsula

Five corals from three different terraces were provided by J. Chappell for age determination. One coral came from reef complex III, three samples came from reef complex IV, and one coral came from reef complex VI.

After the corals had been cleaned, they were analysed by x-ray diffraction for evidence of recrystallization. The corals had previously been analysed by x-ray diffraction by R.K. Matthews (Bloom *et al*., 1974). A comparison of both sets of analyses show them to be in fairly good agreement (Table 2.1).No coral analysed by both studies contained more than 5 percent calcite. This was confirmed by examination of the corals in thin section. Thin section examination also showed that void-filling cement, either by aragonite or calcite, was largely absent, and that borings by microrganisms were rare. A petrographic description of the corals, outlining the diagenetic changes observed, is given in Appendix 4.

The ages of the samples determined by this study, with one exception, fall within the error limits placed on the original ages of Bloom *et al*. (1974), and, as such, they provide an indication of the degree of reproducibility

Table 2.1 Comparison of the Mineralogy of Corals from the Huon Peninsula, New Guinea (The results of Bloom *et al.*, (1974) are shown in parenthesis).

Sample No. (this study)	Sample No. (Bloom *et al.*, 1974)	Reef Complex	Fraction of total carbonate %		
			aragonite	low-Mg calcite	high-Mg calcite
74630111	25	III	97(99)	3(1)	-(-)
74630112	3	IV	99(99)	1(1)	-(-)
74630113A	4	IV	96(100)	1(-)	3(-)
74630113B	4	IV	98(100)	2(-)	-(-)
74630114	14b	VI	95(97)	5(3)	-(-)

of the method (Table 2.2). Two samples from reef complex IV (74630113A and 74630113B) have an age difference of 8,000 years, although both are within the error limits of the original age. The two age determinations were not done on the same piece of coral; these were two distinctly different faviids, one having larger corallites than the other. Bloom *et al* (1974) show that ages for reef complex IV range from 57,000 to 66,000 years B.P., and so the difference in age could be real.

One sample (74630114) did not agree with the original age determined by Bloom *et al.* (1974) there being a difference of 15,000 years between them. This difference is undoubtedly due to the loss of part of the sample and spike during the dissolution stage. The sample was repeated on two separate occasions, but the results were completely unsatisfactory (the repeats are listed at the bottom of Table 2). Both repeats show high uranium values and low Th^{230}/U^{234} activity ratios, but the U^{234}/U^{238} activity ratios are consistent with the original data. It has been illustrated in Appendix 4 (Figs 1I & J) that this particular coral has undergone partial leaching of its aragonite skeleton, and that void-filling low-Mg calcite cement is extensively developed within parts of the coral. Therefore, the repeat analyses could have been done on parts of the coral which have a high proportion of void-filling calcite cement; X-ray diffraction analyses were not carried out on the repeat samples.

Gvirtzman *et al.* (1973), using fission-track analysis,

Table 2.2 Comparison of Th^{230}/U^{234} Ages of Corals from the Huon Peninsula, New Guinea (The results of Bloom *et al.*, (1974) are shown in parenthesis).

Sample No.	Coral species	total U (ppm)	U^{234}/U^{238}	Th^{230}/U^{234}	Age ($\times 10^3$ yr)
	Reef complex III				
74630111	*Hydnophora exesa*	2.63 ± 0.03	1.15 ± 0.01	0.33 ± 0.01	43 ± 2
(25)		(2.53 ± 0.05)	(1.13 ± 0.02)	(0.32 ± 0.02)	(42 ± 3)
	Reef complex IV				
74630112	*Favia stelligera*	2.48 ± 0.06	1.06 ± 0.02	0.40 ± 0.03	55 ± 5
(3)		(2.24 ± 0.05)	(1.11 ± 0.02)	(0.42 ± 0.02)	(58 ± 4)
74630113A	*Favia pallida*	2.39 ± 0.04	1.10 ± 0.02	0.40 ± 0.04	56 ± 6
(4)		(2.22 ± 0.04)	(1.11 ± 0.02)	(0.43 ± 0.02)	(61 ± 4)
74630113B		2.47 ± 0.03	1.12 ± 0.01	0.45 ± 0.03	64 ± 4
	Reef complex VI				
74630114	*Favia speciosa*	2.50 ± 0.03	1.13 ± 0.01	0.69 ± 0.03	122 ± 8
(14b)		(2.56 ± 0.05)	(1.12 ± 0.02)	(0.63 ± 0.03)	(107 ± 9)

The samples listed below are repeats of 74630114

total U (ppm)	U^{234}/U^{238}	Th^{230}/U^{234}	Age ($\times 10^3$ yr)
6.11 ± 0.09	1.12 ± 0.01	0.36 ± 0.02	48 ± 3
4.28 ± 0.06	1.12 ± 0.01	0.48 ± 0.01	70 ± 3

demonstrated that low-Mg calcite that replaces the original aragonite of the coral skeleton during subaerial diagenesis had the highest concentration of uranium in the materials they studied. These values ranged from 2.9 to 5.1 ppm with a mean of 3.9 ± 0.7 ppm. Conversely, void-filling low-Mg calcite cement had a uranium concentration lower than that of the aragonite skeleton (0.8-1.8ppm). They concluded that this was a result of a decrease in the availability of uranium in the waters from which the calcite precipitated. They regarded that the void-filling calcite cement was formed at a later stage in the diagenetic sequence than the calcite that replaced the aragonite skeleton. However, Figure 1J shows that in this case the void-filling calcite cement has formed before there has been complete dissolution of the aragonite skeleton. Therefore, the void-filling low-Mg calcite cement could be expected to have a high uranium concentration. As this cement would have been formed some time after the elevation of the coral above sea level, it would have a lower Th^{230}/U^{234} activity ratio than the coral, and consequently the age determined would be younger than the true age.

Chapter 3 Th^{230}/U^{234} Ages of Corals from the Great Barrier Reef

3.1 Introduction

Corals from three localities on the Great Barrier Reef were dated using the Th^{230}/U^{234} method. A living coral from One Tree Island (Fig. 3.1) was analysed in order to test the closed system assumptions outlined in Chapter 1. Two corals were collected at depth from the reef flanks; one coral was collected at a depth of 20m from Rock Cod Shoal, and another was collected at a depth of 17m from One Tree Island. It was thought that ages of these corals might be significant because they were recovered from depths where coral growth appears to be limited.

Coral samples were provided by the Department of Geography, James Cook University from drill holes put down on the fringing reef of Hayman Island (Fig. 3.3). These corals came from different depths of the drilled interval. It was hoped that they would provide information on the various times of coral growth in the Great Barrier Reef Province.

3.2 Ages of Corals from the Capricorn Group

A living coral from the reef flat of One Tree Island was analysed in order to determine (a) that modern corals have a U^{234}/U^{238} activity ratio of 1.15 ± 0.03, thus confirming Thurber's (1962) conclusion that there is a 15 percent excess of U^{234} to U^{238} in the present-day ocean, and (b) that there is no significant concentration of Th^{230} initially present in modern corals, and therefore the amount of Th^{230} observed in fossil corals has resulted solely from the radioactive decay of its parent uranium.

The coral analysed (74630100) was a *Pocillopera* sp. and the uranium concentration and U^{234}/U^{238} and Th^{230}/U^{234} activity ratios are shown in Table 3.1. Both activity ratios show that the coral obeys the assumptions mentioned above, and that they are basically the same for modern corals from other parts of the world (e.g. Veeh, 1966). No Th^{232} was detected in the coral.

A second coral, an *Acropora* species, was collected from the flanks of One Tree Island at a depth of 17m below sea level. The coral was collected by a diver, and it was definitely in its growth position. The radiochemistry and age of this sample (74630110) are shown in Table 3.1. The coral has a high uranium content which is commonly shown by species of *Acropora*. The coral was dated by the Th^{230}/U^{234} method as being less than one thousand years while the C^{14} method showed that the coral was modern.

Another coral was dredged from a depth of 20m from Rock Cod Shoal, a submerged coral bank some 45 kilometres southwest of One Tree Island (Fig. 3.1). It could not be determined if the coral was in its original growth position, but as corals do not appear to be growing in great abundance on the shoal at the present time, it was thought that this coral might give some indication of the minimum age of the

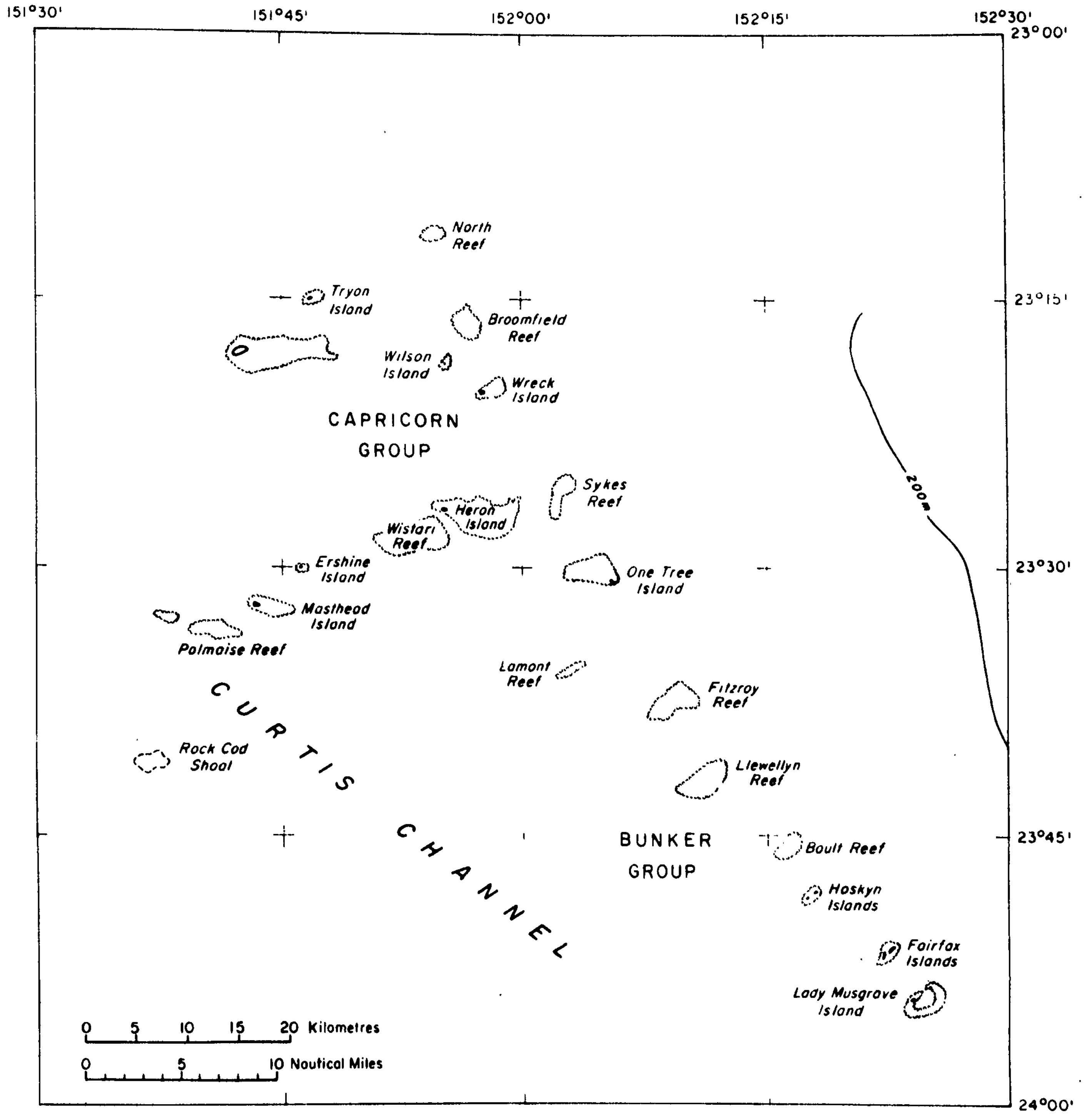


Figure 3.1 Reefs of the Capricorn and Bunker Groups, showing location of One Tree Island and Rock Cod Shoal

Table 3.1 Radiochemistry and Ages from the Capricorn Group,

Great Barrier Reef

Sample Number	total U (ppm)	$\frac{U^{234}}{U^{238}}$	$\frac{Th^{230}}{U^{234}}$	Age (yrs B.P.)	C^{14} Age (yrs B.P.)
			One Tree Island		
74630100	2.49±0.04	1.15±0.02	<0.001	<500	
74630110	4.18±0.07	1.13±0.02	0.006±0.002	<1000	>Modern
			Rock Cod Shoal		
74630106	2.64±0.04	1.16±0.01	0.008±0.001	850±100	440±120

bank. Uranium-series dating shows the coral to be less than one thousand years old (Table 3.1) and this is confirmed by a C^{14} age of 440 ± 120 yr B.P. (ANU-1499).

Although only two samples were collected from the flanks of two reefs of the Capricorn Group it would appear that certain species of corals have been growing at depths of 17-20m below sea level during the past 500 years. P.J. Davies (*pers. comm.*) has identified that many of the reefs of the Great Barrier Reef province grow from a platform at about 20m below present sea level. This platform represents an old surface on which the present reefs began growing during the Holocene transgression. Therefore, corals on the outer parts of the reef above 20m should be Holocene.

3.3 Ages from the Hayman Island Cores

Hayman Island is the northernmost member of the Whitsunday Group and it lies some 25 kilometres off the coast of central Queensland (Fig. 3.2). The island consists of Cretaceous granite and acid-intermediate volcanics and Quaternary alluvium. A fringing reef is present around most of the island and an extensive tract of reef is developed on its southern side (Fig. 3.3).

A series of six drill holes were put down on the fringing reef at the southern end of the island to test if the reef was a suitable foundation for an airport runway. The cores from these drill holes were lodged at the James Cook University of North Queensland. Unfortunately the cores were not continuous, but were put into bags, each bag con-

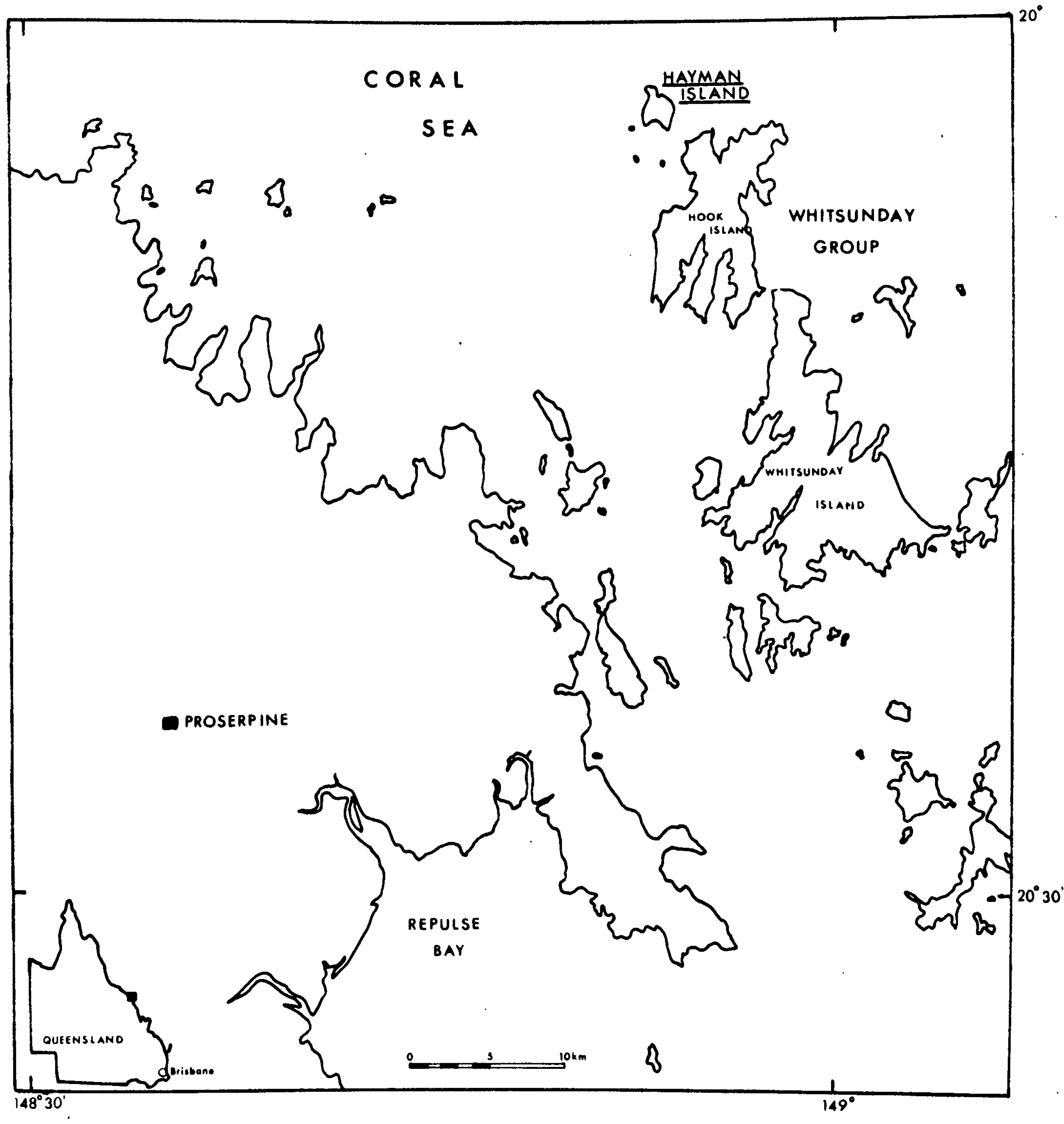


Figure 3.2 Location of Hayman Island, Whitsunday Group

taining anything up to 3m of material.

The stratigraphy of the cores has been described by Smith (1974). The cores recovered from the reef flat (RIO) and the reef margin (R1, R2 and R5) consist mainly of solid coral, coral shingle and some beach sand while the cores seawards of the reef margin (R3 and R4) consist of beach sand, fore-reef sediment and coral shingle (Fig. 3.3). The cores from the reef margin have carbonate values in excess of 90 percent to a depth of about 20m, but below this depth the carbonate values are usually lower. It was also noted that from the surface to about 20m the mineralogy of the cores showed a high aragonite content, but below this depth low-Mg calcite became dominant. Below 20m the stratigraphy showed a high proportion of calcareous nodules set in a yellow silt or clay and in some cases the coral showed signs of iron staining. Smith (1974) interpreted the presence of calcareous nodules and yellow silt and clay as indicative of pedogenic processes. From this she concluded that a discontinuity (the Thurber discontinuity) existed between corals of Holocene and Pleistocene age at about 20-25m. This was confirmed by C^{14} dating of material from one of the cores (R1). A coral from a depth of 15.0 - 16.5m gave a C^{14} age of 8,245 ± 285 yr B.P. while a coral from 19 - 22m gave a C^{14} age of $\gtrsim$ 39,000 yr B.P.

Previous drillings on Eniwetok and Mururoa Atolls in the Pacific Ocean had shown that there is a distinct time break between the Holocene and the Pleistocene. Cuttings from 3.9 to 10.8m from drill hole MU-7 on Mujinkarikku

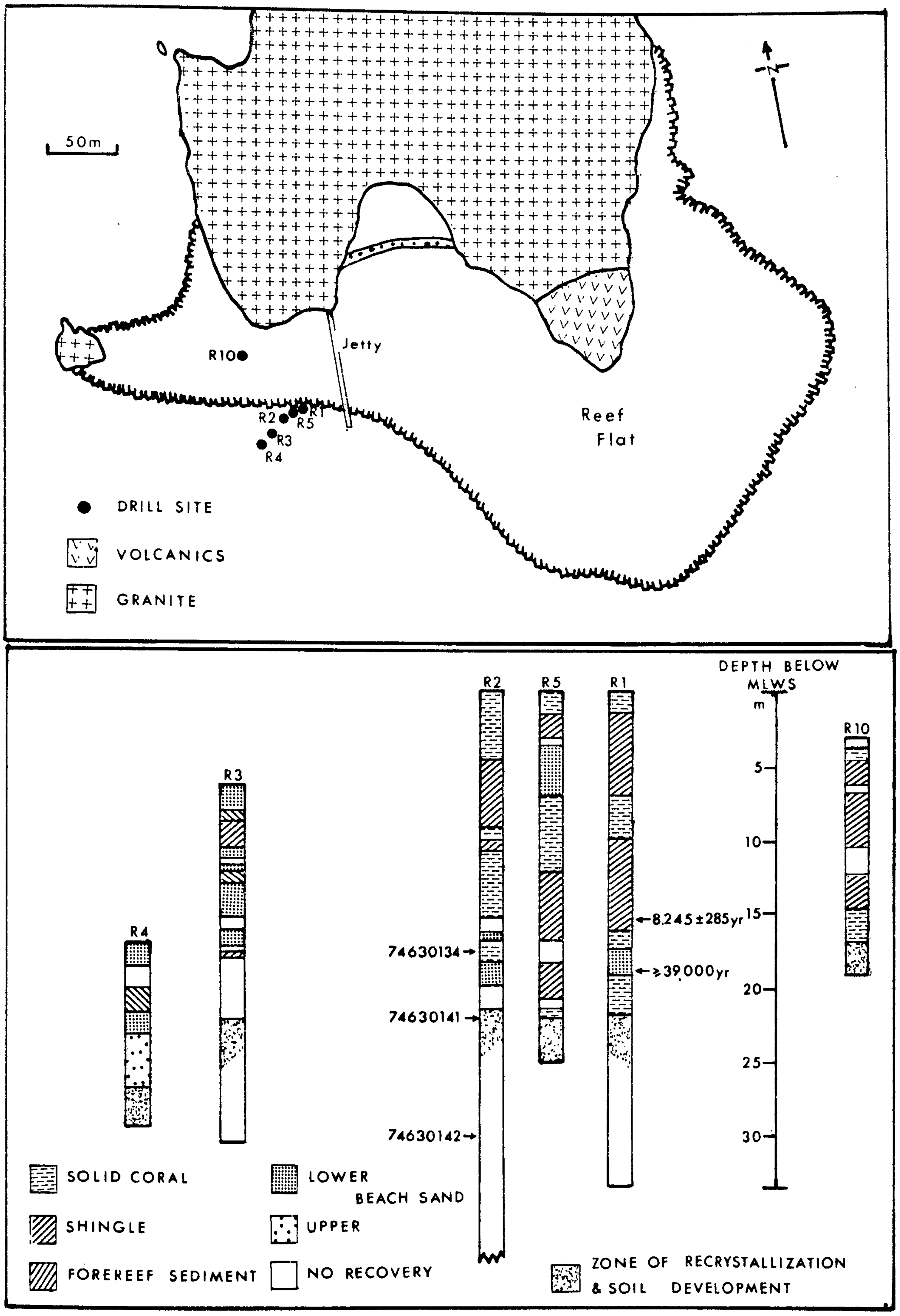


Figure 3.3 Fringing reef at the southern end of Hayman Island showing location of drill holes, and the general stratigraphy within the reef

Island, Eniwetok Atoll gave Th^{230}/U^{234} ages of 4,500 to 6,600 yrs B.P. while corresponding C^{14} ages ranged from 3,800 to 5,900 yrs B.P. Corals from 14.4 to 20.7m gave Th^{230}/U^{234} ages of 100,000 to 120,000 yrs B.P. These ages were supported by dates from other borings at this depth on other islands of Eniwetok (Thurber *et al.*, 1965) On Mururoa Atoll corals from sea level to a depth of -6m gave ages of 5,300 to 8,200 yrs B.P. while coral at -7m gave Th^{230}/U^{234} age of 120,000 yr B.P. (Lalou *et al.*, 1966). The interpretation of this hiatus by both studies was that sea level was much lower between 120,000 years and the present.

The evidence from the Hayman Island cores suggests that a hiatus of similar magnitude is present at about -20m. This is deeper than that observed on Eniwetok and Mururoa, but a hiatus has been postulated at this depth from Heron Island in the Capricorn Group (Davies, 1974). However, the depth to the discontinuity appears to be dependent on the location of the drill hole in relation to the karst topography developed on the subaerially exposed Pleistocene reef surface. Thom (*pers. comm.*) has found that on Bewick Island in the Great Barrier Reef province the discontinuity is present at -3m while on Mururoa Atoll the discontinuity is present at -11m on *Dindon*, but it is at -7m on *Colette* (Lalou *et al.*, 1966).

Samples of core material from R1 and R2 were provided by the Department of Geography, James Cook University for uranium-series dating. The material from core R1 came from depths of 19 to 31.5m while material from core R2 came from depths of 17 to 26m. Apart from the topmost sample from core R2 (74630134, Fig. 3.3) the coral samples were extensively recrystallized, and as a result, unsuitable for dating. A further search through the core material produced two very small samples of coral from core R2 which had an aragonite mineralogy. One sample came from a depth of 21.5 to 23m and the other was from the interval 29 to 30.5m. Although the sample weight of the two corals was considerably smaller than is normally used for uranium-series dating, it was decided to try to determine their approximate ages.

The radiochemistry and ages of the corals are shown in Table 3.2. The topmost sample from a depth of about 17m gave an age of 8,300 ± 500 yr B.P., and this age is consistent with the C^{14} age of 8245 ± 285 yr B.P. at a depth of 16m from core R1. This age is significant as it represents the approximate time of recolonization of the ancient reef surface during the Holocene transgression. It is considered that sea level reached its present position along the east coast of Australia by about 6,000 yr B.P. (Thom and Chappell, 1975). This would indicate that the vertical growth rate of the Hayman Island reef was of the order of 0.74 cm/yr during this period.

The two corals which are presumed to come from depths below the discontinuity give ages that are unacceptable (Table 3.2). The sample from a depth of about 22m has a U^{234}/U^{238} activity ratio greater than that of modern corals, and therefore it does not obey the closed system criteria. The age estimate of 50,000 yrs B.P. is unrealistic in terms

Table 3.2 Radiochemistry and Ages of Corals from Drill Hole R2, Hayman Island

Sample Number	Depth Interval (m)	total U (ppm)	$\frac{U^{234}}{U^{238}}$	$\frac{Th^{230}}{U^{234}}$	Age ($\times 10^3$ yr)
74630134	16.8-17.3	2.47±0.04	1.12±0.02	0.074±0.003	8.3±0.5
74630141	21.4-22.9	3.82±0.07	1.21±0.02	0.37 ±0.02	50±5
74630142	29.1-30.6	3.69±0.07	1.14±0.02	0.091±0.008	10.5±0.5

of previous eustatic sea level changes. The coral from a depth of about 30m gives an apparent age of 10,500 yr B.P. which suggests that this particular sample came from a position higher in the stratigraphic sequence than its presumed position. It seems that this piece of coral had fallen down the hole during drilling operations.

Since most of the coral below 20m examined in this study is extensively recrystallized it has been impossible to determine reliable uranium-series ages from this depth. Age determinations from Pacific atolls suggest that it is possibly 120,000 years old, but until unrecrystallized corals are found it cannot be concluded that a hiatus of similar magnitude exists in the Great Barrier Reef province.

Chapter 4. Th^{230}/U^{234} Ages from the Inner Barrier of New South Wales

4.1 Geomorphology of the Inner Barrier

Systems of multiple bay barriers are a common geomorphic feature along the central and northern coasts of New South Wales. Two distinct barrier systems have been recongised, and they are referred to as the Inner Barrier and the Outer Barrier according to their position relative to the hinterland (Thom, 1965; Hails, 1968). The two barriers are separated by a distinct hiatus, based on morphological, stratigraphical evidence and soil development. The bay barriers may be as long as 50 kilometres and they may be up to 8 kilometres wide (Langford-Smith and Thom, 1969). The Inner Barrier usually encloses a swamp which is considered to be a relic barrier lagoon. The two barriers are separated by an interbarrier depression which usually consists of a tract of shallow lagoon or swamp. The Inner Barrier extends for almost 1000 kilometres along the coast north of Newcastle. It attains an elevation of 6 to 9 metres above present sea level, and there is little variation in this height along its entire length.

The Outer Barrier is a Holocene feature that developed towards the end of the last major transgression. During this transgression sea level reached its present position along the east coast of Australia at about 6000 yr B.P. (Thom and Chappell, 1975), and it is considered that the Outer Barrier began forming at this time. The evidence for a hiatus between the formation of the two barriers suggests a major period of lower sea level. The Inner Barrier was originally thought to have formed during the last interglacial (Thom, 1965), but radiocarbon dating has suggested that it is related to an interstadial high sea level (Warner, 1971; Langford-Smith in Gill, 1970).

4.2 Previous Ages from the Inner Barrier

Most of the material that has been dated from the Inner Barrier has been organic material. Driftwood, freshwater peat, *in situ* tree stumps and roots, and humate have been the types of material submitted for radiocarbon dating. The original ages from the Inner Barrier on the north coast of New South Wales were reasonably consistent, with ages ranging from 21,000 to 35,000 yrs B.P. On this basis the Inner Barrier was thought to have formed during a high interstadial sea level at about 30,000 yr B.P. (Warner, 1971; Langford-Smith in Gill, 1970).

This evidence for a high interstadial sea level at about 30,000 yr B.P. gained support from radiocarbon dating of shell and peat material from other parts of the world (e.g. Curray, 1961; Shepard and Curray, 1967; Milliman and Emery, 1968). However, the reliability of many of these C^{14} ages has been questioned because of the possibility of contamination of the samples by modern carbon, and because glaciologic-climatic evidence indicates that sea level was much lower at this time (Mörner, 1971). Bloom *et al* (1974) suggest that sea level may have been as low as -41m at this time.

There are good reasons to suspect the C^{14} ages on organic material from the Inner Barrier of northern New South Wales. Apart from the ages reported by Warner (1971) and Langford-Smith (Gill, 1970) other C^{14} ages on driftwood have yielded both a background count and a finite age of 42,000 yr B.P. (Thom, 1973). In one case where the organic material of one of the original samples was broken down into its various fractions, three different ages were obtained. These varied from 11,100 to 35,200 yrs B.P.; the original sample had an age of 21,400 ± 250 yr B.P. (Thom, 1973). In this case it is apparent that there has been contamination by younger organic material.

The only published age so far on shell material from the Inner Barrier is from a specimen of *Anadara* collected from 15m below mean sea level (MSL) at Grahamstown near Newcastle (Thom, 1965). This sample gave a C^{14} age of >33,000 yr B.P.

Therefore, although a considerable number of age determinations by the C^{14} method have been made on material from the Inner Barrier (at least twenty), some have not yielded definite ages while others can be regarded as being too young because of contamination. The discovery of corals from the Inner Barrier of New South Wales, at two separate localities, provided an opportunity to check the reliability of the C^{14} ages by using the Th^{230}/U^{234} method.

4.3 Location of Corals from the Inner Barrier

Corals were recovered from the Inner Barrier at two localities. The first discovery was made during the building of an embankment at Grahamstown, near Newcastle. The second discovery was near Evans Head on the north coast of New South Wales.

4.3.1 Grahamstown Embankment

The Inner Barrier that forms part of the Newcastle Bight Embayment barrier system (Thom, 1965) abuts bedrock at a number of places, and it also blocks off several swamps (Fig. 4.1). Such a situation occurs where the Grahamstown Swamp is blocked at its eastern end by the Inner Barrier; at this locality bedrock, swamp, and barrier are in close proximity. The Grahamstown Swamp was recently converted into a water storage area, and the innermost ridge of the Inner Barrier was built up to form an embankment. During investigations of this site a number of corals were recovered from a depth of about 7m below MSL. The corals consist of two species, *Goniopora lobata*(M.E.H.) and *Blastomussa wellsi* (Wijsman-Best, 1973).

The general stratigraphy of the area shows that the Quaternary sediments form a seawards thickening wedge, and that these sediments are representative of a number of facies (Fig. 4.2). The basal section consists of sands and gravels of fluvial origin overlain by clays and sandy clays, locally interbedded with sands and shelly sands. The latter sequence is considered to be estuarine in origin (Roy and Thom, 1975). This is overlain by a marine trans-

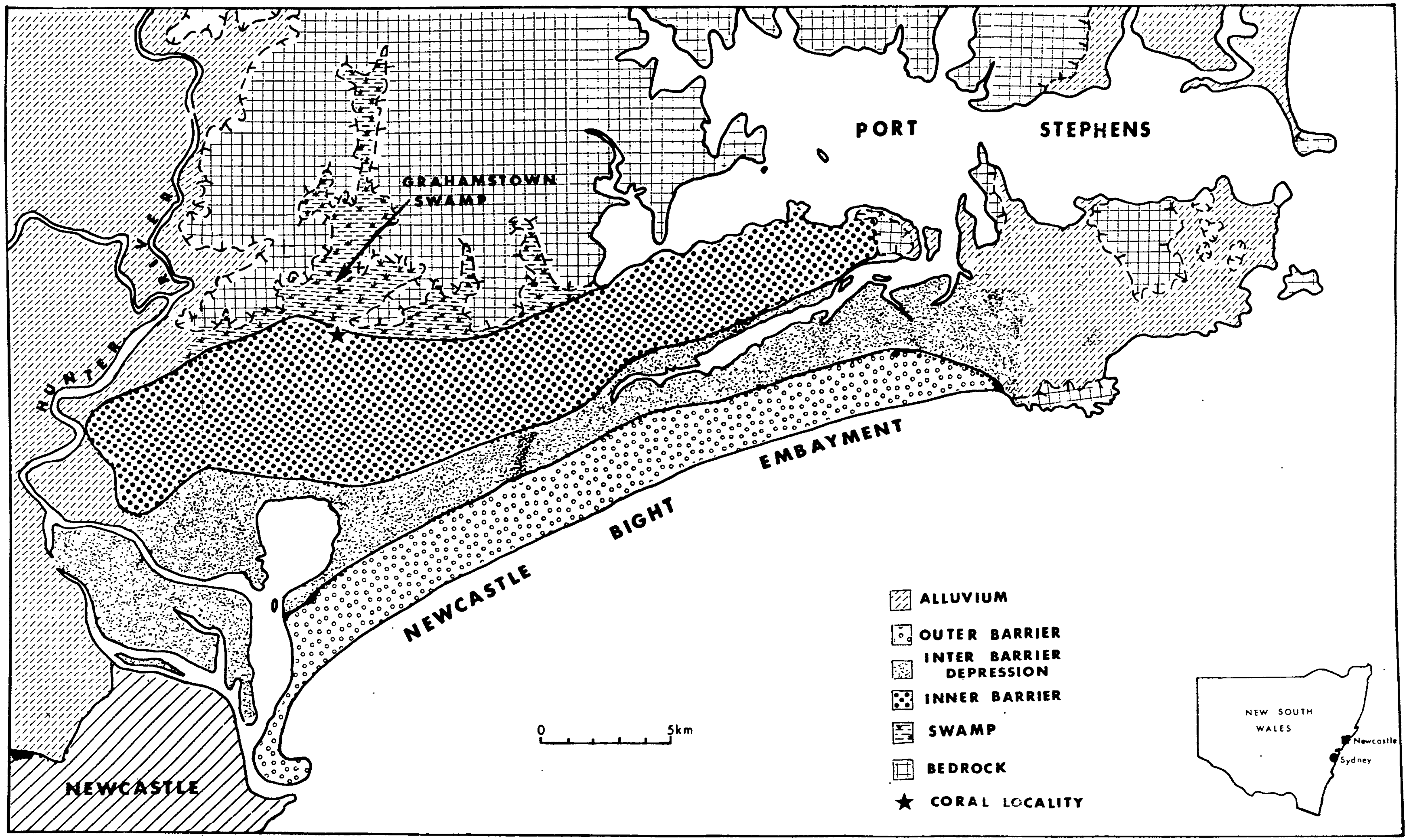


Figure 4.1 Map of the Newcastle Bight Embayment area, showing location of late Quarternary morphologic features, and the coral locality from the Inner Barrier

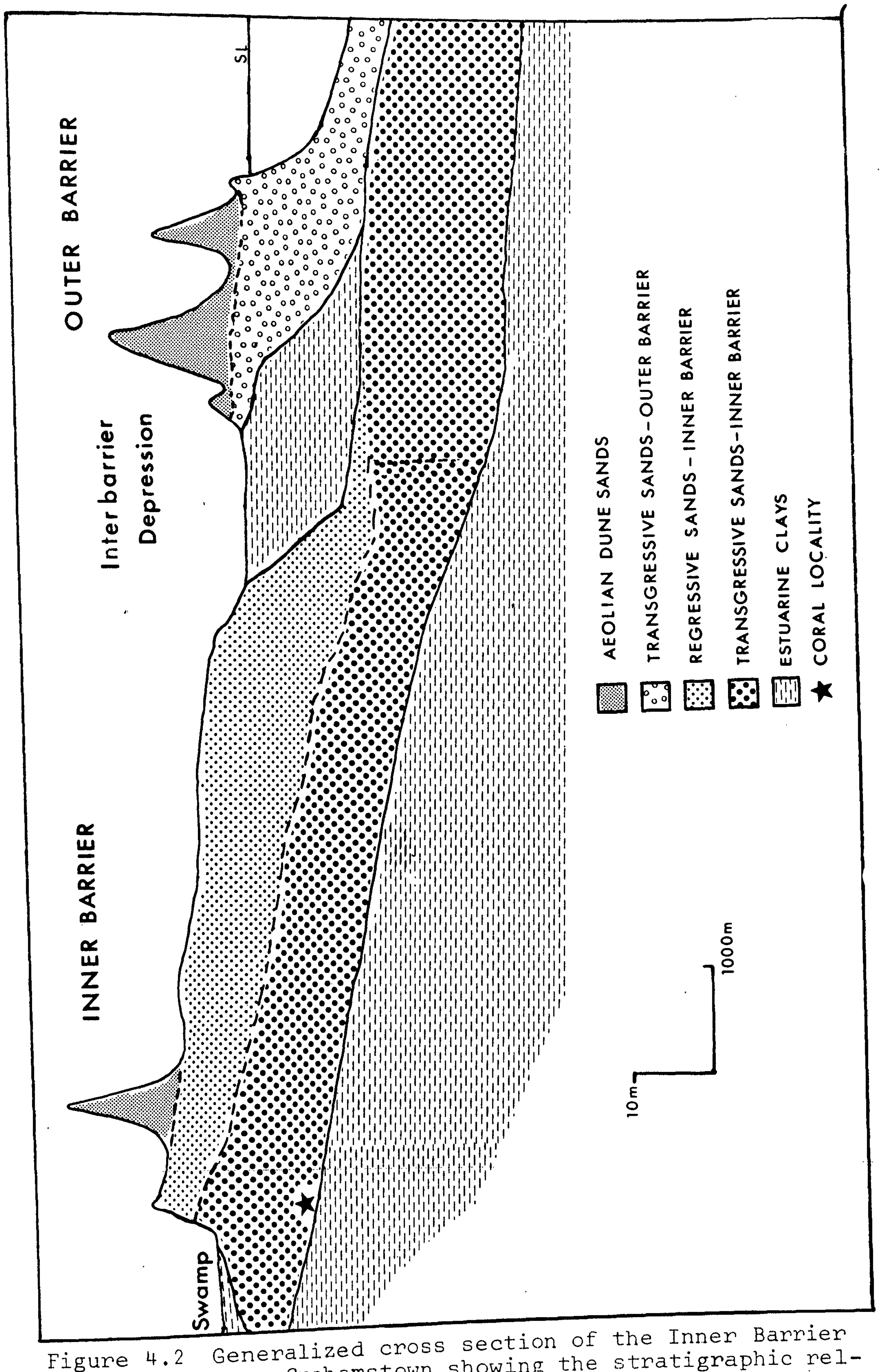


Figure 4.2 Generalized cross section of the Inner Barrier near Grahamstown showing the stratigraphic relationships of the late Quarternary sediments

gressional unit consisting of grey to grey-brown sands with some shells. Some of the molluscs (e.g. *Periglypta* sp., *Fragum* sp. and *Gomphina* sp.) have living counterparts in Queensland waters, but they have not been found in New South Wales (Iredale, 1951). The corals were recovered from near the base of this unit. The marine sands are overlain by well-sorted sands impregnated with organic colloids and locally indurated. These sands are considered to represent a nearshore-beach facies. Lying on top of these are leached aeolian sands that form the dune or beach ridges (Thom, 1965, Fig. 2).

4.3.2 Evans Head

Corals from this locality occur on the southern bank of the Evans River at about present sea level (Fig. 4.3). The corals were found on the western margin of the Inner Barrier. Pickett (1974) considered that the corals rested on bedrock that flanked the estuarine plain of the Richmond River system. He based this assumption on the presence of a ridge of Triassic sediments of the Clarence-Moreton Basin extending northwards to this point. However, R. McLean, P. Roy and B. Thom (*pers. comm.*) discovered *in situ* corals which had grown on a substrate of lagoonal or estuarine sandy muds. It would appear, however,that at this locality, and at the Grahamstown locality, the presence of bedrock near the coral sites had some influence on the colonization and growth of the coral community.

A section through the river bank at the site (Fig.

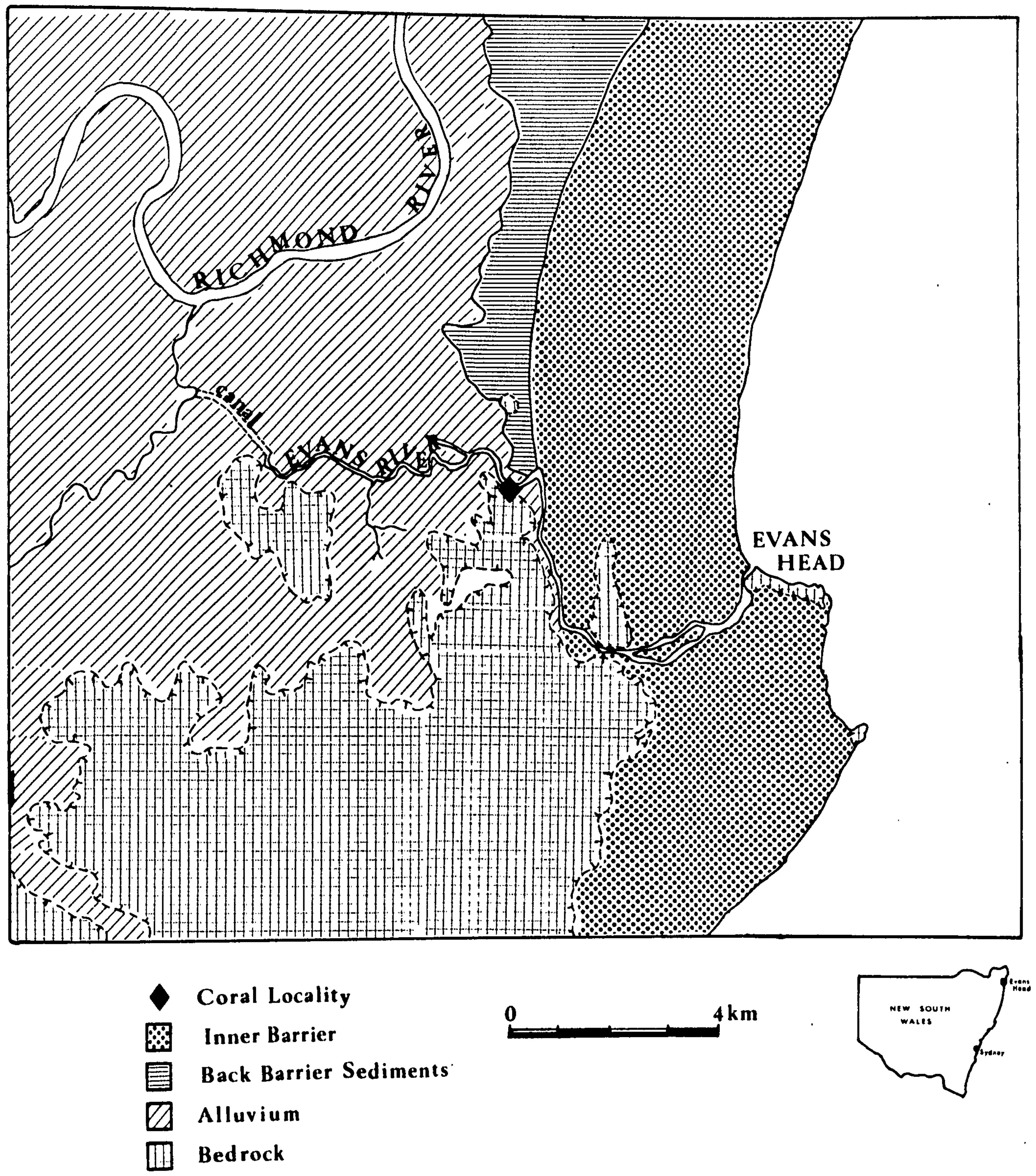
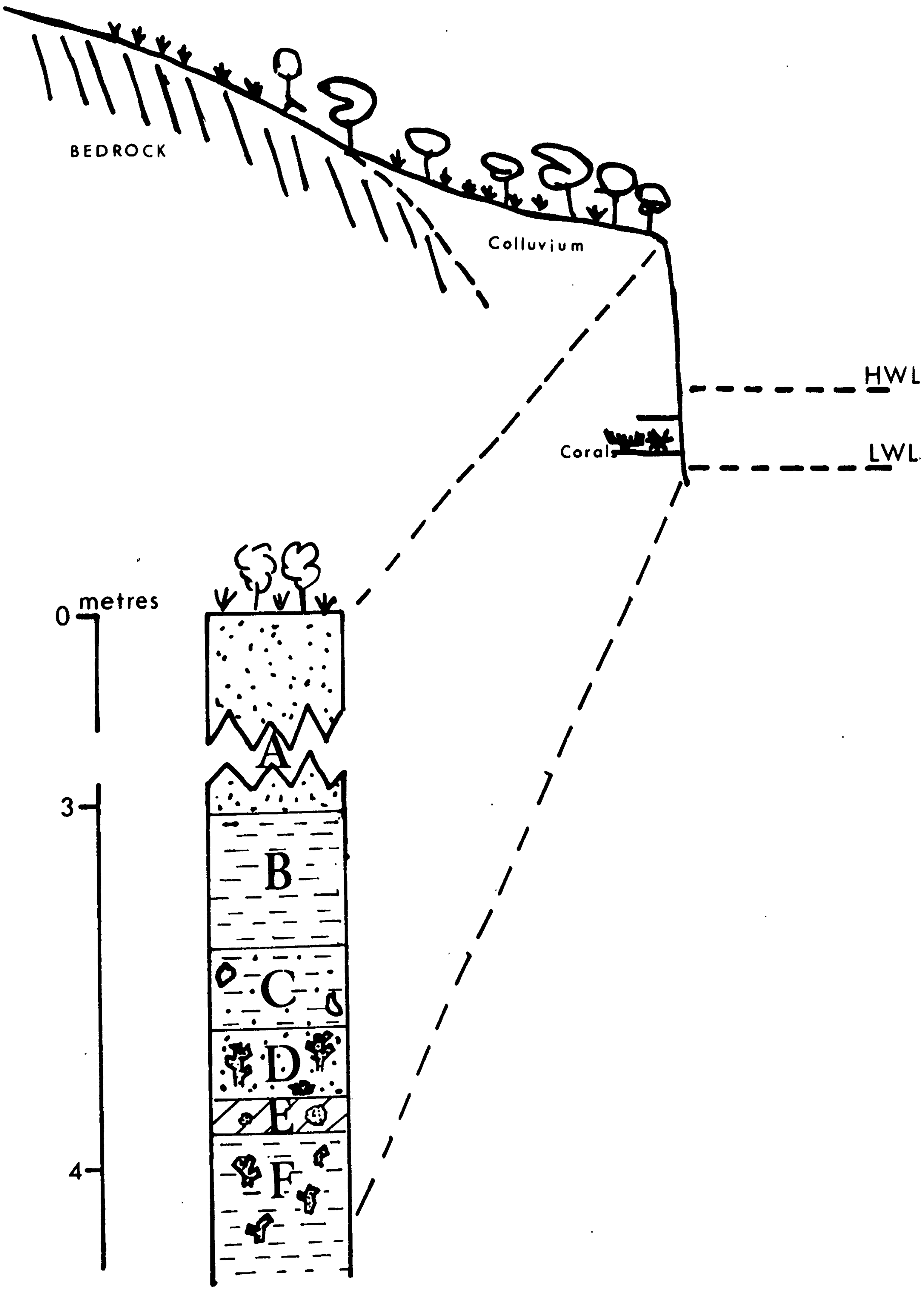


Figure 4.3 Map of the Evans Head area showing the coral locality on the south bank of the Evans River, and its relationship with the Inner Barrier

4.4) shows 2.3m of reddy brown sandy clay (A) extending from the top of the river bank to just below the high water tidal level of the river. Below this there is 30cm of light grey clay (B), followed by a fine-grained, well-sorted sand with ironstone modules up to 2 cm in diameter and scattered coral fragments incorporated (C). The coral fragments are considered to be reworked from the horizon below it. This unit (D) consists of coral rubble and mollusc shells in a dark grey sandy mud. Most of the corals are fragmented, and they often show signs of extensive solution. However, 20 metres downstream from the main site, corals which are definitely considered to be *in situ*, even though there is no hard substrate, were discovered. Below the coral horizon there is a grey clay (E), becoming sandy near the base, which contains shell and some coral fragment. Below this, at about mean low water level, there is 30 + cm of coral debris (mainly *Acropora* sp.) and shell fragments set in an olive grey clay matrix.

The fauna present within the sequence consists of corals, bryozoa, gastropods, pelecypods, and algae. The coral fauna is quite varied, there being at least twelve different genera. Pickett (1974) considered that the corals came from several localities as some are abraded while others are not. Although many of the same species form living communities around the Solitary Islands to the south (Veron, 1974), Pickett (*op. cit.*) cites the presence of *Seriatopora hystrix* (Dana) as possible evidence for a warmer climate than at present. The southernmost



EVANS RIVER,SOUTH BANK

Figure 4.4 Generalized stratigraphy at the coral site, south bank of the Evans River occurrence of living *Seriatopora* along the east coast of Australia is in the Capricorn Group at about 22°S.

4.4 Ages of Corals from the Inner Barrier

Two corals from the Grahamstown Embankment site were provided by B. Thom of the Department of Biogeography and Geomorphology, Australian National University while five corals from the Evans Head locality were provided for dating by J. Pickett of the Geological Survey of New South Wales. Another sample from Evans Head was subsequently collected by B. Thom, P. Roy and R. McLean; this sample was the *in situ* coral mentioned previously. With the exception of the latter coral, all the other samples were fragments of coral which could have been transported from their position of growth, and deposited at another locality. However, the corals from the inner barrier at Grahamstown were extremely fragile, especially *Blastomussa wellsi*, and it seems unlikely that they would have survived any prolonged transportation. Therefore, although most of the corals were not recovered from their growth positions, it is considered that they are not too far removed from them.

X-ray diffraction analysis of the corals showed them to be 100 percent aragonite. Examination of some of the corals in thin section confirmed that there had been no recrystallization. Many of the coral voids were filled with fine grained detrital material, and even after the corals were cleaned some of this material still remained. However, it was considered that it would not affect the ages singificantly.

The radiochemical data and ages of the corals are shown in Table. 4.1 The corals from the inner barrier at Grahamstown give consistent ages of 143,000 and 142,000 yrs B.P. The corals from Evans Head give ages ranging from 112,000 to 127,000 yrs B.P.; the *in situ* coral (74630137) has an age of 118,000 ± 9,000 yr B.P.

The ages for the Grahamstown samples appear to be reliable, both have fairly uniform uranium values and activity ratios, while the Th^{232}/Th^{230} activity ratios are well within the accepted limits. Of the five samples from Evans Head two are considered to be doubtful even though their ages agree reasonably well with the others. One coral (74630127) has a high uranium concentration and a high Th^{232}/Th^{230} activity ratio. The other coral (74630128) has a U^{234}/U^{238} activity ratio greater than that of modern corals, and it has a very high Th^{232}/Th^{230} activity ratio. In this case it appears that the fine-grained detrital material present within the voids of the coral has affected the isotopic ratios. The three remaining corals obey the closed system criteria. Their uranium values are slightly higher than normal, but this appears to be a common feature of species of *Acropora*. Therefore, the ages of these corals are considered to be reliable.

The corals from the two localities show a significant difference in their ages; the corals from Evans Head are approximately 20,000 years younger than those from Grahamstown. However, there is reasonably good evidages singificantly.

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The corals from the two localities show a significant difference in their ages; the corals from Evans Head are approximately 20,000 years younger than those from Grahamstown. However, there is reasonably good evid-

Table 4.1 Radiochemistry and Ages of Corals from the Inner Barrier of New South Wales

Sample Number	Coral Species	total U (ppm)	$\frac{U^{234}}{U^{238}}$	$\frac{Th^{230}}{U^{234}}$	$\frac{Th^{232}}{Th^{230}}$	Age ($\times 10^3$yr)
		Grahamstown Embankment				
74630115A	*Goniopora lobata*	2.73±0.05	1.11±0.02	0.75±0.03	0.01	143±12
74630115B	*Blastomussa wellsi*	3.30±0.04	1.10±0.01	0.74±0.03	0.02	142±12
		Evans Head				
74630127	*Montipora* sp.	4.37±0.07	1.13±0.01	0.65±0.03	0.05	112± 9
74630128	*Platygyra lamellina*	3.12±0.08	1.18±0.03	0.69±0.07	0.28	122±23
74630129	*Acropora* sp.	3.75±0.05	1.11±0.01	0.66±0.03	0.02	114± 9
74630130	*Acropora* sp.	3.62±0.07	1.13±0.01	0.70±0.05	0.02	127±18
74630137	*Acropora*	3.44±0.05	1.11±0.01	0.67±0.03	0.02	118± 9

All samples are 100 percent aragonite

ence from corals of about this age from other parts of the world to suggest that this age difference is real.

Reef complex VII from the Huon Peninsula has in places two reefs, a fossil barrier reef separated by a lagoon from a fringing reef (Bloom *et al.*, 1974). On a stratigraphic basis there appears to be a time difference between the two reefs, and so reef complex VII was subdivided into VIIa (older) and VIIb (younger). This difference was confirmed by Th^{230}/U^{234} dating of corals from the two reefs. A reinterpretation of Veeh and Chappell's (1970) data showed that VIIb has a mean age of 118,000 ± 5,000 yr B.P. while VIIa has ages of 133,000 ± 10,000, 140,000 ± 10,000 and 142,000 ± 8,000 yrs B.P. (Chappell, 1974a; Bloom *et al.*, 1974). The stratigraphy at one locality suggested that there may have been a temporary cessation of reef growth and a possible minor regression during this period (Bloom *et al.*, 1974).

The Falmouth Formation (Pleistocene) on Jamaica contains two units separated by an unconformity. (Moore and Somayajulu, 1974) The top of the upper unit is a terrace 5m above present sea level, and the unconformity is present between 2 and 3m below the terrace. Moore and Somayajulu (1974) have determined the ages of corals from both above and below the unconformity. Th^{230}/Th^{234} ages from the upper unit gave results of 117,000 ± 4,000 yrs B.P. (twice) while ages for the lower unit ranged from 130,000 to 142,000 yrs B.P. The unconformity between the two units and the ages suggest that there was a hiatus and possibly a regression during this interval.

Chappell and Veeh (in press) have shown a similar pattern from raised coral terraces on the island of Atauro near Timor. They consider that there was a major transgression which culminated at about 135,000 yr B.P. This was followed by a minor regression, and then a second high sea level between 125,000 and 118,000 yrs B.P.

The corals from the Grahamstown Embankment were recovered from a shelly sand unit which overlies lagoonal or estuarine sandy clays. The shelly sand is considered to be a transgressive unit within the Inner Barrier which was deposited when sea level rose to a position slightly higher than at present. The transgressive shelly sand is overlain by colloid impregnated sands indicative of a regressive unit. The corals from Evans Head were recovered at a position of present sea level from sediments representative of a lagoonal facies on the western (landwards) side of the Inner Barrier. This implies that the Inner Barrier had already formed during the time when the corals were growing. Therefore, the corals from the Grahamstown Embankment were formed during the major transgression prior to 135,000 yr B.P. while the Evans Head corals did not begin to grow until the second high sea level between 125,000 and 118,000 yrs B.P. Whether or not a minor regression occurred between the two periods could not be determined.

4.5 Conclusion

Th^{230}/U^{234} ages of corals from the Inner Barrier of New South Wales confirm that this feature was formed during the last interglacial when sea level was some 6m higher than present. The Inner Barrier was formed as a result of a major transgression that reached a position within 7m of the present sea level by 143-142,000 yrs B.P. Growth of the Inner Barrier continued until at least 118,000 yr B.P.

The interpretation of the results of Th^{230}/U^{234} and C^{14} dating from the Inner Barrier provides two alternatives:

(i) the Inner Barrier was formed during two periods of high sea level at about 120,000 and 30,000 yrs B.P.

(ii) the ages determined by one of the methods are incorrect.

The first alternative was proposed by Warner (1971) to explain the apparent discrepancy between his C^{14} ages which indicated a high sea level between 28,000 and 30,000 yrs B.P. and Thom's (1965) interpretation that the Inner Barrier was formed during the last interglacial. However, if a time difference of this magnitude was involved then such a hiatus would be apparent from the morphology and stratigraphy of the Inner Barrier, much the same way as the hiatus between the Inner and Outer Barriers. There is no evidence for a stratigraphic break within the Inner Barrier but rather that it was formed during a single transgression/regression cycle.

It was mentioned previously that some of the organic material and the only shell sample did not give definite

C^{14} ages, and that for other samples contamination by modern carbon was suspected. The Th^{230}/U^{234} ages were all done on unrecrystallized corals, and the ages are in good agreement with each other. Also the evidence for a high sea level at about 120,000 yr B.P. is consistent with glaciologic-climatic data whereas evidence for a high interstadial sea level at about 30,000 yr B.P. is not. Therefore, the formation of the Inner Barrier was basically a single stage event, and the time of its formation was during the last interglacial, about 120,000 yrs ago.

Chapter 5 - Th^{230}/U^{234} Ages of Corals from the Loyalty Islands

5.1 Introduction

Eight corals from three islands of the Loyalty Archipelago were provided by M. Jean Launay of the Office de la Recherche Scientifique et Technique Outre Mer (ORSTOM) for uranium-series dating. Five samples were corals from the island of Beautemps-Beaupre at the northern end of the Loyalty Island chain, one coral was from Ouvea, while two corals came from the island of Lifou (Fig. 5.2). All the corals were collected in their growth position from a reef terrace that surrounds each island. Terrace elevation is +2 to 3m for Lifou and Beautemps-Beaupre, while on Ouvea it is +6·5m. The corals from Beautemps-Beaupre had previously been dated by C^{14}, and they all gave ages of $\geqslant$37,000 yr B.P. The coral samples from Lifou gave C^{14} ages of 24,030 ± 2000 yr and 23,820 ± 580 yr B.P.

5.2 Tectonic Setting

The Loyalty Islands lie on a submarine volcanic ridge whose strike is parallel to the island of New Caledonia (Dubois *et al.*, 1974). To the east of the Loyalty Islands lies the New Hebrides trench (Fig.5.1). The main structural features of the area indicate migration of the Indian plate and its eventual subduction at the New Hebrides trench. Dubois *et al.* (*op.cit.*) consider that uplift of parts of the Loyalty Islands and New

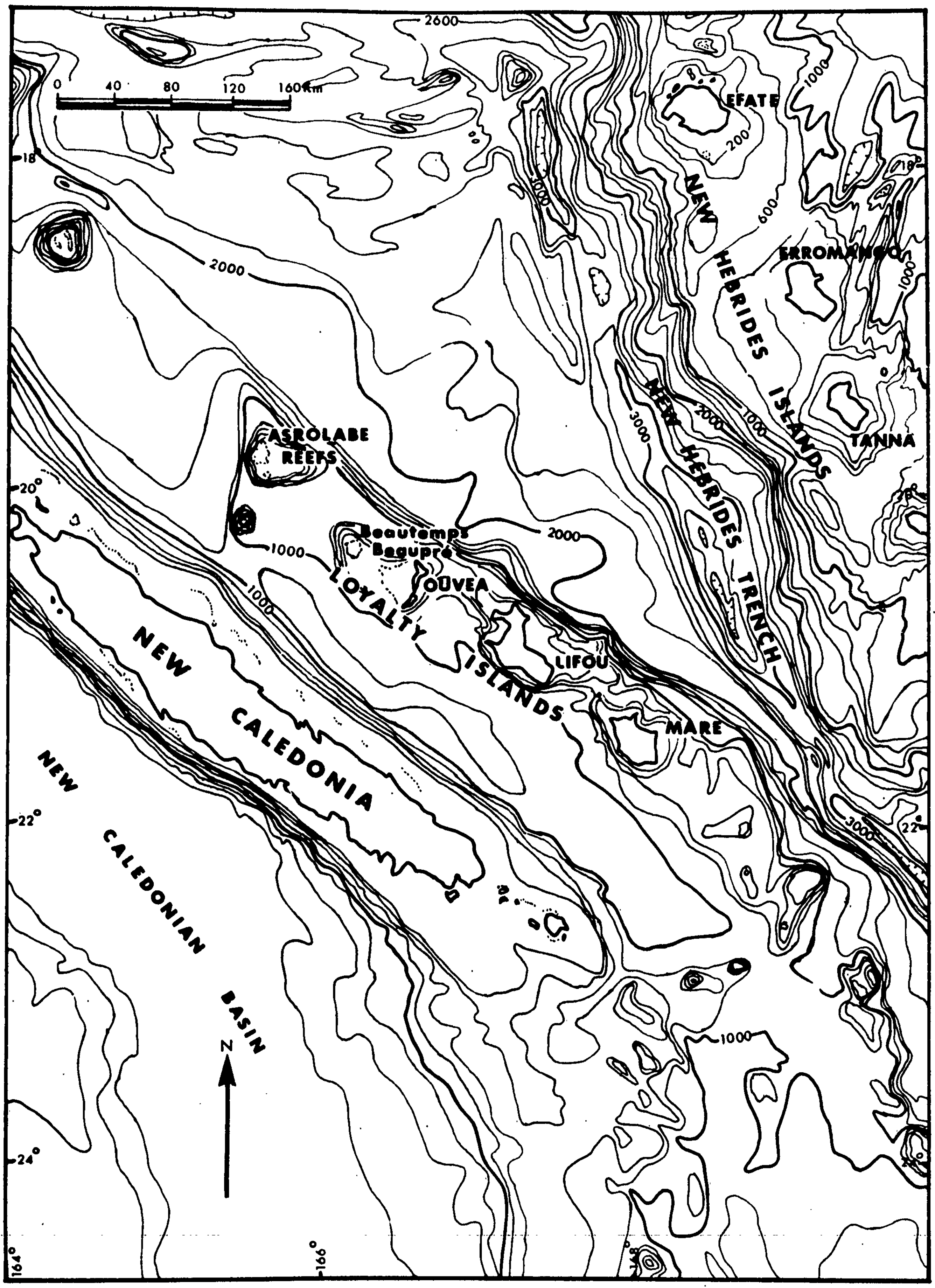


Figure 5.1 Regional bathymetry of the New Caledonia-New Hebrides area, showing the relationship of the Loyalty Islands and New Caledonia with the New Hebrides trench

Caledonia can be explained by a flexure or a bulge of the lithosphere prior to its subduction below the New Hebrides arc. The orientation of the axis of the bulge would be parallel to the axis of the trench, but this is different to the orientation of New Caledonia and the Loyalty Islands. During the Quaternary the migration of the Indian plate would have brought parts of New Caledonia and the Loyalty Islands into the zone of deformation generated by the lithospheric bulge, the zones nearest the axis suffering the greater uplift.

5.3 Regional Geology of the Loyalty Islands

The Loyalty Islands are a series of uplifted atolls, the altitude of which decreases from southeast to northwest. Marè is 138m high, Lifou is 104m, Ouvea is only uplifted along the eastern edge of the island, and its maximum elevation is 46m, while Beautemps-Beaupre is about 3m above sea level (Fig.5.2).

The islands consist predominantly of limestone, dolomitic limestone, and dolomite. On Mare olivine basalt and dolerite, indicative of oceanic volcanism, are present on the floor of the ancient lagoon. These volcanic rocks range between 9 and 11 m.y. in age (Guillon and Recy, pers. comm. in Dubois *et al.*,*op. cit.*). The oldest limestones on Lifou and Ouvea are Miocene (Chevalier, 1973). Therefore, the subsidence phase during which the atolls were formed probably began in the late Miocene and continued during the Pliocene. After the subsidence phase the atolls were gradually uplifted, the uplift rate being

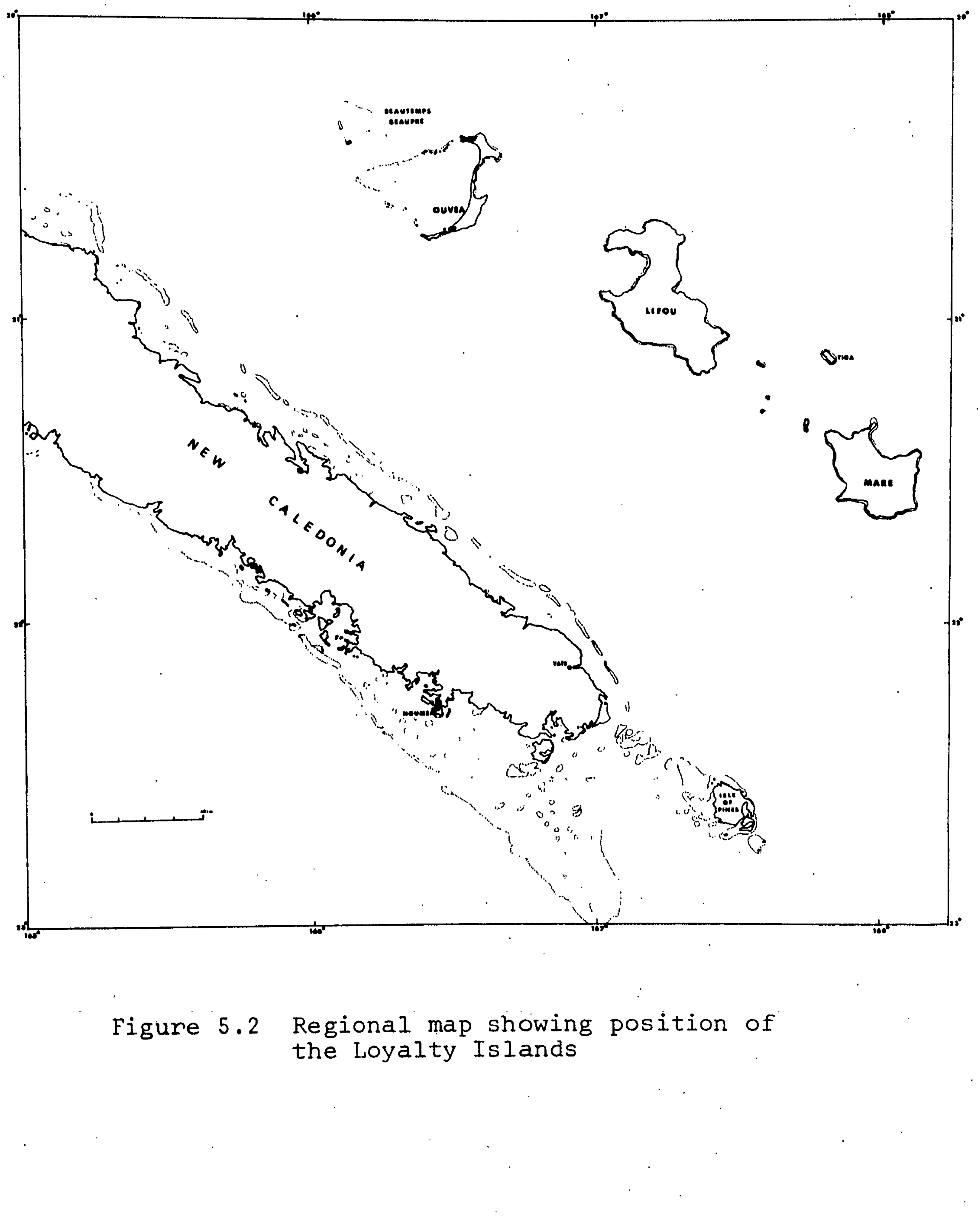


Figure 5.2 Regional map showing position of the Loyalty Islands

greater in the south and decreasing to the north. Corals collected from the top of the emerged reef on Mare are early Pleistocene (Chevalier, 1968), and it is considered that uplift began at about this time.

During this uplift phase a number of terraces were cut into the limestone cliffs of the atolls, and small fringing reefs, similar to the present fringing reefs of the islands, were developed. These terraces have been formed by sea level oscillations superimposed on a rising landmass, similar to the formation of reef terraces along the northeast coast of the Huon Peninsula (Bloom *et al.*, 1974; Chappell, 1974a). Therefore, the terraces represent ancient sea levels.

On Mare there are fifteen terraces; the lower ones occur at levels of 12, 8-9, 3-4, 2-2·5, and 1·5m above sea level. The lower terraces have horizontal surfaces whereas the higher terraces slope to the northeast, and they are slightly distorted (Chevalier, 1973). The tilting of the higher terraces is probably a reflection of the greater uplift rates in the southeast, as well as Mare being the closest island to the New Hebrides trench. Lifou has five well developed terraces, while on Ouvea there are four terraces.

Beautemps-Beaupre is a half-atoll lying on an old submerged atoll. The highest elevation is found on the southeastern rim where a small limestone island rises to about 3·5m above low tide level (Haeberle, 1952; Chevalier, 1973). Northwest of Beautemps-Beaupre lie the Astrolabe

Reefs. These are half-atolls with the surface of the reef lying at sea level.

5.4 Ages of Corals from the Loyalty Islands

All the corals selected for age determination were large hemispherical types, and x-ray diffraction analysis showed them to be 100 per cent aragonite. Thin-section examination of the corals showed only minor amounts of aragonite cement, and some minor infilling by fine-grained carbonate material. Neither the aragonite cement nor the fine-grained carbonate was considered sufficiently abundant to affect the ages of the corals significantly.

The radiochemical data and ages of the corals from the Loyalty Islands are shown in Table 5.1. The ages for Beautemps-Beaupre are at the upper limits of the Th^{230}/U^{234} method, and all ages are reported as older than 200,000 yr B.P. This conclusion is supported by the U^{234}/U^{238} ratios. The U^{234}/U^{238} ages, as determined from the ratios, range from 400,000 to almost one million years (this excludes the repeat age determination of sample 74630120). However, Th^{230}/U^{234} ages for samples 74630116 and 74630118 both give a result of 240,000 yr B.P. If the U^{234}/U^{238} ratios are incorrect for these two samples, possibly as a result of a spread in the U^{234} peak, then this age might be correct. This could be a possibility in view of the U^{234}/U^{238} value of 1·11 ± 0·02 for 74630120B which was done as a repeat some four months after 74630120A. However, during the running of the Beautemps-Beaupre samples, corals from

Table 5.1 : Radiochemistry and Ages of Coral Samples from the Loyalty Islands

BMR Sample No.	ORSTOM Sample No.	U ppm	$\frac{U^{234}}{U^{238}}$	$\frac{Th^{230}}{U^{234}}$	Age ($\times 10^3$yr)
			Beautemps-Beaupre		
74630116	BTP-3	2.94 ± 0.04	1.02 ± 0.01	0.90 ± 0.04	> 200
74630117	BTP-4	2.39 ± 0.04	1.04 ± 0.01	0.97 ± 0.03	> 200
74630118	BTP-6	1.96 ± 0.03	1.05 ± 0.01	0.90 ± 0.03	> 200
74630119	BTP-7	1.86 ± 0.03	1.01 ± 0.01	0.95 ± 0.03	> 200
74630120A	BTP-8	2.25 ± 0.04	1.05 ± 0.01	1.08 ± 0.07	> 200
74630120B	BTP-8	2.18 ± 0.04	1.11 ± 0.02	1.07 ± 0.05	> 200
		Ouvea			
74630136	Ouvea 3	2.83 ± 0.04	1.11 ± 0.01	0.67 ± 0.02	117 ± 6
		Lifou			
74630131	Lif 11	2.32 ± 0.03	1.09 ± 0.01	0.84 ± 0.03	189 ± 17
74630132	Lif 12	2.30 ± 0.04	1.12 ± 0.01	0.82 ± 0.03	174 ± 16

All samples 100 percent aragonite

$Th^{232}/Th^{230} << 0.01$ for all samples

Lifou and New Guinea were being run at the same time, and these show normal U^{234}/U^{238} ratios when corrected for age. Therefore, the U^{234}/U^{238} values for Beautemps-Beaupre are probably correct, and the only conclusion that can be reached at this time is that all corals from the +2m terrace on Beautemps-Beaupre are older than 200,000 yr B.P.

A coral from the +6.5m terrace on Ouvea (74630136) gave an age of 117,000 ± 6000 yr B.P. This age is well documented for coral reefs standing at 2-9m above present sea level on what are considered to be stable islands and coastlines throughout the world (e.g. Veeh, 1966; Thomson and Walton, 1972; Ku *et al.*, 1974). This age represents the time of the last interglacial when sea level stood slightly higher than the present. Therefore, the +6·5m terrace on Ouvea was formed during the last interglacial.

The Th^{230}/U^{234} ages of the corals from the +2m terrace on Lifou of 189,000 ± 17,000 and 174,000 ± 16,000 yrs B.P. are in fairly good agreement, and they give an average age of about 180,000 yr B.P. This age has been reported previously from New Guinea and Barbados (Veeh and Chappell, 1970; Mesolella, *et al.*, 1969). Reef complex VIII from the Huon Peninsula (Chappell, 1974a) has two Th^{230}/U^{234} ages on corals of 190,000 ± 17,000 and 180,000 ± 15,000 yrs B.P. while on Barbados two corals gave ages of 170,000 ± 10,000 and 190,000 ± 10,000 yrs B.P. (Mesolella *et al.*, 1969). Although the Barbados data is not as clear as that from New Guinea, this new data from Lifou lends support to the interpretation of a sea level maximum at about 180,000 yr B.P. Chappell (1974b; Fig.1) shows that at this time, sea level stood at about 25m below present sea level.

5.5 Uplift Rates of the Loyalty Islands

In their hypothesis of a lithospheric bulge, Dubois *et al.* (1974) consider that the Loyalty Islands act as markers of the uplift component of the plate movement. They consider that the southwestern and central parts of the Loyalty Islands and the southern extremity of New Caledonia have been affected by an "epiorogenic wave" that commenced in the early Quaternary. This wave has not affected the northern part of the Loyalty ridge or most of New Caledonia.

Th^{230}/U^{234} dating of the raised coral terraces on the Loyalty Islands can provide valuable information on the uplift rates of the various islands in the archipelago. Unfortunately no corals have been dated from Mare. This island appears to have undergone the greatest amount of uplift, and dating of the lower terraces would have proved invaluable in determining the differential uplift rates of the islands. Dubois *et al.* (*op.cit.*) calculated an uplift rate of 0·07m/1000 yr for the past 2m.y. on Mare based on the presence of early Pleistocene corals on the ancient reef crest and their present elevation above sea level. However, this figure is open to interpretation as no definite age of the corals is known. On Lifou there is enough data to determine its rate of uplift. Dubois *et al.* (*op. cit.*) report a Th^{230}/U^{234} age on a coral at an elevation of +12m on Lifou. This age determination was carried out by M. Bernat, and the age is reported as being about 120,000 yr B.P. Therefore, corals at +12m on Lifou were formed during the last interglacial, and they are coeval with corals from the +6·5m terrace on Ouvea. This indicates that Lifou has been uplifted by about at least 6m more than Ouvea since the last interglacial, or that Lifou has been rising at a rate of 0·05m/1000 yr relative to Ouvea. Also, since most workers estimate that sea level during the last interglacial was 6(±2)m above present sea level (Matthews, 1973; Ku *et al.*, 1974; Bloom *et al.*, 1974) then the rate of uplift of Lifou during the past 120,000 years is also of the order of 0·05m/1000 yr.

The average age of 180,000 yr B.P. for the +2m terrace on Lifou provides another datum for determining the uplift rate of the island. If we accept Chappell's (1974 a & b) interpretation that at this time sea level was about 25m below present sea level, then this represents a rise of 27m during the past 180,000 years or an uplift rate of 0·15m/1000 yr. This is three times as rapid as the uplift rate determined for the past 120,000 years. This would indicate that the amount of uplift is waning or has not been uniform during the past 180,000 years. Another possibility is that the estimate of a -25m sea level is too low, and that sea level stood somewhat higher at this stage. On the basis of a uniform uplift rate of 0·05m/1000 yr, sea level would have been at about 7m below present sea level 180,000 years ago. Chappell (pers. comm., 1975) considers that such a difference between the two estimated levels (i.e. -25m and -7m) would have been detected from his leveling measurements on the Huon Peninsula terraces. Therefore, it can be assumed that sea level was nearer -25m at 180,000 yr B.P., and this would confirm that uplift has not been uniform on Lifou.

From the Th^{230}/U^{234} age of 117,000 yr B.P. for the +6·5m terrace on Ouvea it can be concluded that this island has not undergone any significant uplift since the last interglacial.

One confusing aspect of this study is the absence of 120,000 year old corals from Beautemps-Beaupre. Dubois *et al.* (*op.cit.*) consider that this part of the Loyalty Island chain has remained stable during the Quaternary. Since many stable islands throughout the Pacific have corals of last interglacial age at about +2m (Veeh, 1966) it is surprising that corals at this elevation on Beautemps-Beaupre are older than 200,000 yr B.P. The island which is about 1000m long and 500m wide was sampled in sufficient detail to detect any differences in age, and there appears to be only one coral terrace surrounding the island. The absence of corals about 120,000 years old from this island suggests that it may not be as stable as was originally thought.

5.6 Conclusions

Raised coral terraces from the Loyalty Islands at elevations of 2 and 6.5m above sea level give significantly different ages, and as such, they reflect the degree of vertical tectonic movement in this area. While no age determinations were made for the Mare terraces, it is considered from the number of terraces present and from the maximum elevation of the island that it has the highest uplift rate. Th^{230}/U^{234} ages from Lifou indicate that the rate of uplift of this island has not been uniform, and it has possibly been waning since the last interglacial. The age of 117,000 yr B.P. for the +6·5m terrace on Ouvea indicates that there has been no tectonic uplift of the island since that time and the present. Beautemps-Beaupre remains somewhat of an enigma, but it may not be as stable as was originally thought.

If the hypothesis of Dubois *et al.* (*op. cit*) of a lithospheric bulge of the Indian plate before it descends at the New Hebrides trench is correct, then on the basis of vertical movement of coral terraces on Mare and Lifou, as well as on New Caledonia at Yate and the Isle of Pines (Fig.5.1) during the past 120,000 years, and on the absence of any noticeable uplift on Ouvea during this period, it can be postulated that the axis of such a lithospheric bulge would be present between 167° and 168°E.

Chapter 6 Th^{230}/U^{234} Ages of Corals from Moreton Bay, Queensland

6.1 Introduction

Moreton Bay lies directly offshore from the city of Brisbane (Fig. 6.1). The bay has been formed by the development of two massive sand dune islands, Moreton Island and North Stradbroke Island. These islands form a series of sand dunes with northwesterly trending ridges, and they attain a maximum elevation of 280m above sea level. Bribie Island also consists of a series of sand dunes, but in this case the topography is more subdued. The bay is approximately 110 kilometres long and about 40 kilometres wide. The bay is relatively shallow with depths commonly less than 10m. It tends to be enclosed by a series of sand banks to the north while to the south it is reduced to a series of narrow, shallow channels where North Stradbroke Island approaches the mainland.

Within the bay there are several islands, some of which have small fringing reefs around them. At a number of sites the living reef corals are growing on dead reef material which is now about one metre higher than low tide level. The presence of dead coral above low water was originally thought to have been caused by uplift (Stutchbury, 1855), but later it was attributed to a eustatic high sea level (Fairbridge, 1961).

Twenty four species of coral, representing 12 genera, are known to be living in Moreton Bay (Wells, 1955). The hermatypic species are all common surface reef types of the Great Barrier Reef and elsewhere in the tropical Pacific. The dead reef material contains a subfossil fauna of which there are an extra 16 species represented in comparison to the modern fauna. The explanation for the presence on the slightly raised reef patches of coral species which are no longer living in the bay is varied. Saville-Kent (1893) attributed the decline of the number of *Acropora* species to the gradual enclosing of the bay by the development of sand banks and islands. Another factor is the influence of fresh water discharges by rivers, especially during times of heavy floods. Wells (1955) considered that the decline of the reef corals was due to a worsening of the physical conditions within the bay; amongst these conditions he included the effects of a slight lowering of sea level.

The presence of fringing reefs in a position slightly higher than present sea level within Moreton Bay has been interpreted as representing a eustatic sea level higher than the present. Fairbridge (1961) cited a 3m emerged coral reef in Moreton Bay as evidence for his "Younger Peron Terrace". A coral from this reef gave a C^{14} age of 3710 ± 250 yr B.P. (Rubin and Alexander, 1958). Thom *et al.* (1969) rejected this date because of lack of a detailed description of the site and the presence of only one date on material which could have been contaminated. In a reply to this paper Gill and Hopley (1972) claim that the coral was collected by an experienced geologist, but they did not give any details about the locality. Lowell (1975)

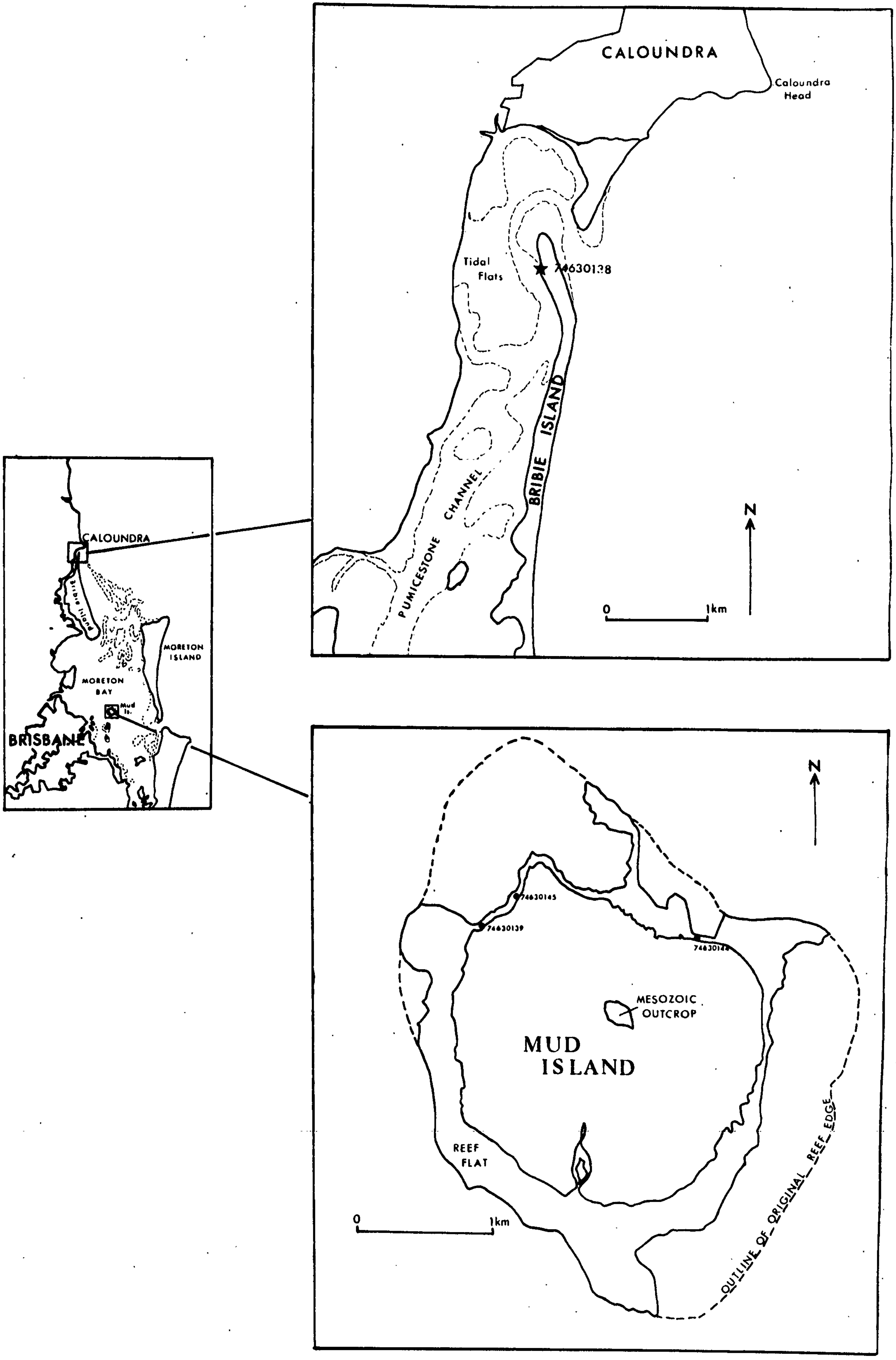


Figure 6.1 Bribie and Mud Islands, Moreton Bay showing location of dated coral samples

attempted to relocate this reef which was reported to be present on the western spit of Peel Island, an island some 15 kilometres south of Mud Island. Lovell (*op. cit.*) was unsuccessful in relocating this reef, and because of lack of information as to the collector and the locality he concluded that the evidence for a sea level of +3m could not be substantiated. However, Lovell (*op.cit.*) did obtain a C^{14} age of 2,540 ± 85 yr B. P. for a mollusc shell from the top of a beachrock horizon at approximately 2.5m above MSL on St Helena Island in Moreton Bay.

6.2 Coral Ages from Moreton Bay

Samples of coral and coral fragments within beachrock and humic sandrock were collected for uranium-series dating from Moreton Bay. Samples of coral from the beachrock on St Helena Island were collected to substantiate Lovell's (1975) age of 2,540 ± 85 yr B.P. However, these corals were unsuitable for absolute age determination because they were partly recrystallized. One sample which had a low-Mg calcite content of about 25 percent gave an "apparent" age 7,800 ± 400 yr B.P. The samples from Bribie and Mud Islands were 100 percent aragonite.

6.21 Bribie Island

A sample of coral was collected from a humic sandrock on the eastern side of Pumicestone Passage near the northern tip of Bribie Island (Fig. 6.1). This sandrock is presently at a depth of about one metre below low water level. The radiochemistry and age of the sample (74630138) are shown in Table 6.1. The sample has a high U^{234}/U^{238} activity ratio and a very high Th^{232}/Th^{230} activity ratio. Both ratios indicate that the sample has been contaminated, presumably by humic sandrock material that was present within the coral. Although most of this material was removed during the cleaning process, not all of it could be completely removed. Because of the high activity ratios not much emphasis can be put on the age of 6,300 ± 500 yr B.P.

6.2.2 Mud Island

The dead fringing reef around this island has been dredged as a source of cement for several years. The dredging front which extends to a depth of 7m below sea level has exposed a rich coral fauna with *Acropora* species predominant. Many of the species exposed by the dredging are atypical of the present day forereef facies around Mud Island. They are more comparable with the coral fauna of the Capricorn Group in the southern part of the Great Barrier Reef. Some of the species are indicative of deeper water conditions than those that now exist in Moreton Bay (Wells, 1955).

Three coral samples from the outer edge of the dead reef flat of Mud Island were collected for uranium-series dating (Fig. 6.1). The reef flat is presently at an elevation of about 1m above MLW. Although many of the corals do not appear to be in their growth positions, they do not appear to be too far removed from them. Many *Acropora* sp.

Table 6.1 Radiochemistry and Ages of Corals from Moreton Bay, Southern Queensland

Sample Number	total U (ppm)	$\frac{U^{234}}{U^{238}}$	$\frac{Th^{230}}{U^{234}}$	$\frac{Th^{232}}{Th^{230}}$	Age ($\times 10^3$yr)
			Bribie Island		
74630138	3.51 ± 0.05	1.18 ± 0.01	0.056 ± 0.005	0.55	6.3 ± 5
			Mud Island		
74630139	4.18 ± 0.05	1.16 ± 0.01	0.053 ± 0.002	0.06	6.0 ± 0.2
74630144	4.69 ± 0.05	1.12 ± 0.01	0.041 ± 0.002	0.03	4.6 ± 0.2
74630145	3.01 ± 0.09	1.12 ± 0.03	0.037 ± 0.002	0.03	4.1 ± 0.3

All samples 100 percent aragonite

are now upside down which suggests that they have merely fallen over after death. One *Acropora* that was selected for dating (74630144) was still in its original growth position. The other two samples, an *Acropora* sp. (74630139) and a *Favia* sp. (74630145) are considered to be near their original growth positions.

The radiochemistry and ages of the corals are shown in Table 6.1. The *in situ* coral (74630144) obeys the closed system criteria and the age of 4,600 ± 200 yr B.P. appears to be reliable. Similarly the age of 4,100 ± 300 yr B.P. for sample 74630145 is also reliable. The other sample (74630139) has slightly high U^{234}/U^{238} and Th^{232}/Th^{230} activity ratios, but the age of 6,000 ± 200 yr B.P. does appear to be reliable.

6.3 Interpretation of High Sea Levels in Moreton Bay

The ages from Mud Island indicate that sea level was about one metre higher than present during the interval of 4,000 to 6,000 yrs B.P. Although the age of the humic sandrock from Bribie Island is not as reliable it does possibly indicate a sea level of about -1m during this same interval. Dated material from these two levels which are about the same age tends to complicate the interpretation of Holocene sea levels.

The study of Holocene sea levels in eastern Australia has been a subject of considerable debate. On one hand it has been maintained that there has been no Holocene sea level higher than present (Thom *et al.*, 1969, 1972; Cook and Polach, 1973) while on the other hand it has been maintained that sea level was higher than present at certain times during this period (Gill and Hopley, 1972).

The presence of fringing reefs and beachrock above present sea level within Moreton Bay that have been dated as Holocene suggests that there was a high sea level during this time. However, it could be that this effect was entirely local. It could be that this situation was brought about by fluctuations in the tidal range within the bay. Such a difference in the tidal range could have been brought about by opening or closing of the bay entrances by shifting sand banks.

Chapter 7. Conclusions

The uranium-series method of dating has proved itself in recent years to be a useful tool both in respect to late Pleistocene sea level fluctuations and neo-tectonic uplift rates. The ability to extend the range of dating beyond the C^{14} method has allowed geologists and geomorphologists to obtain a more complete picture of eustatic and tectonic events during this period. The documentation of periods of high sea levels, especially since the last interglacial at about 120,000 yr B.P., has enabled palaeoclimatologists to better understand the mechanisms of sea level changes. Data from this study, from the Inner Barrier of New South Wales and from Ouvea, has added to the growing list of ages that indicate that sea level was slightly higher than present at about 120,000 yr B.P. The ages from the Inner Barrier also support the theory of two high sea levels between 120,000 - 140,000 yrs B.P. Ages from the island of Lifou of about 180,000 yr B.P. reinforce the interpretation of Chappell (1974a) of a relatively high sea level at about this time (Fig. 7.1).

The reproducibility of the method has been demonstrated by repeat age determinations on previously dated corals from the Huon Peninsula, New Guinea. Dating of this material has also demonstrated the necessity of closely examining each sample for signs of recrystallization. The two repeat age determinations of sample 74630114 (Table 2.2) give an indication of the gross errors involved in

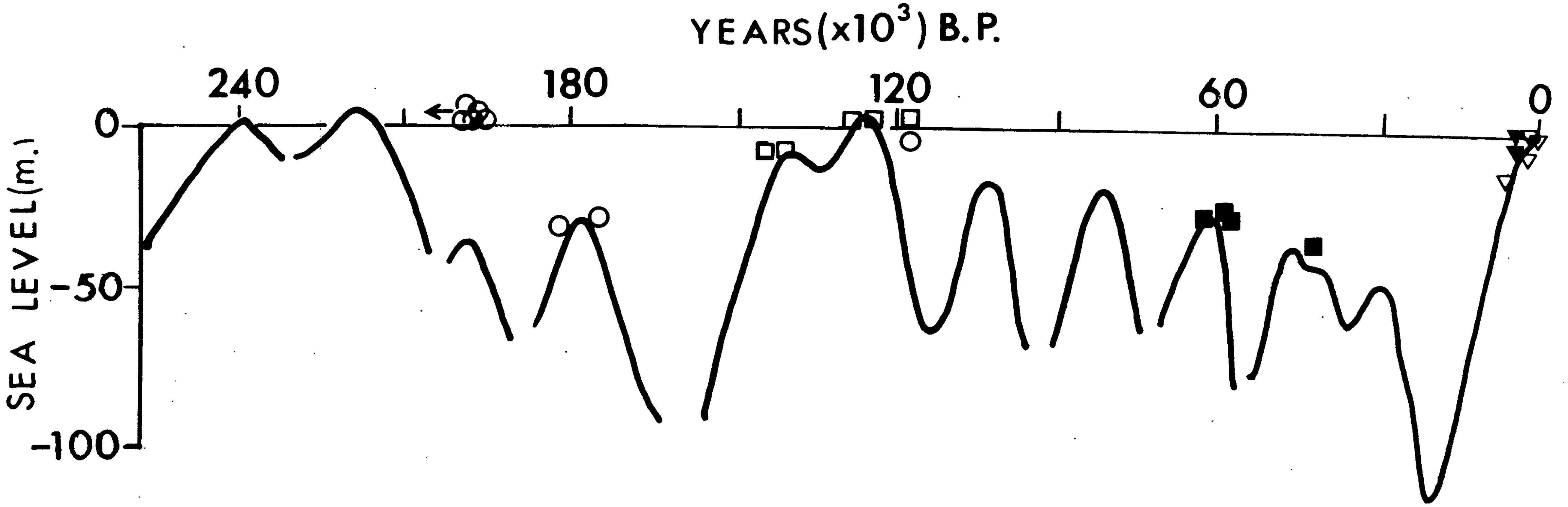


Figure 7.1 Late Quarternary sea level curve (after Chappell, 1974a and Bloom *et al.*, 1974) showing coincidence of ages from this study with periods of relative high sea level

dating material that contains appreciable amounts of low-Mg calcite, whether as void-filling cement or where it has replaced the original aragonite skeleton. Detailed x-ray diffraction analysis and, if possible, thin section examination of the corals is essential before age determinations are carried out.

Th^{230}/U^{234} ages from Moreton Island and the Great Barrier Reef provide information on the times of reef growth during the Holocene. Ages from Moreton Bay indicate a period of high sea level of at least 1m between 4000-6000 yrs B.P. Whether this high sea level was a result of eustatic processes or of local conditions in the bay remains to be resolved. Ages from Hayman Island show that reef colonization within the Great Barrier Reef province began towards the end of the Holocene transgression at about 8,300 yr B.P. Unfortunately corals below an obvious discontinuity were largely recrystallized and they proved unsuitable for dating. Ages from below this discontinuity are important in order to determine the time of reef colonization prior to the Holocene.

During this study it became apparent that where species of the coral *Acropora* were involved the uranium concentration was higher than that of other coral species. The six corals that were positively identified as *Acropora* had uranium values ranging from 3.44 to 4.69ppm, with a mean value of 3.98 ± 0.46ppm. These values are consistently higher than other species analysed in this study. Of a total of 19 non Acroporiid species the range of uranium values was from 1.86 to 3.12ppm, with a mean of 2.53 ± 0.35 ppm. Uranium values for *Acropora* sp. from previously published results show a range of 3.06 to 4.12ppm, with a mean of 3.57 ± 0.31ppm. Although there is some overlap with other species, most of the previously published uranium values for *Acropora* sp. are higher than the others. Because of its higher uranium values, the reliability of dating *Acropora* has in some cases been questioned (e.g. Bloom *et al.*, 1974). The six *Acropora* specimens analysed by this study have ages ranging from <1000 yr to 127,000 yr B.P. and all samples appeared to give reliable ages, especially where they could be checked against other species. Previous dating of *Acropora* has also been shown to be reliable (Broecker *et al.*, 1968). The reason for its high uranium concentration is at present unkown, but as this type of coral is often the most abundant species present, both on living and dead reefs, in some cases it may be the only type available for dating. Therefore, an attempt should be made to substantiate the reliability of this important genus of scleractinian coral for uranium-series dating. An understanding as to why it has a higher uranium concentration would probably enhance its reliability as a useful dating material.

Appendix 1. Preparation of Iron Carrier

The iron carrier is prepared by dissolving 13.67gm $FeNH_4(SO_4)_2$ in 50ml 4N HCl (≈ 4 percent Fe^{3+} soln). The solution is twice passed through a cation exchange column (Bio-Rad AG 50W-X8, 100-200 mesh) previously washed with 4N HCl. The iron solution is then made up to a strength of 8N HCl (by doubling the volume of 4N HCl solution with conc. HCl). The solution is twice passed through an anion exchange column (Bio-Rad AG 1-X8, 200-400 mesh) previously washed with 8N HCl. The anion resin is washed with three column volumes of 8N HCl. Iron on the column is eluted into a clean beaker with $0.25N(NH_4)_2SO_4$ solution saturated with SO_2 (see Appendix 2). The eluted iron is then precipitated by bubbling ammonia gas through the solution until a pH of 7 is reached. The ferric hydroxide precipitate was centrifuged and washed three times with triple distilled water. The ferric hydroxide is then dissolved in approximately 50ml 8N HCl and stored in a clean polypropylene bottle.

Appendix 2. Preparation of $0.25N(NH_4)_2SO_4$ solution

SO_2 gas is bubbled into 250ml of distilled water until there is no change in weight. 4.13gm $(NH_4)_2SO_4$ then dissolved in the solution.

Appendix 3: Preparation of Th^{234} Yield Tracer

(after Golderg and Koide, 1962)

1. Add 10ml of conc. perchloric acid to 10gm of uranyl nitrate in enough water to effect solution, and take to fumes of perchloric acid.
2. Dilute solution to 40ml (3M) and pass through a cation exchange column (4mm x 150mm, packed with Bio-Rad AG 50W-X8, 200-400 mesh resin, and a 50ml resevoir) previously washed in 3M perchloric acid.
3. Save the eluate and discard the resin. Repeat Step 2 and pass through a new column. Save the eluate and discard the resin. Let the uranyl solution stand for several weeks. Repeat Step 2 and save the eluate for future milkings.
4. Carefully wash the resin and the sides of the resevoir with five 1ml portions of 3M HCl.
5. Elute the thorium with 2ml of 0·5M oxalic acid. To the eluate add 5ml conc. perchloric acid and 5ml conc. nitric acid, and take to fumes of perchloric acid three times, washing down the sides of the beaker with distilled water after each fuming.
6. Dilute to 20ml (3M) and repeat Steps 2,4 and 5. For a clean separation this must be done twice.
7. To the final oxalic acid - HCl eluate, add 5ml of conc. perchloric acid and 5ml of conc. nitric acid and take to dryness. Dilute to 30ml with 5N nitric acid.

Appendix 4. Petrography of Corals from the Huon Peninsula

Reef Complex III

74630111 In this coral the centres of calcification are well displayed (Fig 1A). In transmitted light these are the dark lines running along the centre of the trabeculae. Voids are present along parts of these central lines. James (1974) has shown that during dissolution of the coral skeleton in the vadose environment, the centre of calcification is preferentially leached with respect to the rest of the skeleton. Therefore, these voids may be an indication of early diagenesis. The rest of the coral shows no signs of solution; there is no leaching of the aragonite fibres radiating from the centres of calcification (Fig. 1B).

Reef Complex IV

74630112 Parts of this coral have relatively large borings which have been filled with micrite together with skeletal fragments and some ferromagnesian minerals. The recognised skeletal fragments are of coral, coralline algae, *Halimeda*, foraminifera, and molluscs. Figure 1C shows a gastrapod (?)within one of the borings which has its chamber filled with micrite and clear aragonite cement.

Acicular aragonite cement is present in some of the voids of the coral, and in one or two cases it has completely filled the void (Fig. 1D). However, both micrite and aragonite cement are only sporadically developed throughout the coral, and in most cases they are present near the outer surface.

74630113A Some of the voids of this coral are partly filled with micrite and skeletal fragments (fine sand - silt size). A number of borings are present; these are filled with dark grey micrite. Most of the larger borings are quite obvious, and the material filling them was easily removed during cleaning. Aragonite cement lines some of the voids, and it is present on septa and dissepiments (Fig. 1F). This aragonite cement makes up less than one percent of the total rock. In one case a thick layer of what is possibly low-Mg calcite was observed (Fig. 1E).

74630113B Some of the voids are partly filled with a dark micrite (Fig. 1H), but this is not as extensively developed as the photomicrograph suggests. Some microborings are present, some of which appear to be filled by micrite (Fig. 1G).

Reef Complex VI

74630114 This coral exhibits a fabric that is not observed in the younger corals. In transmitted light much of the clear skeletal aragonite is replaced by dark, irregular patches (Fig. 1I). The dark patches are a result of the internal reflection of light in submicroscopic solution voids between aragonite needles (James, 1974). This is caused by the dissolution of sheafs of aragonite fibres from the coral skeleton by waters undersaturated with calcium carbonate; Alexanderson (1972) has applied the term "selective leaching" to this phenomenon. It is known to affect metastable carbonates in cold-water marine environments and in the subaerial vadose environment.

Although aragonite fibres have been removed, there does not appear to be any replacement by low-Mg calcite at this stage. However, in parts of this coral there is a considerable development of clear, void-filling low-Mg calcite cement (Fig. 1J).

Figure 1.

A. Photomicrograph under plane polarized light showing the skeletal structure of the coral *Hydnophora excesa.* The dark lines along the axial parts of the skelton are the centres of calcification. Scale bar = 500 µm.

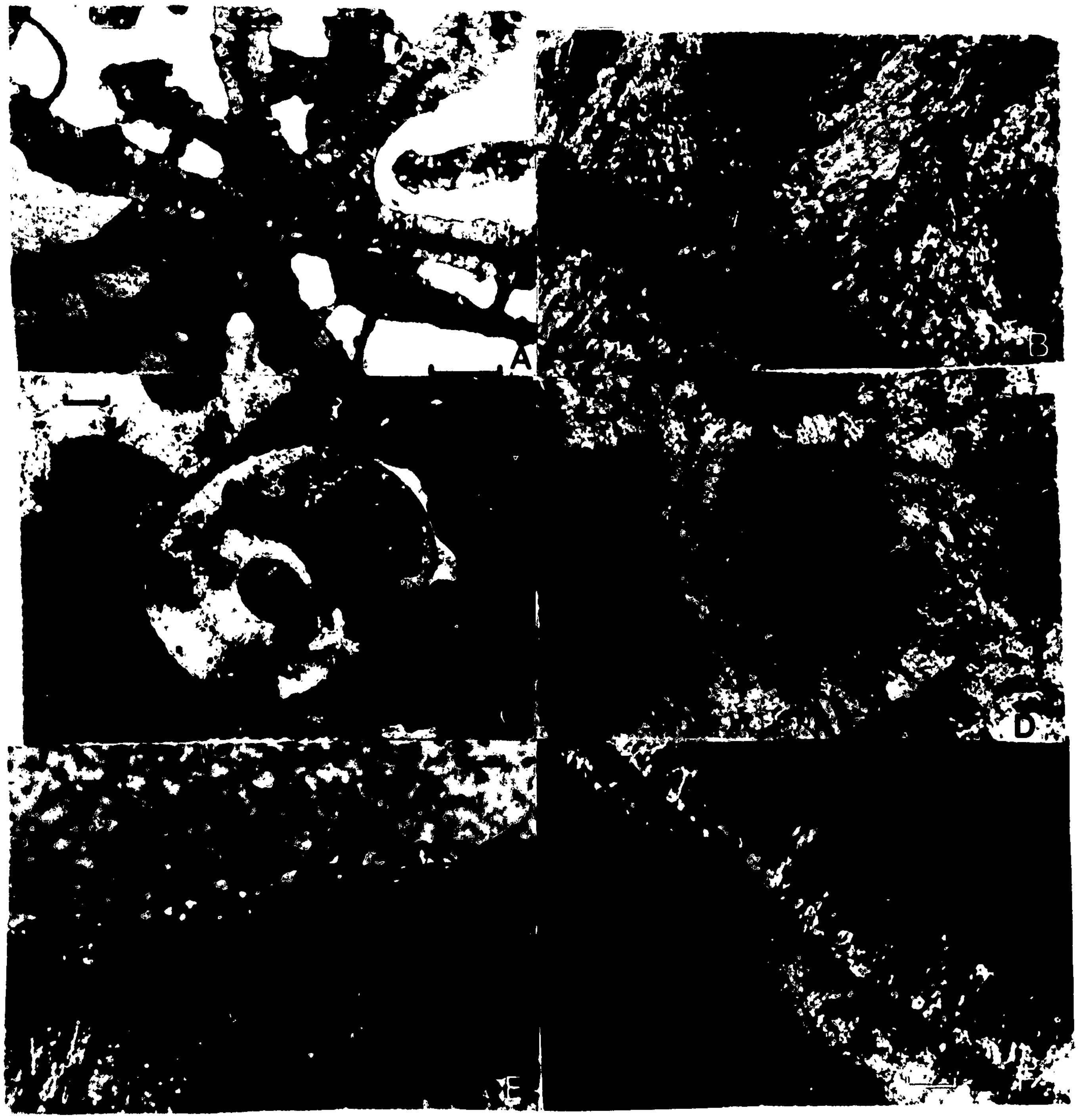
B. Photomicrograph under crossed polerizers showing aragonite fibres radiating from the centres of calcification. Scale bar = 30 µm.

C. Photomicrograph under crossed polarizers showing a large boring which has been filled by dark grey micrite and skeletal fragments. The large skeleton has been filled with dark micrite and clear aragonite cement. Scale bar = 100 µm.

D. Acicular aragonite cement partly filling a void of the coral. Crossed polarizers. Scale bar = 100 µm.

E. Fibrous aragonite cement growing on one side of a dissepiment. Crossed polarizers. Scale bar = 50 µm.

F. Photomicrograph under plane polarized light showing the development of small calcite crystals along part of the coral wall. Scale bar = 30 µm.


A
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E

Figure 1.

G. Photomicrograph under plane polarized light showing borings by microrganisms. Some of the borings are filled with dark micrite. Scale bar = 50 µm.

H. Longitudinal section of the coral showing septa and dissepiments. Some of the voids are partly filled with dark micrite. Plane polarized light. Scale bar = 100 µm.

I. Photomicrograph under plane polarized light showing dark patches in the coral skeleton. These dark patches, as they appear in transmitted light, are a result of removal of some of the aragonite fibres by groundwater during subaerial diagenesis. Scale bar = 100 µm.

J. Photomicrograph under plane polarized light showing the development of large, clear crystals of low-Mg calcite cement partly or wholly filling the voids of the coral. Scale bar = 100 µm.

Figure 1.

G. Photomicrograph under plane polarized light showing borings by microrganisms. Some of the borings are filled with dark micrite. Scale bar = 50 µm.

H. Longitudinal section of the coral showing septa and dissepiments. Some of the voids are partly filled with dark micrite. Plane polarized light. Scale bar = 100 µm.

I. Photomicrograph under plane polarized light showing dark patches in the coral skeleton. These dark patches, as they appear in transmitted light, are a result of removal of some of the aragonite fibres by groundwater during subaerial diagenesis. Scale bar = 100 µm.

J. Photomicrograph under plane polarized light showing the development of large, clear crystals of low-Mg calcite cement partly or wholly filling the voids of the coral. Scale bar = 100 µm.


H

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