

Radiocarbon Ages from the Northern Great Barrier Reef

H. A. Polach, R. F. McLean, J. R. Caldwell and B. G. Thom

Phil. Trans. R. Soc. Lond. A 1978 **291**, 139-158

doi: 10.1098/rsta.1978.0095

Email alerting service

Receive free email alerts when new articles cite this article - sign up in the box at the top right-hand corner of the article or click [here](#)

To subscribe to *Phil. Trans. R. Soc. Lond. A* go to: <http://rsta.royalsocietypublishing.org/subscriptions>

Radiocarbon ages from the northern Great Barrier Reef

BY H. A. POLACH,† R. F. McLEAN,‡ J. R. CALDWELL§ AND B. G. THOM||

†*Radiocarbon Laboratory, Australian National University, Canberra, Australia 2600*

‡*Department of Geography, University of Auckland, Auckland, New Zealand*

§*Department of Biogeography and Geomorphology, Australian National University, Canberra, Australia 2600*

||*Department of Geography, Faculty of Military Studies, University of New South Wales, Duntroon, Australia 2600*

1. INTRODUCTION

The aims of the 1973 Great Barrier Reef Expedition's radiocarbon dating programmes were: (i) to collect live specimens from various reef environments to serve as modern reference standards; (ii) to evaluate the suitability of materials from the drilling, geomorphic and sediment programmes for dating purposes; and (iii) to date appropriate samples related to those programmes. The radiometric ages provide a time scale for the evolution of reefs and reef islands, and the history of sea level in the area.

The purpose of this paper is to report results of all ages determined to date, to describe field and laboratory methods used and to assess the reliability of the ages in terms of (i) the actual materials dated and (ii) the geomorphic, ecological or stratigraphic units from which the samples were obtained. Seventy-nine determinations based on 74 samples are reported. No interpretation of the results is attempted here.

2. FIELD COLLECTION

Samples were obtained from various reef environments within a 5° latitudinal range between Raine Island (11° 36' S) and Low Isles (16° 23' S) on the northern Great Barrier Reef. However, nearly 90% of the samples were collected within a 1° band between Stapleton Island (14° 19' S) and Three Isles (15° 07' S). Samples can be grouped into the following categories: (1) live specimens, (2) fossils, rocks and sediments, and (3) samples from drill cores.

2.1. *Live specimens*

Specimens of living corals were collected from reef flats and reef slopes at Houghton and Magaera reefs; these included species of *Symphyllia*, *Favia*, *Turbinaria*, *Physogyra*, *Porites*, *Goniastrea*, *Acropora*, *Fungia*, *Astrospora* and *Platygyra*. Other living material collected included *Nerita*, *Lithophaga*, *Trochus*, *Tridacna*, *Cypraea* and other molluscs, and *Acanthaster* and *Halimeda*. Of this collection only the last is reported here. All living specimens were preserved with flesh in salt water under vacuum in Agee jars to check ¹⁴C distribution and ¹³C/¹²C isotopic compositions. Polach was assisted by Thom, J. E. N. Veron and T. P. Scoffin in collecting this living material; Veron identified the corals.

2.2. *Fossils, rocks and sediments*

A large number of fossils, limestone rocks and sediments were collected during the Expedition, but only a small proportion of these have been dated. About half of the total samples reported here were collected with dating explicitly in mind at the time of collection.

All dated samples in this group were collected from above low water level and many were located on transects surveyed by McLean, D. R. Stoddart, D. Hopley, and A. L. Bloom. Of the samples reported 51 were collected by McLean, 10 by Hopley, 3 by Polach and 10 by Thom.

2.2.1. *Fossils*

Parts of entire specimens of individual fossil corals and molluscs were taken from a variety of reefs and situations, including coral colonies, boulder tracts, reef flats, shingle ramparts and ridges. Some specimens were in position of growth, others were not. Commonly, a number of different specimens were taken from the one locality, stratigraphic or geomorphic unit. Individual samples normally weighed 0.5–5.0 kg and were carried untreated in plastic bags to the laboratory. Massive and branching corals and tridacnids were most frequently obtained.

2.2.2. *Limestone rocks*

Rock types exhibiting some degree of consolidation included rampart-rock, beach-rock, boulder-tract-rock, reef-rock, island-rock and phosphorites. Descriptions of these rock types are given in Scoffin & McLean (1978, this volume). For dating purposes most attention was paid to rampart-rocks, which based on morphological and altitudinal criteria were called bassett edges, and lower and upper platform in the field.

Both large and small samples were broken off with geological or sledgehammer and crowbar; the samples normally contained both skeletal material and matrix. In some instances, particularly in the loosely consolidated deposits, it was possible to prise individual corals and clams from the matrix, although this was only rarely possible in the tougher rocks. Notes were made on position, facies, geometric form and relations of the samples and whether or not skeletal materials were in growth position.

2.3.3. *Sediments*

These comprised either carbonate sands of mixed skeletal composition or loose coral gravels from soil pits, scarp sections or surface deposits of sand and shingle cays. Details of the nature of these sediments are given by McLean & Stoddart (1978, this volume). Individual horizons or sediment units were sampled and bulk samples collected by hand, spade or trowel. Samples were packaged in plastic bags without treatment.

2.3. *Drill cores*

The drilling programme yielded both consolidated and unconsolidated material suitable for dating. The technique of drilling and method of sampling has been described by Thom (1978). Sample size was limited by the 35.5 mm internal diameter core barrel and highly variable lithologies with depth. Quantity of material submitted for dating was barely adequate, inhibiting further treatment (see Thom, Orme & Polach 1978, this volume).

3. LABORATORY EXAMINATION

Potential samples were carefully examined before submission to the Radiocarbon Laboratory. Modes of examination were determined by the nature of the samples and the submitter's reasons for obtaining a radiocarbon age. The validity of ages was regarded as of utmost importance and special attention was paid to removing post-death contaminants, in those samples which consisted of single organisms.

3.1. *Corals and molluscs*

Samples in individual isolated corals, and molluscs from colonies in growth position, boulder tracts and shingle ramparts, were sawn into cubes. Where possible, massive corals possessing thick walled corallites and large valves of *Tridacna* clams were selected. Interior portions of cut samples were checked initially in hand specimen and then under the binocular microscope for the presence of loose sediment of cement, filled or unfilled boreholes and bore-linings and areas of discoloration, which if present were cut out. The resulting cuttings were split into different portions for mineralogical determination, thin section preparation, radiocarbon determination, sample identification and archives. Thin sections of corals were studied to ascertain the degree of secondary carbonate deposition, recrystallization and foreign organism intrusion.

Contamination of massive corals in growth position and of reef blocks was found to be minimal. Thin sections were not prepared of tridacnids and reliance was placed on aragonite-calcite determinations (see below) for evaluation of the degree of contamination (which also was proved to be minimal). Of the 19 samples in this group submitted for radiocarbon dating, 11 were corals and 8 tridacnids.

3.2. *Limestone rocks*

These included beach-rocks, and the various categories of rampart-rocks which varied from loosely cemented bassett edges, through more firmly cemented lower platform rocks to the tough, firmly lithified rocks of the higher platform. With the rampart-rocks, ages were desired on both skeletal materials and some cements. Where massive corals and tridacnids were present in rampart-rocks these were cut out or broken from the matrix and prepared and examined in the manner indicated above (§ 3.1) with similar results.

Separation of smaller branching corals and molluscs from the cementing matrix, and removal and isolation of cement from within coral pores, proved much more difficult. Tiny slabs of coral and cement were cut and examined microscopically, and contaminants (either coral or cement) removed by saw and/or dentist's drill. Examination of thin sections of these samples suggests that it is unlikely that all contamination was removed. Thus the ages for this suite of samples, notably ANU-1208 (coral), ANU-1380 (coral), ANU-1381 (matrix), ANU-1601 (matrix), ANU-1602 (matrix), ANU-1607A (coral), and ANU-1607 (matrix) must be interpreted accordingly.

Only three beach-rocks were dated. Two contained *Tridacna* valves (ANU-1386, ANU-1581) on the surface, which were prised out, cut and examined in the usual manner. The third (ANU-1596) was a bulk sample; thin section examination indicated the presence of acicular aragonite cement. In this case no attempt was made to separate allochems and cement.

Dated samples from limestone rocks included 6 corals, 12 tridacnids, 4 matrix cements and 1 bulk calcarenite.

3.3. *Sediments*

Samples of loose sediments from individual horizons and sediment units comprised three types: sand (17 samples), coral fragments (4 samples) and mud (1 sample). The last, a fibrous mud, was submitted in bulk to the Radiocarbon Laboratory (ANU-1480) where rootlets and fibres were separated from the organic mud. Age determinations were made on the organic carbon of the fibrous material (ANU-1480A) and the mud fines (ANU-1480B). Clay sands were sieved at $\frac{1}{2} \phi$ intervals and a split of the total detritus falling between medium to very coarse sand (2.0 to -1.0ϕ units) was submitted for bulk age determination. Thin section examination

indicated a variety of skeletal constituents, mainly Foraminifera, *Halimeda*, other calcareous algae, and molluscan and coral fragments, the proportion of each constituent varying between samples. In a number of instances secondary material was present in intraskeletal voids and chambers, but not in sufficient quantities to affect significantly the validity of ages.

Four samples of sandy-gravels from reef islands were dated. Between 5 and 15 stick coral fragments in the -1.0 to -4.0ϕ size range were selected from each sample and physically cleaned of surface contaminants. Interior void sediment and borehole linings were not removed; but such contaminants were estimated to compose less than 3% of total sample mass.

3.4. *Drill core samples*

Nine samples recovered from the shallow coring on Bewick and Stapleton were radiocarbon dated. Of the six samples from Bewick, five were coral fragments and one was a biomicrite. ANU-1283, 1284 and 1395 were non-recrystallized corals with a high aragonite content. ANU-1281 and 1282 were clearly recrystallized samples in which the primary aragonite of the coral specimens had been converted to calcite. Similar modification is suggested by the low Mg calcite content of the biomicrite (ANU-1280).

Only three dates were obtained from the Stapleton core. Two of these were on samples of high aragonite content, while one, a reef calcerenite fragment possibly containing coralline algae, had a high magnesium calcite content (ANU-1664). The other samples were coral fragments (ANU-1721) and loose carbonate sand (ANU-1663).

3.5. *Living specimens*

At this stage dating has been restricted to *Halimeda*, a calcified green algae growing on reef flats of many islands. Both the organic carbon fraction (living plant tissue) and the inorganic carbonate plates have been dated (ANU-1272A, 1272B, ANU-1273A, 1273B).

4. MINERALOGICAL EXAMINATION

Corals and tridacnids build skeletons of aragonite. Thus detection of calcite serves as a guide to the degree of post-death contamination resulting from either recrystallization of the original skeleton, or the presence of calcitic cement or sediment. However, contamination by secondary aragonite cannot be gauged by this technique, hence the need for microscopic examination. Percentages of aragonite and calcite were determined for most of the samples submitted for radiocarbon dating. In the case of bulk carbonate sands, all of which possessed a mixed constituent composition, the proportion of aragonite and calcite reflects the relative abundance of aragonitic and calcitic organisms and the presence of calcite is not diagnostic of contamination. The calcite phase was also determined, because separation of low and high magnesium calcite is important in evaluating environments in which cementation and recrystallization occur. Sample validity is not affected by the presence of non-carbonate minerals, but these were determined as a matter of routine.

4.1. *Infrared quantification of calcite and aragonite*

Infrared spectrophotometry was used to analyse carbonate minerals present in a sample. The following methods were adopted to calculate quantities of calcite and aragonite.

A carbonate aliquot of 10–50 g was crushed by hand to pass 35-mesh. A 0.25 g aliquot if this

was reduced in a rotomill for 8 min with one agate ball and 2 ml isopropanol, the latter acting as a mechanical buffer to reduce the likelihood of any aragonite being converted to calcite during grinding. The resulting 'milk' was diluted with ethanol and vacuum-sucked through a 5 μm sieve and desiccated with phosphorus pentoxide for 24 h. After this, 20.0 mg of desiccated carbonate was mixed with 1.0 g desiccated potassium bromide for 1 min in the rotomill and pressed into a 30 mm disk in a vacuum die taken quickly up to 196 MPa, and retained at that pressure for a minute.

Up to this point, standards and unknown samples must be treated in exactly the same manner, including grinding technique to ensure duplication of artificially prepared grain sizes. This must be done because the behaviour of the peaks is dependent on grain size duplication. Without grain size similarity, results will be erroneous. Using the above methods, no mineral segregation due to differences in hardness between calcite and aragonite was detected, nor was there a grinding or pressure induced conversion of aragonite into calcite.

Measurements were taken with a Unicam SP1000 at 4 cm/min scan, using pure potassium bromide as reference. Aragonite absorbs at wavenumbers of 694, 709, 860, 1078 and calcite at 709 and 880. By using pure standard minerals, the unknowns are quantified by measuring the peak height at 694 and adjusting that linearly to a predetermined constant value for 860/880 twins. That is to say, if the carbonate mixture is low in one component (up to 20%), either calcite or aragonite, then one of these peaks is zero. For low calcite values the 880 peak is zero; for low aragonite values the 860 peak is zero. For all other combinations, both peaks will be measurable and must be summed to account for the total energy emanation due to both carbonates. It is this summed height that becomes the common reference between all samples. This also corrects for carbonate concentration variations due to non-carbonate impurities which, if present in the sample, reduce the effective sample mass. The accuracy which is $\pm 2\%$ is unaffected by variations in magnesium contents and crystallinity.

4.2. X-ray diffraction determination of Mg calcite phase

The calcite phase quantified by infrared spectrophotometry was identified by X-ray diffraction. The following techniques, which basically follow standard procedures, were adopted.

A cleaned carbonate aliquot of 70–50 g was crushed by hand to pass 35-mesh; a 250 mg aliquot of crushed carbonate was mixed with 25 mg either NaCl or CaF₂ and reduced in a rotomill (RM 100) for 8 min with one agate ball and 2 ml isopropanol. The resulting 'milk' was air-dried; a 50 mg portion of the dry product was mixed with six drops of acetone and placed on a 4 cm² etched circle on a glass slide and allowed to dry while being gently tapped.

The X-ray work was done with the use of a Philips PM 8000 diffractometer fitted with a Siemens horizontal goniometer having a spinning and oscillation attachment. Nickel-filtered copper radiation and tube constants of 50 kV/35 mA were used throughout. Chart speed was 20 mm/min with scanning speed $\frac{1}{4}^\circ$ 20 P.M., *T/C* 4 s, and range variable 200–400 Hz depending on calcite content.

Fluorite or halite internal references provided a constant check on the accuracy of angle measurement as well as providing correction factors. Fluorite *hkl* (111) reflexion at 3.15 Å† and halite *hkl* (200) at 2.821 Å are conveniently close to pure calcite *hkl* (104) 3.035 Å and its Mg-phases up to dolomite *hkl* (104) at 2.886 Å. One or more sharp peaks are produced depending on how many calcite phases are present. Provided the peaks were large enough to locate

† 1 Å = 10⁻¹⁰ m = 10⁻¹ nm.

accurately, these were converted to atomic percentages Mg in the calcite structure based on the curve of Chave (1952, fig. 1, p. 192).

4.3. Results

A split of most samples selected for radiocarbon dating was analysed by the i.r. and X-ray diffraction methods outlined above. All analyses were carried out by Caldwell. Results are presented in table 1.

TABLE 1. MINERALOGICAL RESULTS, GREAT BARRIER REEF EXPEDITION, 1973

A.N.U. code	aragonite (%)	calcite (%)	MgCO ₃ (mol %)	non-carbonates (%)	sample type
1207	96	4	n.a.	t	C
1208	92	8	n.a.	t	C
1280	2	94	2	6	BM
1281	0	100	0	0	C
1282	0	99	n.a.	1	C
1283	90	10	n.a.	0	C
1284	99	1	n.a.	0	C
1285	99	0	0	1	C
1286	98	2	0	0	T
1287	100	0	0	0	C
1380	95	5	1	0	C
1381	29	68	8	3	M
1382	99	1	0	0	T
1383	98	2	0	0	T
1384	99	0	0	1	C
1385	99	1	0	0	C
1386	96	4	0	0	T
1387	50	49	n.a.	1	S
1388	100	0	0	0	C
1389	98	2	0	0	T
1390	98	2	1	0	C
1391	99	1	0	0	T
1392	98	2	0	0	T
1393	97	3	0	0	C
1394	100	0	0	0	C
1395	37	56	3	7	C
1410	62	38	n.a.	0	S
1411	98	2	0	0	T
1412	59	41	n.a.	0	S
1413	98	2	0	0	T
1414	49	51	n.a.	0	S
1475	99	1	n.a.	t	T
1476	100	0	0	0	T
1477	100	0	0	0	T
1478	90	10	n.a.	0	T
1479	100	0	0	0	C
1554	53	47	13	t	S
1555	58	40	3	2	S
1556	62	35	3	3	S
1557	51	48	13	1	S
1558	57	42	9	1	S
1559	50	50	13	t	S
1560	63	36	13	t	S
1591	97	3	0	0	T
1592	100	0	0	0	T
1593	92	8	9	t	C
1594	94	4	9	2	C
1595	99	0	0	1	C

TABLE 1 (*cont.*)

A.N.U. code	aragonite (%)	calcite (%)	MgCO ₃ (mol %)	non-carbonates (%)	sample type
1596	36	63	13	1	B
1597	59	41	15	0	S
1598	92	8	11	0	C
1599	96	2	13	2	C
1600	1	95	3	4	C
1601	15	80	25	5	M
1602	16	80	13	4	M
1603	97	3	3	t	C
1604	97	3	3	0	T
1605	98	2	13	t	C
1606	68	32	9	t	S
1607	38	53	13	9	C/M
1608	97	3	3	0	T
1609	98	2	0	0	T
1639	96	3	13	1	C
1640	95	2	0	3	T
1641	32	68	15	0	S
1642	52	48	13	0	S
1643	21	79	13	0	S
1663	48	52	7	0	S
1664	5	95	13	0	R
1721	70	30	13	0	C

Sample types: C, coral; T, *Tridacna*; M, matrix cement; B, beach-rock; S, sand; BM, biomicrite; R, reef calcarenite; n.a., not available; t, trace.

These results, together with thin section analysis, show that post-depositional contamination of dated samples was minimal, except in a few instances. Of the 19 tridacnid samples, calcite ranged from 0 to 4% and magnesium calcite (low) was detected in only two samples (ANU-1604 and 1608). Minimal post-death contamination was indicated, likewise for the reef and island corals which had calcite values up to 5%, being zero in seven samples. Calcite was generally pure; the low magnesium phase was identified in three samples and high magnesium phase in another three.

However, a number of samples possessed calcite values in excess of 5% (e.g. ANU-1208, 1280, 1281, 1282, 1283, 1395, 1593, 1598, 1600, 1607, 1721) and this must be taken into account in interpreting the dates. Many of these samples contained aggregates of a number of coral specimens either from shingle ramparts (ANU-1593, 1598) or rampart-rocks (ANU-1208, 1607) or in drill core (ANU-1281, 1282). The presence of high magnesium calcite in some cases suggests contamination. Hand specimens and thin section analysis shows that contamination in rampart environment results from the presence of matrix cements in rock corals and secondary carbonate deposition or intrusion in the interior of rampart corals, and not recrystallization of the original skeletons, except in the case of ANU-1600 and deeper drill core specimens from Bewick (e.g. ANU-1281). Sample ANU-1600 comprised a number of coral fragments collected from the surface of an old coral shingle ridge at West Hope Island. Although in hand specimen the corals (mainly *Acropora*) appeared similar to those on adjacent ridges, calcite–aragonite determinations showed the presence of an abnormally large amount of calcite (33% in a split of the dated sample and 95% in another sample from the same locality) of the low magnesium phase. Thin section and s.e.m. examination of stick corals from the same unit indicated post-death contamination

by both the presence of intraskeletal void deposits (minor) and recrystallization (major). The radiocarbon age reported here is therefore not considered a valid age for the death of coral.

Separation of matrix and skeletal components proved difficult in some of the rampart-rocks (see § 3.2). The presence of aragonite (15–29%) in high magnesium cement samples (ANU-1381, 1601, 1602) may reflect the occurrence of precipitated aragonite. However, it is unlikely that all coral and other aragonitic skeletal particles incorporated in the matrix were removed.

Regrettably, the effect the observed degree of contamination has on the validity of the radiocarbon ages cannot be quantified. Nevertheless, mineralogical and microscope examination suggests that the great bulk of skeletal, rock and sediment sample ages are valid. Of the groups of samples listed in table 1 it is believed that of the surface samples only ANU-1600 gives an unreliable age, although some others should be used with caution. Drill core dates beyond 30 000 a B.P. on recrystallized material should be considered as minimum ages only. The last interglacial (*ca.* 120 000 a B.P.) is a more likely age for coral growth (Thom *et al.* 1978, this volume), but until unrecrystallized corals can be found this assumption cannot be tested, for example by uranium series dating.

5. RADIOCARBON AGE DETERMINATIONS

5.1. *Pretreatment in the Radiocarbon Laboratory*

Selection of samples, based on stratigraphic and geomorphologic criteria and physical pretreatment (see § 3) was carried out by the collector in consultation with the ^{14}C laboratory. Hence samples considered for ^{14}C age determinations were dated by the A.N.U. Radiocarbon Laboratory *as submitted*, without any further physical or chemical pretreatment.

5.2. *Method of radiocarbon age determination*

All results listed here were produced at the A.N.U. Radiocarbon Dating Laboratory. The low level liquid scintillation counting techniques used were described by Polach & Stipp (1967) and Polach (1969, 1974). However, it cannot and should not be taken for granted that errors of measurement, as expressed by the statistical error term associated with the results, fully expresses the range of possible laboratory errors. Indeed, proof of correlation and cross-checking on an international basis as well as duplicate pair agreement analysis and long term stability, such as given by Polach (1972), ought to be sought by the discriminating user wishing to evaluate the validity of the radiocarbon ages produced. The standard used for dating is the A.N.U. sucrose contemporary radiocarbon dating standard, a secondary standard whose ^{14}C activity with respect to the international standard N.B.S. oxalic acid, has been carefully evaluated. All ages are reported with respect to 0.95 oxalic acid as reference standard and are in conventional radiocarbon years B.P. (see below).

5.3. *Calculation of ^{14}C ages for the Great Barrier Reef samples*

In this paper all radiocarbon ages are expressed as Conventional Radiocarbon Ages B.P. (Olsson 1970). This means that the age was calculated relative to 95% of the activity of the National Bureau of Standards (N.B.S.) oxalic acid normalized for isotopic fractionation to $\delta^{13}\text{C} = -19.0\text{‰}$ (editorial statement in *Radiocarbon* 3, 1961) with respect to the $^{13}\text{C}/^{12}\text{C}$ ratio of a marine standard, PDB, a Cretaceous belemnite, *Belemnitella americana* from the Pee Dee formation of South Carolina (Craig 1957). Further, these conventional radiocarbon ages were

calculated using Libby ^{14}C half-life of 5568; they were not corrected for secular variations of the $^{14}\text{C}/^{12}\text{C}$ ratio, but were corrected for $^{13}\text{C}/^{12}\text{C}$ isotopic fractionation of the sample.

The normal procedures for calculating ^{14}C ages have been published by Callow, Baker & Hassall (1965) and Polach (1969, 1976) and can be presented, somewhat simplified, as follows:

The activity of the sample is expressed as a per mille ($\%$) ratio of the standard:

$$d_{14\text{C}} = 10^3 \left(\frac{A_{\text{sample}}}{0.95A_{\text{oxal}}} - 1 \right), \quad (1)$$

where A_{sample} is the statistically averaged activity of the sample from which the natural background count rate was subtracted, and A_{oxal} is the activity, in 1950, of N.B.S. oxalic acid corrected for background and isotopic fractionation; 95% of A_{oxal} is assumed to be equal to the activity of terrestrial plants (more precisely wood) in 1950.

Variation in the isotopic composition of the samples, caused by observed natural $^{13}\text{C}/^{12}\text{C}$ isotopic fractionation processes in nature (Rafter 1955) is corrected by normalizing the $d_{14\text{C}}$ activity to the value which it would have been if the sample measured had been wood. The average values for terrestrial plants (wood) is taken to be $\delta^{13}\text{C} = -25\%$ with respect to PDB (cf. tabulation of mean $\delta^{13}\text{C}$, relative to PDB, of materials used for radiocarbon dating in Polach (1969, fig. 5, p. 6; 1976, fig. 4, p. 268) and Olsson & Osadebe (1974, fig. 1, p. 141)).

$$D_{14\text{C}} = d_{14\text{C}} - 2(\delta^{13}\text{C} + 25) (1 + 10^{-3}d_{14\text{C}}). \quad (2)$$

(The annotation $D_{14\text{C}}$ has been used to denote the relative ^{14}C activity corrected for $^{13}\text{C}/^{12}\text{C}$ isotopic fractionation ($\delta^{13}\text{C}$), but not age corrected, secular variation corrected or industrial effect corrected.)

Then, by using the half-life of 5568 years the conventional ^{14}C age B.P. (a_c) is obtained from:

$$a_c = -\{8033 \ln (1 + 10^{-3}D_{14\text{C}})\}, \quad (3)$$

where 8033 is the *mean life* derived from $5568/\ln 2$.

6. VALIDITY OF ^{14}C AGE DETERMINATIONS

In order to evaluate further the validity of the ^{14}C ages, the following effects have to be considered.

6.1. *Isotopic fractionation effect*

The isotopic composition of carbon found in nature is *ca.* 98.9% ^{12}C , 1.1% ^{13}C and $1 \times 10^{-10}\%$ ^{14}C . Of these, ^{12}C and ^{13}C are non-radioactive. The isotopic composition of carbon-bearing compounds in nature varies, and isotopic fractionation is one of the factors responsible for this variation. While all carbon isotopes follow the same chemical reaction pathways, the rate at which they do so is related to their respective mass differences. Craig (1953) was the first to point out that there is a need to allow for the effect of carbon isotopic fractionation in nature by applying a correction to radiocarbon dates based on mass spectrometric measurement of the stable ^{13}C and ^{12}C isotopes. Lerman (1972) and Olsson & Osadebe (1974) have discussed and presented the total evidence available including references to early work in great detail, and Polach (1969, 1976) has presented in graphical form the observed variations. The stable isotopic composition of ^{13}C and ^{12}C is expressed as a ratio, $^{13}\text{C}/^{12}\text{C}$ of the

sample (R) and its millesimal ($\%$) deviation ($\delta^{13}\text{C}$) from the $^{13}\text{C}/^{12}\text{C}$ ratio of a standard (R_0)[†], by following the equation

$$10^3 \left(\frac{R - R_0}{R_0} \right) = \delta^{13}\text{C} = 10^3 \left[\frac{R}{R_0} - 1 \right]. \quad (4)$$

The way in which this $\delta^{13}\text{C}$ correction factor enters our $^{14}\text{C}/^{12}\text{C}$ ratio measurement, our enrichment or depletion with respect to oxalic standard, is shown in equation (2). However, a further explanation may be appropriate. According to Craig (1954), '... the enrichment of C^{14} in a given compound should be almost exactly twice that of C^{13} in both equilibrium and rate reaction isotopic effects'. This works out in radiocarbon dating in the following way: for a 10% change in the $\delta^{13}\text{C}$ value we must expect a 20% change in the $d_{14}\text{C}$ value. Given that a 1% change in $d_{14}\text{C}$ throughout the age range represents a change of *ca.* 80 years and taking the extremes of $\delta^{13}\text{C}$ variations in nature into account, a marine shell at $\delta^{13}\text{C} = +3\%$ and terrestrial plant remains (peat) at $\delta^{13}\text{C} = -30\%$ with respect to PDB have a natural difference in ^{13}C of 33% and consequently in ^{14}C a difference of 66%, giving an apparent age discrepancy of some 545 years for these materials living at the same time.

The importance of the dating error due to fractionation, which may be much larger than the ^{14}C counting standard deviation, is the primary reason why some radiocarbon dating laboratories have made mass spectrometric measurements of $\delta^{13}\text{C}$ an integral part of their work (e.g. the British Museum, New Zealand, Gröningen, Uppsala; see *Radiocarbon*) and why we at A.N.U. have since 1968 (Polach, Golson, Lovering & Stipp 1968) either measured or estimated the $\delta^{13}\text{C}$ value and applied a fractionation correction accordingly. Thus, for the study reported here, a value of $\delta^{13}\text{C} = 0 \pm 2\%$ with respect to PDB has been assumed to represent the mean of the natural $^{13}\text{C}/^{12}\text{C}$ ratio variations of samples in this marine environment. This, as a first approximation, is adequate considering the context in which the results are going to be used as the approximate age errors involved can be shown to be *ca.* 20 years; ± 20 years is then the expected order of magnitude of variation in age due to natural $\delta^{13}\text{C}$ variations of the Great Barrier Reef samples.

Nevertheless, it is our intention in the near future to determine the precise $^{13}\text{C}/^{12}\text{C}$ ratio of all samples reported here, not only to derive a more correct radiometric age, but also to evaluate some geochemical aspects of carbonate deposition, mobility and exchange.

6.2. Environmental effects

The ^{14}C concentration of a sample is affected by the environment in which the material to be dated lived or was deposited. The inference in radiocarbon dating is that during its biological life (or at time of deposition) the ^{14}C concentration of the sample was equal to that of the radiocarbon *modern* reference standard.

The ocean and marine species living in the ocean are unevenly depleted in ^{14}C with respect to the land environment. For example, Rafter, Jansen, Lockerbie & Trotter (1972) report a value for cockle shells (*Protothaca crassitesta* (Deshayes)) collected in October 1955 (I.N.S. R.42) of $D_{14}\text{C} = -54 \pm 5\%$ [‡], a value which appeared to be in equilibrium with the Makara (N.Z.)

[†] A few early $\delta^{13}\text{C}$ values may be found reported with respect to wood, air, limestone, etc. We at A.N.U., together with the majority of radiocarbon laboratories, report $\delta^{13}\text{C}$ variations exclusively with respect to PDB.

[‡] Note that Rafter further corrects this value for industrially produced CO_2 dilution which, because it is ^{14}C free, caused a depletion of ^{14}C activity in both the terrestrial and marine environments. Thus Rafter *et al.* (1972) obtained an industrial effect corrected value, $D_{14}\text{C} = -40\%$ for the cockle shell, which gives thus an apparent industrial effect corrected age of 330 a. This is the value used by Rafter as his marine environment age correction.

surface seawater D_{14C} values at that time. This value gives an apparent age for the cockle shell of 446 ± 40 a B.P., which is in excellent agreement with an average apparent age of 450 ± 40 a for marine shells from the Norwegian coast (Mangerud 1972), and the average apparent age of 450 ± 35 a for marine shells from the Australian east and south coast (Gillespie & Polach 1976). Contrast this with the higher southern latitudes, particularly where there is a much greater variation due to deep water upwelling. Rafter (1968) reports $D_{14C} = -269\text{‰}$, which is equivalent to an apparent age of surface waters of 2520 a B.P. Nevertheless, based on the study by Gillespie & Polach (1976), one can assume a relatively stable surface layer of ocean waters between latitudes 40° N and 40° S, with an apparent ^{14}C age of 450 ± 35 a, a value which we suggest be subtracted from the conventional radiocarbon ages reported here. Should one wish or have need to establish a chronology relative to the Christian calendar, this environmental correction has to be applied before looking up the secular variation correction factors in one of the many published tables (see, for example, Damon, Long & Wallick 1972). We have not made any of these corrections in this paper.

The assumption of uniform mixing of the marine environment at the Great Barrier Reef will be further investigated by us, as we have collected a cross section of living coral and other marine life and plant species, of which the *Halimeda* (ANU-1272 and 1273, table 2) constitute a preview. These results confirm, considering the overall increase of ^{14}C due to atom bomb testing, that our first assumptions of uniform mixing are essentially correct.

TABLE 2. RADIOCARBON RESULTS, GREAT BARRIER REEF EXPEDITION, 1973

A.N.U. code	$\delta^{13}C \pm \sigma$ (‰)	$d_{14C} \pm \sigma$ (‰)	$D_{14C} \pm \sigma$ (‰)	% modern $\pm \sigma$	conventional radiocarbon years B.P. \pm error
1207	0.0 ± 2.0	-426.0 ± 4.4	-454.7 ± 4.7	54.5 ± 0.5	4870 ± 70
1208	0.0 ± 2.0	-260.5 ± 5.8	-297.5 ± 6.2	70.3 ± 0.6	2840 ± 70
1272A	-4.0 ± 2.0	$+178.7 \pm 6.4$	$+129.2 \pm 7.7$	112.9 ± 0.8	>modern
1272B	-24.0 ± 2.0	$+175.5 \pm 7.1$	$+173.1 \pm 8.5$	117.3 ± 0.9	>modern
1273A	-4.0 ± 2.0	$+171.3 \pm 4.9$	$+122.2 \pm 6.6$	112.2 ± 0.7	>modern
1273B	-24.0 ± 2.0	$+117.5 \pm 7.1$	$+115.3 \pm 8.4$	111.5 ± 0.8	>modern
1280	0.0 ± 2.0	-975.9 ± 3.2	-977.1 ± 3.1	2.3 ± 0.3	>30350 \pm 1150
1281	0.0 ± 2.0	-985.5 ± 3.9	-986.2 ± 3.7	1.4 ± 0.4	>34400 ⁺²⁵⁰⁰ ₋₁₉₀₀
1282	0.0 ± 2.0	-989.8 ± 2.4	-990.4 ± 2.3	1.0 ± 0.2	>37300 ⁺²²⁰⁰ ₋₁₇₀₀
1283	0.0 ± 2.0	-537.5 ± 6.9	-560.6 ± 6.8	43.9 ± 0.7	6610 ± 130
1284	0.0 ± 2.0	-555.0 ± 7.1	-577.3 ± 6.9	42.3 ± 0.7	6920 ± 130
1285	0.0 ± 2.0	-335.7 ± 6.6	-368.9 ± 6.8	63.1 ± 0.7	3700 ± 90
1286	0.0 ± 2.0	-448.5 ± 7.7	-514.0 ± 7.6	48.6 ± 0.8	5800 ± 130
1287	0.0 ± 2.0	-492.0 ± 10.1	-517.4 ± 9.9	48.3 ± 1.0	5850 ± 170
1380	0.0 ± 2.0	-340.1 ± 8.6	-373.1 ± 8.6	62.7 ± 0.9	3750 ± 110
1381	0.0 ± 2.0	-205.6 ± 7.3	-245.4 ± 7.6	75.5 ± 0.8	2260 ± 80
1382	0.0 ± 2.0	-280.0 ± 5.1	-316.0 ± 5.6	68.4 ± 0.6	3050 ± 70
1383	0.0 ± 2.0	-322.1 ± 5.8	-356.0 ± 6.2	64.4 ± 0.6	3540 ± 80
1384	0.0 ± 2.0	-216.7 ± 6.2	-255.9 ± 6.7	74.4 ± 0.7	2370 ± 70
1385	0.0 ± 2.0	-28.4 ± 6.9	-77.0 ± 7.6	92.3 ± 0.8	640 ± 70
1386	0.0 ± 2.0	-182.6 ± 6.4	-223.5 ± 6.9	77.7 ± 0.7	2030 ± 70
1387	0.0 ± 2.0	-270.5 ± 6.1	-307.0 ± 6.5	69.3 ± 0.7	2950 ± 80
1388	0.0 ± 2.0	-303.8 ± 6.0	-338.6 ± 6.3	66.1 ± 0.6	3320 ± 80
1389	0.0 ± 2.0	-11.9 ± 7.1	-61.3 ± 7.9	93.9 ± 0.8	510 ± 70
1390	0.0 ± 2.0	-47.8 ± 6.8	-95.5 ± 7.5	90.5 ± 0.8	810 ± 70
1391	0.0 ± 2.0	-132.0 ± 6.6	-175.4 ± 7.1	82.5 ± 0.7	1550 ± 70
1392	0.0 ± 2.0	-124.4 ± 6.7	-168.2 ± 7.2	83.2 ± 0.7	1480 ± 70
1393	0.0 ± 2.0	-27.9 ± 6.9	-76.5 ± 7.6	92.4 ± 0.8	640 ± 70

TABLE 2 (cont.)

A.N.U. code	$\delta^{13}\text{C} \pm \sigma$ (‰)	$d_{14}\text{C} \pm \sigma$ (‰)	$D_{14}\text{C} \pm \sigma$ (‰)	% modern $\pm \sigma$	conventional radiocarbon years B.P. \pm error
1394	0.0 \pm 2.0	-384.5 \pm 6.7	-415.3 \pm 6.8	58.5 \pm 0.7	4310 \pm 100
1395	0.0 \pm 2.0	-524.0 \pm 6.5	-547.8 \pm 6.5	45.2 \pm 0.7	6380 \pm 120
1410	0.0 \pm 2.0	-295.9 \pm 6.0	-331.2 \pm 6.3	66.9 \pm 0.6	3230 \pm 80
1411	0.0 \pm 2.0	-79.1 \pm 5.1	-125.2 \pm 6.1	87.5 \pm 0.6	1070 \pm 60
1412	0.0 \pm 2.0	-277.1 \pm 5.9	-313.2 \pm 6.3	68.7 \pm 0.6	3020 \pm 70
1413	0.0 \pm 2.0	-323.6 \pm 5.8	-357.4 \pm 6.1	64.3 \pm 0.6	3550 \pm 80
1414	0.0 \pm 2.0	-295.0 \pm 5.8	-330.2 \pm 6.2	67.0 \pm 0.6	3220 \pm 80
1475	0.0 \pm 2.0	-122.3 \pm 6.9	-166.2 \pm 7.4	83.4 \pm 0.7	1460 \pm 70
1476	0.0 \pm 2.0	-13.1 \pm 7.4	-62.5 \pm 8.1	93.8 \pm 0.8	520 \pm 70
1477	0.0 \pm 2.0	-118.5 \pm 7.1	-162.6 \pm 7.6	83.7 \pm 0.8	1430 \pm 70
1478	0.0 \pm 2.0	-392.9 \pm 6.1	-423.3 \pm 6.3	57.7 \pm 0.6	4420 \pm 90
1479	0.0 \pm 2.0	-428.4 \pm 6.0	-457.0 \pm 6.1	54.3 \pm 0.6	4910 \pm 90
1480A	-24.0 \pm 2.0	-126.7 \pm 7.7	-128.4 \pm 8.4	87.2 \pm 0.8	1100 \pm 80
1480B	-24.0 \pm 2.0	-239.4 \pm 15.1	-240.9 \pm 15.4	75.9 \pm 1.5	2210 \pm 170
1553	0.0 \pm 2.0	-305.9 \pm 5.7	-340.6 \pm 6.2	65.9 \pm 0.6	3350 \pm 80
1554	0.0 \pm 2.0	-331.1 \pm 5.6	-364.5 \pm 6.0	63.5 \pm 0.6	3640 \pm 70
1555	0.0 \pm 2.0	-296.8 \pm 5.7	-331.9 \pm 6.2	66.8 \pm 0.6	3240 \pm 70
1556	0.0 \pm 2.0	-212.5 \pm 6.0	-251.9 \pm 6.5	74.8 \pm 0.6	2330 \pm 70
1557	0.0 \pm 2.0	-233.6 \pm 6.0	-272.0 \pm 6.4	72.8 \pm 0.6	2550 \pm 70
1558	0.0 \pm 2.0	-352.1 \pm 5.6	-384.5 \pm 6.0	61.6 \pm 0.6	3900 \pm 80
1559	0.0 \pm 2.0	-389.5 \pm 5.5	-420.0 \pm 5.7	58.0 \pm 0.6	4380 \pm 80
1560	0.0 \pm 2.0	-271.3 \pm 6.0	-307.8 \pm 6.3	69.2 \pm 0.6	2960 \pm 70
1591	0.0 \pm 2.0	-90.9 \pm 6.2	-136.4 \pm 7.0	86.4 \pm 0.7	1180 \pm 65
1592	0.0 \pm 2.0	-311.9 \pm 5.6	-346.3 \pm 6.0	65.4 \pm 0.6	3420 \pm 75
1593	0.0 \pm 2.0	-47.4 \pm 6.5	-95.1 \pm 7.2	90.5 \pm 0.7	800 \pm 70
1594	0.0 \pm 2.0	-47.3 \pm 6.5	-95.0 \pm 7.2	90.5 \pm 0.7	800 \pm 60
1595	0.0 \pm 2.0	-304.7 \pm 5.7	-339.4 \pm 6.1	66.1 \pm 0.6	3330 \pm 80
1596	0.0 \pm 2.0	-244.8 \pm 5.9	-282.6 \pm 6.3	71.8 \pm 0.6	2670 \pm 70
1597	0.0 \pm 2.0	-227.4 \pm 6.1	-266.0 \pm 6.5	73.4 \pm 0.6	2480 \pm 70
1598	0.0 \pm 2.0	-253.7 \pm 6.6	-291.0 \pm 6.9	70.9 \pm 0.7	2760 \pm 80
1599	0.0 \pm 2.0	-94.7 \pm 6.7	-140.0 \pm 7.4	86.0 \pm 0.7	1210 \pm 70
1600	0.0 \pm 2.0	-52.5 \pm 6.8	-99.9 \pm 7.5	90.0 \pm 0.8	(?) > 850 \pm 70
1601	0.0 \pm 2.0	+3.7 \pm 9.3	-46.5 \pm 9.7	95.4 \pm 1.0	380 \pm 80
1602	0.0 \pm 2.0	-214.4 \pm 5.9	-253.7 \pm 6.5	74.6 \pm 0.6	2350 \pm 70
1603	0.0 \pm 2.0	-506.1 \pm 5.3	-530.8 \pm 5.4	46.9 \pm 0.5	6080 \pm 90
1604	0.0 \pm 2.0	-304.1 \pm 5.7	-338.9 \pm 6.1	66.1 \pm 0.6	3320 \pm 70
1605	0.0 \pm 2.0	-221.2 \pm 6.2	-260.2 \pm 6.7	74.0 \pm 0.7	2420 \pm 70
1606	0.0 \pm 2.0	-212.8 \pm 6.3	-252.2 \pm 6.7	74.8 \pm 0.7	2330 \pm 70
1607A	0.0 \pm 2.0	-40.0 \pm 6.7	-88.0 \pm 7.5	91.2 \pm 0.8	740 \pm 70
1607B	0.0 \pm 2.0	-18.3 \pm 12.2	-67.4 \pm 12.2	93.3 \pm 1.2	560 \pm 110
1608	0.0 \pm 2.0	-42.2 \pm 6.4	-90.1 \pm 7.2	91.0 \pm 0.7	760 \pm 65
1609	0.0 \pm 2.0	-183.3 \pm 6.4	-224.2 \pm 6.9	77.6 \pm 0.7	2040 \pm 70
1639	0.0 \pm 2.0	-433.8 \pm 5.2	-462.1 \pm 5.5	53.8 \pm 0.6	4980 \pm 80
1639R	0.0 \pm 2.0	-432.2 \pm 4.9	-460.6 \pm 5.2	53.9 \pm 0.5	4960 \pm 80
1640	0.0 \pm 2.0	-520.3 \pm 5.0	-544.3 \pm 5.1	45.6 \pm 0.5	6310 \pm 90
1641	0.0 \pm 2.0	-198.3 \pm 6.2	-238.4 \pm 6.7	76.2 \pm 0.7	2190 \pm 70
1642	0.0 \pm 2.0	-300.3 \pm 6.0	-335.3 \pm 6.3	66.5 \pm 0.6	3280 \pm 80
1643	0.0 \pm 2.0	-274.5 \pm 6.0	-310.8 \pm 6.4	68.9 \pm 0.6	2990 \pm 80
1663	0.0 \pm 2.0	-287.0 \pm 6.1	-322.6 \pm 6.5	67.7 \pm 0.7	3130 \pm 80
1664	0.0 \pm 2.0	-289.8 \pm 7.5	-325.3 \pm 7.7	67.5 \pm 0.8	3160 \pm 90
1721	0.0 \pm 2.0	-453.0 \pm 8.3	-480.3 \pm 8.5	52.0 \pm 0.8	5260 \pm 130

6.3. Post-depositional and contamination effect

It is also important to evaluate whether the sample submitted for radiocarbon dating remains unaffected by possible isotopic and other chemical processes causing an addition or exchange with extraneous carbon of different ^{14}C activity.

The standard technique used in radiocarbon laboratories is to wash shell samples to be dated in a weak acid, thus attempting to remove the outer part, the one most likely to be contaminated by secondary carbonate or, in other circumstances, by solution and ionic exchange of carbonate forms. No one has shown that acid treatment removes the carbonate from shells in a definite time sequence. In coral, with its multifaceted internal labyrinth, such treatment is certainly not appropriate. Dating the inner and outer portions of shells, as suggested by Olsson & Blake (1962) with the assumption that agreement is proof of validity, is also often undertaken. However, inner and outer portions often yield no ^{14}C concentration differences, suggesting no isotope replacement (cf. Shotton, Blundell & Williams 1970); yet such agreement would also be expected even if a sample has fully recrystallized in an open system where exchange of secondary carbon of different ^{14}C activity is possible (Chappell & Polach 1972†). Thus dating of fractions, in absence of X-ray diffraction data, may not constitute proof of validity of the ^{14}C age determination.

6.4. Summary and conclusions

The foregoing multidisciplinary approach to the problem of obtaining valid radiocarbon dates can be summarized as follows:

- (a) careful selection of dating material according to visual and stratigraphic criteria;
- (b) removal of the part most likely to be contaminated; in molluscs, physical removal of the outer part and in corals physical removal of all parts showing secondary carbonate (calcite or aragonite) deposition or intrusion;
- (c) mineralogical analysis to determine aragonite/calcite content and Mg calcite phase;
- (d) thin section microscopic analysis;
- (e) $^{13}\text{C}/^{12}\text{C}$ ratio determinations;
- (f) $^{14}\text{C}/^{12}\text{C}$ ratio (age) determinations and evaluation of their validity.

Thus where it can be shown that post-depositional exchange and contamination of samples dated for the Great Barrier Reef project were minimal (or their magnitude could be evaluated) the conventional ^{14}C ages B.P. reported here may be considered as valid.

7. DESCRIPTION OF SAMPLES

The following list has been arranged on an island-by-island basis starting from Raine Island in the north and continuing southward to Low Isles. Each entry includes the island or reef name and location, Australian National University Radiocarbon Dating Laboratory code number, Expedition sample number, and radiocarbon date in conventional ^{14}C years. These data are followed by brief sample descriptions, locations and collector's name.

Raine Island ($11^{\circ} 35' \text{ S}; 144^{\circ} 02' \text{ E}$)

ANU-1591 RAI-172 1180 ± 65 a B.P.

Tridacna shell from surface of beach-rock near beacon at eastern end of Raine Island. Beach-rock overlain by guano rock. Coll. D. Hopley.

† Chappell & Polach (1972) have shown that two modes of carbonate recrystallization are possible: the open system, allowing exchange with secondary carbon, and the closed system, where recrystallization occurs involving only the carbonate species already locked into the material. They have further shown that the $^{13}\text{C}/^{12}\text{C}$ isotopic ratio, even coupled with calcite/aragonite ratio determinations, is not a good guide towards establishing whether secondary contamination has occurred during recrystallization. Indeed, microscopic thin section examination of crystalline forms involved in the two processes appears to be a more reliable guide of evaluating the validity of ^{14}C ages. Thus demonstration of recrystallization does not prove that exchange of secondary carbonate has occurred unless it is accompanied by the coarse sparry calcite crystalline structure of the open system.

Fisher Island

ANU-1640 FIS-228 6310 ± 90 a B.P.

Tridacna shell resting on fossil microatolls in growth position at base of cemented coral shingle platform on southern side of Fisher Island. Sample from 0.6 m below platform surface. Coll. D. Hopley.

Stainer Reef (13° 57' S:143° 50' E)

ANU-1639 STA-106 4980 ± 80 a B.P.

ANU-1639R STA-106 4960 ± 80 a B.P.

Coral *Favites abdita* from area of fossil microatolls in growth position which emerge 5 cm above sandy reef flat, some 250 m ESE of Stainer sand cay. ANU-1639R is a repeat determination of the same specimen. Coll. D. Hopley.

Stapleton Reef (14° 20' S:144° 50' E)

ANU-1663 CORE-1-1 3130 ± 80 a B.P.

ANU-1664 CORE-1-2-3 3160 ± 90 a B.P.

ANU-1721 CORE-1-2-3 5260 ± 130 a B.P.

Drill core series: ANU-1663 was collected from a depth of 8.5 m below h.w.s.t. and consists of loose calcareous sand; ANU-1664 is a reef calcarenite fragment from ca. 10 m below h.w.s.t.; ANU-1721 is an unidentified coral fragment (possibly *Galaxa* sp.) from 13 m below h.w.s.t. Coll. B. G. Thom.

ANU-1555 ST-6D 3240 ± 70 a B.P.

Moderately well sorted clean coarse calcareous sand. Bulk sample from depth of 55–80 cm beneath grassed surface of 2.3 m high sand cliff exposure on south side of Stapleton cay some 100 m from its western end. Coll. R. McLean.

Bewick Reef (14° 28' S:144° 47' E)

ANU-1387 BE-5B 2950 ± 80 a B.P.

Moderately sorted medium sized calcareous sand. Bulk sample of partly weathered creamy-brown sand from soil pit horizon 25–40 cm beneath grassed surface on eastern slope of easternmost ridge on Bewick sand cay, some 25 m west of cay–mangrove margin. Coll. R. McLean.

ANU-1559 BE-1A 4380 ± 80 a B.P.

Moderately sorted medium sized calcareous sand. Bulk sample of greyish weathered sand from depth of 15 cm beneath surface at crest of westernmost ridge on Bewick sand cay. Located some 25 m southeast of drill hole site. Coll. R. McLean.

ANU-1386 BE-D1 2030 ± 70 a B.P.

Tridacna shell from surface of high beach-rock outcrop on north shore of Bewick sand cay close to drill site. Base of tridacnid valve was lightly cemented to beach-rock surface, which had *Sesuvium* and algae growing on it. Beach-rock outcrop was fronted by mangroves and backed by a sandy slope covered with grasses and *Pemphis*. Coll. R. McLean.

ANU-1280 CORE 2-15-4 > 30 350 ± 1150 a B.P.

ANU-1281 CORE 2-13-2 > 34 400⁺²⁵⁰⁰₋₁₉₀₀ a B.P.

ANU-1282 CORE 2-9-1 > 37 300⁺²²⁰⁰₋₁₇₀₀ a B.P.

ANU-1283 CORE 2-7-1 6610 ± 130 a B.P.

ANU-1284	CORE 2-3-5	6920 ± 130 a B.P.
ANU-1395	CORE 2-4-1	6380 ± 120 a B.P.

Drill core series: samples ANU-1280, 1281 and 1282 were recovered below a disconformity in the drill core, as indicated by recrystallization of biomicrite (1280) and corals (1281, 1282) to low magnesium calcite. The ^{14}C results must be considered as *minimum ages* only. Samples ANU-1283, 1284 and 1395 are aragonite rich coral fragments (possibly *Porites* sp.). Sample 1283 was recovered from below the disconformity. The sample's location is believed to be a product of cave-in during drilling. The disconformity occurs at *ca.* 4 m below l.w.s.t., with sample ANU-1395 located at the contact. Coll. B. G. Thom.

ANU-1272A	% modern = 112.9 ± 0.8
ANU-1272B	% modern = 117.3 ± 0.9
ANU-1273A	% modern = 112.2 ± 0.7
ANU-1273B	% modern = 111.5 ± 0.8

Contemporary environment ^{14}C levels check: two samples of calcium carbonate secreting algae ANU-1272, 1273 were collected to check contemporary ocean bicarbonate ^{14}C levels. Both the organic carbon (fraction B, assumed $\delta^{13}\text{C} = -24\text{‰}$ PDB) and the inorganic carbonate (fraction A, assumed $\delta^{13}\text{C} = -4\text{‰}$ PDB) were dated. Results indicate the predictable increase in ^{14}C activity due to atom bomb testing and confirm that it is appropriate to subtract 450 ± 35 a (Gillespie & Polach 1976) from the conventional radiocarbon years B.P. (as given with all results reported here) in order to allow for pre-atom bomb (i.e. pre-1950) depletion of ^{14}C in the Coral Sea water mass. Coll. H. Polach.

ANU-1385	BE-D10B	640 ± 70 a B.P.
----------	---------	-----------------

Coral *Platygyra* from loosely cemented coral shingle deposit with basset edge – lower platform morphology on northeastern side of Bewick reefs, traverse no. 1. Outcrop located 100 m landward of reef edge, between inner edge of reef flat and 1.5 m high scarp of high platform which forms seaward side of gravel cay. Coll. R. McLean.

ANU-1208	BE-D11	2840 ± 70 a B.P.
ANU-1609	BE-D111	2040 ± 70 a B.P.

Coral (ANU-1208) and *Tridacna* (ANU-1609) from strongly cemented rampart rock of high platform 20 m southwest of ANU-1385 on traverse no. 1, northeastern part of gravel cay on Bewick reef. Both samples were firmly embedded in the corroded platform surface. Coll. R. McLean.

ANU-1608	BE-115	760 ± 65 a B.P.
----------	--------	-----------------

Tridacna shell from surface of the innermost of three shingle ramparts on traverse no. 2, on eastern side of Bewick reef. The sample was exposed on a grassy slope which abutted the mangrove swamp 100 m west of the gravel cay's active beach. Coll. R. McLean.

Ingram–Beanley Reef (14° 25' S; 144° 55' E)

ANU-1393	IN-D1	640 ± 70 a B.P.
ANU-1394	IN-D2	4310 ± 100 a B.P.

Coral *Porites* from separate reef blocks of boulder tract on northern side of reef, 300 m northeast of Ingram Island. ANU-1393 was collected from the largest single coral head of the boulder tract. Its top was 2.2 m above reef flat level and was located 80 m from the reef edge. ANU-1394 was the innermost solitary coral head, 1.5 m high, surrounded by sandy reef flat 130 m from the reef edge. Coll. R. McLean.

ANU-1642	IN-3	3280 ± 80 a B.P.
ANU-1410	IN-6B	3230 ± 80 a B.P.

Two calcareous sand samples from Ingram Island. Both bulk samples were moderately well sorted coarse sand collected from 2–5 cm beneath the cay surface. ANU-1642 was located at 50 m from the beachline in the centre of a low cusped promontory on the western side of the island. ANU-1410 came from the highest part of the cay, 120 m northwest of its southeastern end. Coll. R. McLean.

Watson Island (14° 29' S:144° 56' E)

ANU-1389	WN-103	510 ± 70 a B.P.
ANU-1390	WN-105	810 ± 70 a B.P.
ANU-1391	WN-109	1550 ± 70 a B.P.
ANU-1392	WN-110	1480 ± 70 a B.P.

A series of samples taken from the outer rampart to innermost fossil ridge across the southeastern end of Watson, a coral shingle island. All samples were loose surface shingle. ANU-1389 was a *Tridacna* shell from the highest part of the contemporary outer rampart. ANU-1390, a coral favid from the top of lower platform. ANU-1391 and ANU-1392 were tridacnids from the penultimate and innermost ridges respectively on the northern side of the island proper abutting a mangrove swamp. Coll. R. McLean.

Howick Cay (14° 30' S:144° 57' E)

ANU-1605	HCK-D3	2420 ± 70 a B.P.
----------	--------	------------------

Coral *Diploastrea heliopora* from series of massive coral heads cemented into high calcarenite platform on southwestern corner of Howick Cay. Coll. R. McLean.

Houghton Reef (14° 32' S:144° 58' E)

ANU-1287	HON-D7A	5850 ± 170 a B.P.
----------	---------	-------------------

Faviid coral head from area of fossil microatolls in mangrove swamp north-central part of reef, 220 m south of reef edge and 400 m east of sand cay. Coll. R. McLean.

ANU-1595	HON-D6	3330 ± 80 a B.P.
ANU-1596	HON-D5	2670 ± 70 a B.P.
ANU-1413	HON-D3	3550 ± 80 a B.P.

Vertical sequence from high calcarenite platform at western end of Houghton sand cay. ANU-1595, faviid coral head beneath calcarenite at juncture of inner edge of reef flat and rocky scarp. Coll. R. McLean. ANU-1596, calcarenite bulk sample containing calcareous sand and cement. Coll. R. McLean. ANU-1413, *Tridacna* shell from 20 cm thick cemented stick coral layer overlying calcarenite. Coll. H. Polach.

Coquet Island (14° 32' S:145° E)

ANU-1411	CQT-D5	1070 ± 60 a B.P.
----------	--------	------------------

Tridacna shell from surface of highest part of broad coral shingle ridge 80 m southeast of navigation light on main cay. Coll. R. McLean.

Leggatt Reef (14° 33' S:144° 51' E)

ANU-1556	LEG-105	2330 ± 70 a B.P.
----------	---------	------------------

Moderately sorted coarse calcareous sand. Bulk sample from surface of high flat in centre of sand cay. Coll. R. McLean.

ANU-1286 LEG-D4A 5800 ± 130 a B.P.

Tridacna shell in growth position among high microatoll field exposed in area of fallen mangrove immediately east of sand cay and south of sand spit. Coll. R. McLean.

Hampton Reef (14° 33' S: 144° 52' E)

ANU-1207 HAM-D15 4870 ± 70 a B.P.

Faviid coral in growth position from area of high microatolls covered by *Rhizophora* mangroves and mangrove mud. Coll. B. G. Thom.

East Pethebridge Island (14° 45' S: 145° 05' E)

ANU-1384 EPE-D1A 2370 ± 70 a B.P.

Faviid coral in growth position from area of high microatolls in gap between cemented shingle platforms at southwestern end of island. Coll. R. McLean.

Turtle I Island (14° 44' S: 145° 13' E)

ANU-1597 TON-103 2480 ± 70 a B.P.

ANU-1598 TON-107 2760 ± 80 a B.P.

Calcareous sandy-gravel from soil pit 1 on lower terrace northwestern side of island 25 m south of beach line. Bulk samples. ANU-1597 at depth of 25–35 cm and ANU-1598 at depth of 85–100 cm. Coll. R. McLean.

ANU-1388 TON-111 3320 ± 80 a B.P.

Coral *Acropora* fragments from soil pit 2 on high shingle ridge 25 m south of pit 1. Sample from depth of 40–55 cm. Coll. R. McLean.

ANU-1477 TURT-028 1430 ± 70 a B.P.

ANU-1478 TURT-024 4420 ± 90 a B.P.

Tridacna shells from separate outcrops of cemented rampart rock between mangrove swamp and moat on southwestern part of reef. ANU-1477 from outer platform 10 cm below upper level of cementation. ANU-1478 from inner platform 24 cm below surface. Coll. D. Hopley.

ANU-1480A TURT-030 1100 ± 80 a B.P.

ANU-1480B TURT-030 2210 ± 170 a B.P.

ANU-1479 TURT-027 4910 ± 90 a B.P.

Samples from shallow borehole in small enclosed depression between two old coral shingle ridges at southeastern end of main island. Depression is occupied by living mangroves and floored by a 0.6 m thick deposit of black fibrous mud which overlies at least 0.3 m of coral shingle. ANU-1480, fibrous mud, was separated into two fractions: 1480A, coarse fibres, rootlets and bark retained of sieve meshes 10 and 25; and 1480B, fine grey clayey sediment which passed through 44 mesh and contained black organics but not fibres. ANU-1479, coral *Cyphastrea* from shingle containing corals and shells beneath mangrove mud horizon. Coll. D. Hopley and A. Bloom.

Nymph Island (14° 38' S: 145° 15' E)

ANU-1285 NY-D4A 3700 ± 90 a B.P.

Faviid coral in growth position from high microatoll field exposed in drainage outlet to large pool in southwest portion of island. Coll. R. McLean.

ANU-1592 NYM-033 3420 ± 75 a B.P.

ANU-1383 NY-D6 3540 ± 80 a B.P.

ANU-1602 NY-D5 2350 ± 70 a B.P.

Samples from high platform of cemented rampart rock located 100 m southeast of pond outlet in southwest part of reef. ANU-1592, *Tridacna* shell from cemented stick shingle layer at top of high platform. Coll. D. Hopley. ANU-1383, *Tridacna* shell firmly embedded in rock, 0.5 m from base of scarp. ANU-1602, calcitic cement from 30 cm beneath platform surface. Coll. R. McLean.

ANU-1476 NYM-035 520 ± 70 a B.P.

Tridacna shell from cemented lower platform at southeastern end of small shingle island on southwestern part of reef. Sample embedded in rock 15 cm below upper surface of platform. Coll. D. Hopley.

Eagle Reef (14° 25' S:145° 23' E)

ANU-1560 EAG-101 2960 ± 70 a B.P.

Well sorted coarse calcareous sand. Bulk sample from main sand ridge in centre of northern side of cay, 50 m from beach. Coll. R. McLean.

Two Isles (15° 03' S:145° 27' E)

ANU-1558 TWO-198 3900 ± 80 a B.P.

Well sorted coarse calcareous sand. Bulk sample from depth of 45–60 cm in soil pit located beneath forest on backslope of high sand ridge 60 m from beach in north central part of main cay. Coll. R. McLean.

Low Wooded Island (15° 06' S:145° 25' E)

ANU-1594 LWI-D7 800 ± 60 a B.P.

Coral *Porites* cf. *lobata* microatoll in growth position at junction of inner edge of contemporary shingle rampart and moat 190 m southeast of aeroplane wreckage at western end of island. Coll. R. McLean.

ANU-1603 LWI-010 6080 ± 90 a B.P.

Coral *Platygyra lamellina* microatoll passing beneath lower cemented shingle platform at junction with moat in south central part of island. Coll. D. Hopley.

ANU-1604 LWI-D2 3320 ± 70 a B.P.

Tridacna shell from surface of high cemented platform outcropping at southwestern end of enclosed pool 80 m west of beach on eastern side of island. Coll. R. McLean.

Three Isles (15° 06' S:145° 27' E)

ANU-1641 THR-105 2190 ± 70 a B.P.

Moderately well sorted coarse calcareous sand. Bulk sample from depth of 20 cm in soil pit on lower terrace, 75 m west of beacon at western end of sand cay. Coll. R. McLean.

ANU-1554 THR-112 3640 ± 70 a B.P.

Well sorted coarse calcareous sand. Bulk sample from depth of 60 cm in soil pit in shallow basin in high ridge 40 m east of beacon at western end of cay. Coll. R. McLean.

ANU-1553 THR-119 3350 ± 80 a B.P.

ANU-1414 THR-122 3220 ± 80 a B.P.

Well sorted coarse calcareous sand from two horizons exposed in 2.5 m high cliff at eastern end of cay. Bulk samples at 43–68 cm (ANU-1553) and 100–160 cm (ANU-1414) below top of cliff. Coll. R. McLean.

ANU-1475 THR-017 1460 ± 70 a B.P.

Tridacna shell cemented 20 cm beneath surface of lower platform at exposed edge above moat on southeastern side of Third Island. Coll. D. Hopley.

ANU-1380 THR-D31 3750 ± 110 a B.P.

ANU-1381 THR-D32 2260 ± 80 a B.P.

ANU-1382 THR-D1 3050 ± 70 a B.P.

Sequence from high rampart rock platform outcropping in central eastern part of mangrove-shingle cay. ANU-1380, coral *Pavona* firmly cemented in basal facies of platform. ANU-1381, calcitic matrix surrounding ANU-1380. ANU-1382, *Tridacna* shell from loosely cemented 20 cm thick coral shingle veneer on upper surface of high platform. Coll. R. McLean.

East Hope Island (15° 45' S:145° 28' E)

ANU-1412 EHO-110 3020 ± 70 a B.P.

ANU-1643 EHO-116 2990 ± 80 a B.P.

Moderately well sorted coarse calcareous sand. Bulk samples from 79–86 cm horizon in soil pit 1 located on highest ridge in centre of cay (ANU-1412) and 30 cm depth in pit 3 located on low sand terrace, 15 m from beach line at eastern end of cay (ANU-1643). Coll. R. McLean.

West Hope Island (15° 45' S:145° 27' E)

ANU-1599 WHO-105 1210 ± 70 a B.P.

Coral *Acropora* fragments from 40 cm beneath surface of easternmost ridge in shingle ridge sequence found on northeastern side of island. This ridge is being cut back exposing a 0.5 m high scarp immediately behind the present beach. Coll. R. McLean.

ANU-1600 WHO-108 (?) > 850 ± 70 a B.P.

Coral *Acropora* fragments from surface of highest shingle ridge in sequence 75 m from eastern beach and 25 m from mangrove swamp to west. Sample possessed large quantity of post-death contaminants. Coll. R. McLean.

Pickersgill Cay (15° 52' S:145° 33' E)

ANU-1606 PIK-101 2330 ± 70 a B.P.

Well sorted coarse calcareous sand. Bulk sample from top of unvegetated sand bank. Coll. R. McLean.

Low Isles (16° 24' S:145° 33' E)

ANU-1607A LOW-D18 740 ± 70 a B.P.

ANU-1607B LOW-D18 560 ± 110 a B.P.

ANU-1601 LOW-D18C 380 ± 80 a B.P.

Samples from cemented coral shingle deposit forming bassett edges on inner edge of reef flat 250 m northwest of Green Ant Island on eastern side of reef. ANU-1607A, coral *Acropora*. ANU-1607B and ANU-1601 were high magnesium calcite matrix. Coll. R. McLean.

ANU-1593 LOW-108 800 ± 70 a B.P.

Tridacna shell from surface of inner shingle rampart at southern end of mangrove-shingle island on eastern side of reef. Coll. R. McLean.

ANU-1557 LOW-106 2550 ± 70 a B.P.

Moderately sorted very coarse calcareous sand. Bulk sample from sand cay surface 75 m west of lighthouse. Coll. R. McLean.

We wish to thank J. Head and J. Gower from the A.N.U. Radiocarbon Dating Laboratory for their technical assistance throughout this project; Dr J. Veron, Australian Institute of Marine Science, Townsville; and Dr D. R. Stoddart, University of Cambridge, for his leadership throughout the Expedition.

REFERENCES (Polach *et al.*)

- Callow, W. J., Baker, M. J. & Hassall, G. I. 1965 *Radiocarbon* **7**, 156–161.
- Chappell, J. & Polach, H. A. 1972 *Quat. Res.* **2**, 244–252.
- Chave, K. E. 1952 *J. Geol.* **60**, 190–192.
- Craig, H. 1953 *Geochim. cosmochim. Acta* **3**, 53–92.
- Craig, H. 1954 *J. Geol.* **62**, 115–149.
- Craig, H. 1957 *Geochim. cosmochim. Acta* **12**, 133–140.
- Damon, P. E., Long, A. & Wallick, E. I. 1972 In *Proceedings of 8th International Conference on Radiocarbon Dating*, Lower Hutt, New Zealand, pp. 44–59. Wellington: Royal Society of New Zealand.
- Gillespie, R. & Polach, H. A. 1976 In *Proceedings, 5th International Conference on Radiocarbon Dating*, University of California, Los Angeles and San Diego, July 1976. (In the press.)
- Lerman, J. C. 1972 In *Proceedings of 8th International Conference on Radiocarbon Dating*, Lower Hutt, New Zealand, pp. 612–624. Wellington: Royal Society of New Zealand.
- McLean, R. F. & Stoddart, D. R. 1978 *Phil. Trans. R. Soc. Lond. A* **291**, 101–117 (this volume).
- Mangerud, J. 1972 *Boreas* **1**, 263–273.
- Olsson, I. U. 1970 In *Radiocarbon variations and absolute chronology*, p. 17. Stockholm: Almqvist & Wiksell.
- Olsson, I. U. & Blake, W. Jr 1962 *Saetr. norsk geog. Tidsskr. XVIII*: **12**, 1–18.
- Olsson, I. U. & Osadebe, F. A. N. 1974 *Boreas* **3**, 139–146.
- Polach, H. A. 1969 *Atomic Energy in Australia* **12**(3), 21–28.
- Polach, H. A. 1972 In *Proceedings of 8th International Conference on Radiocarbon Dating*, Lower Hutt, New Zealand, pp. 688–717. Wellington: Royal Society of New Zealand.
- Polach, H. A. 1974 In *Liquid scintillation counting: recent developments* (eds P. E. Stanley & B. A. Scoggins), pp. 153–171. New York: Academic Press.
- Polach, H. A. 1976 In *Proceedings of Symposium on Scientific Methods of Research in the Study of Ancient Chinese Bronzes and Southeast Asian Metal and other Archaeological Methods* (ed. N. Barnard), pp. 255–298. Canberra: Department Far Eastern History, A.N.U.
- Polach, H. A. & Stipp, J. J. 1967 *Int. J. appl. Radiat. Isotopes* **18**, 359–364.
- Polach, H. A., Golson, J., Lovering, J. F. & Stipp, J. J. 1968 *Radiocarbon* **10**, 179–199.
- Rafter, T. A. 1955 *N.Z. J. Sci. Technol.* **B 37**, 20–38.
- Rafter, T. A. 1968 *N.Z. J. Sci.* **11**, 551–589.
- Rafter, T. A., Jansen, H. S., Lockerbie, L. & Trotter, M. M. 1972 In *Proceedings of 8th International Conference on Radiocarbon Dating*, Lower Hutt, New Zealand, pp. 625–675. Wellington: Royal Society of New Zealand.
- Scoffin, T. & McLean, R. F. 1978 *Phil. Trans. R. Soc. Lond. A* **291**, 119–138 (this volume).
- Shotton, F. W., Blundell, D. J. & Williams, R. E. G. 1970 *Radiocarbon* **12**, 385–399.
- Thom, B. G. 1978 In *Coral reefs: research methods* (eds D. R. Stoddart & R. E. Johannes). Monographs on Oceanographic Methodology, Unesco.
- Thom, B. G., Orme, G. R. & Polach, H. A. 1978 *Phil. Trans. R. Soc. Lond. A* **291**, 37–54 (this volume).