the inconsistencies are most likely due to chemical alteration.

The Th^{230} method of dating coral appears to be valid for samples obeying the seven criteria specified. It would appear that assignment of ages in this set of samples is limited to samples less than 150,000 years, either by the analytical precision now available or by the fact that truly unaltered samples have not been used.

Because of the considerable scatter in the age-corrected U^{234}:U^{238} values, the validity of ages based on the disappearance of the excess U^{234} remains to be demonstrated. The He:U dating method, discussed by Fanale and Schaeffer (*6*), should be very valuable in future evaluations of both the Th^{230}:U^{234} and the U^{234}:U^{238} methods.

The presence of coral-bearing horizons aged 120,000 years in the lagoons of mid-Pacific atolls strongly suggests that sea level and climate at that time resembled modern conditions. The absence of horizons aged between 5000 and 100,000 years suggests (*2*) that the ocean level was considerably lower during this period than at present, causing a hiatus in coral deposition. The temptation to use this information to establish the ages of one or more of the Pleistocene interglacials must be subdued pending more absolute age information.

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Uranium-Series Dating of Corals and Oolites from Bahaman and Florida Key Limestones

Abstract. *Samples of fossil coral and oolite from marine formations of the Bahamas and the Florida Keys have been analyzed for their concentrations of uranium and thorium isotopes. Ages calculated from the ratio* Th^{230} : U^{234} *clearly indicate periods of marine limestone formation at about 85,000, 130,000, and 190,000 years ago, implying that the surface of the ocean was then close to its present level.*

The uranium-series method of dating, as applied to Pleistocene coral from mid-Pacific atolls, has been described in some detail (*1*); we refer the reader to that paper for discussion of the method and the establishment of criteria used in judging the reliability of these ages. These criteria may be summarized as follows: (i) the samples should show no evidence of recrystallization; (ii) the uranium content should ordinarily be about 2.7 parts per million (ppm); (iii) the activity ratio of Th^{230} to Th^{232} should exceed 20; (iv) the activity ratio of Ra^{226} to Th^{230} should be 1.0 ± .1; (v) the activity ratio of U^{234} to U^{238}, corrected for decay of U^{234}, should be 1.15 ± .02; (vi) the ages should agree with independent age estimates; and (vii) the ages should be consistent with stratigraphic information.

Table 1 contains data on recent corals in the Florida Keys. The U^{234} : U^{238} ratio is about that found in sea water; scatter of the data on the U^{234} : U^{238} ratio probably results from analytical uncertainty. The concentrations of Th^{232} and Th^{230} are low, as one would expect from their low concentrations in sea water (*2*). Similar uranium concentrations and ratios of Ra^{226} : U^{238}, Th^{232} : U^{238}, Th^{230} : U^{238}, and U^{234} : U^{238} have been reported for currently forming oolite (*3, 4*).

Table 2 summarizes results of tests on samples of fossil oolite and coral from the Florida Keys and the Bahamas; this work complements that of Osmond *et al.* (*4*).

Newell (*5*) finds Bahaman deposits representing at least two distinct sea-level stands near that of present-day sea level in formations above a well-consolidated basement of marine limestone. Two formations of eolianite dunes of marine oolite are separated by a weathered zone. Terraces, veneered with beach deposits containing coral and molluscs, are cut into the lower formation.

The samples from the Berry Islands, Bahamas, for which ages have been determined, include two corals. One sample, from the basement rock, shows an age of 200,000 years. The other sample, the younger, is from one of the terraces, and gives an age of 80,000 years. Both samples satisfy the criteria, and the ages are supported by He-U ages determined by Fanale and Schaeffer (*6*).

Two samples of the dune rock have been analyzed, one from the younger eolianite (717M) and one from the older (717N); both contain a large fraction of calcite. However, the other criteria are satisfied for the younger dune, and the age of 140,000 years may be judged reliable. The other sample may be judged unreliable on the basis of its low Ra^{226} : Th^{230} ratio and high initial U^{234} : U^{238} ratio. This sample, while forming a reasonable stratigraphic sequence with the other samples, cannot be assigned ages based on the Th^{230} : U^{234} ratio at present with any certainty.

The oolite sample from Bimini appears to have a reliable age of 155,000 years, but its position in the stratigraphic sequence, as defined in the case of the samples from the Berry Islands, is unknown.

We feel it appropriate to comment on the event being dated by the oolite rock.

The oolite grains themselves are formed by inorganic precipitation in ocean water (*7*). The grains are exposed by a lowering of the sea level, swept into dunes by the wind, and rapidly cemented under subaerial conditions. The cement appears normally to be calcite; the simplest assumption is that the cementation process does not add or remove any uranium or daughter products from the oolite. The age is thus that of the formation of the oolite grains and not of the dune itself.

In the Florida Keys the Miami oolite overlies a thick bed of coral known as the Key Largo limestone (*8*). Both coral and oolite have been collected. These samples, numbered 801 (*9*), are duplicates of samples reported separately by Osmond *et al.* (*4*). Comparison of the analytical data from the two laboratories shows excellent agreement. The ages of these samples are about the same as those reported by Osmond *et al.* (*4*).

Other samples of Miami oolite and coral (765, 744) were collected (*10*); two of them, 774-A and 774-B, from the Key Largo formation have ages much greater than the others, but may be judged unreliable because they are almost completely recrystallized. The great ages can be explained by preferential loss of uranium relative to thorium during recrystallization. The apparent equilibrium of Ra^{226} and Th^{230} would indicate that this process took place more than 5000 years ago.

The one sample of Miami oolite that may be judged reliable has an age of 120,000 years, again in agreement with ages reported by Osmond *et al.* (*4*); the other is considered unreliable because of the disagreement between Th^{230} and Ra^{226} and the high $\mathrm{U}^{234}:\mathrm{U}^{238}$ ratio.

Table 1. Uranium-series isotope data for samples of recent coral from the Florida Keys.

Lamont No.	Calcite (%)	U (ppm)	Activity ratio			
			$\mathrm{U}^{234}:\mathrm{U}^{238}$	$\mathrm{Th}^{232}:\mathrm{U}^{234}$	$\mathrm{Th}^{230}:\mathrm{U}^{234}$	$\mathrm{Ra}^{226}:\mathrm{U}^{234}$
765B	3	2.36 ± 0.04	1.19 ± 0.02	0.001	0.002	0.043 ± 0.004
765C	<1	2.65 ± .03	1.17 ± .01	< .001	.005	.09 ± .01
801A		2.79 ± .05	1.14 ± .03	.002	.002	.027 ± .003
801B		2.95 ± .05	1.13 ± .04			.082 ± .008

Both samples appear to have a higher than normal uranium content. The age of 120,000 years suggests that this formation is not different in age from the Key Largo limestone. The coral sample from Windley Key, Florida, gives an age of 95,000 years, somewhat less than the other samples and perhaps reflecting a different time of limestone formation.

Previous attempts to date coralline material from the Florida Keys were made by Rosholt and Antal (*11*); they measured Pa^{231} and Th^{230}. This material was obviously badly altered, having lost uranium preferentially to thorium and protactinium. The calculated ages, based on the $\mathrm{Pa}^{231}:\mathrm{Th}^{230}$ ratio, have little meaning because this ratio is not a simple function of sample age, but also depends on the time and magnitude of uranium loss. Their conclusion that the dating method has little promise does not appear warranted, because of the poor state of preservation of their samples.

The data are currently too few to draw many firm conclusions about sea-level stands in Florida and the Bahamas. However, the banks definitely appear to have been submerged at various times during the interval between 150,000 and 80,000 years ago, with no evidence of any submergence between 80,000 and 4000 years ago. Definition of separate intervals will require furth-

Table 2. Results of tests on samples of fossil oolite and coral from the Florida Keys and the Bahamas.

Lamont No.	Material, description	Calcite (%)	U^{238} (ppm)	$\mathrm{U}^{234}:\mathrm{U}^{238}$	$\mathrm{Th}^{232}:\mathrm{U}^{234}$	$\mathrm{Th}^{230}:\mathrm{U}^{234}$	$\mathrm{Ra}^{226}:\mathrm{Th}^{230}$	Th^{230} age (10^3 yrs)	$(\mathrm{U}^{234}:\mathrm{U}^{238})_0$
	Berry Islands, Bahamas (collected by Newell)								
717F	Marine terrace cut in eolianite II (coral)	< 1	2.87 ± 0.04	1.14 ± 0.02	<0.001	.56 ± 0.04	1.00 ± 0.06	80 ± 8	1.17 ± 0.03
717M	Eolianite II (oolite)	25	2.39 ± .03	1.12 ± .01	< .005	.74 ± .04	1.00 ± .06	140 ± 20	1.18 ± .02
717N	Eolianite I (oolite)	30	2.48 ± .08	1.13 ± .04	< .025	.80 ± .04	.64 ± .07	165 ± 20	1.21 ± .04
717A	Platform rock (coral)	10	2.67 ± .04	1.11 ± .02	< .001	.85 ± .04	.86 ± .09	195 ± 20	1.18 ± .03
	South Bimini Island, Bahamas (collected by Broecker)								
712E	Dredged from quarry (oolite)	< 1	2.73 ± .06	1.10 ± .01	< .007	.77 ± .03	.81 ± .10	155 ± 10	1.15 ± .02
	Florida Keys (744 and 765 series collected by Hoffmeister; 801 series by Osmond)								
744D	Miami oolite, Key West (oolite)	2	4.41 ± .08	1.10 ± .03	< .02	.59 ± .03	.60 ± .11	90 ± 9	1.21 ± .04
744C	Miami oolite, Key West (oolite)	2	3.90 ± .03	1.09 ± .03	< .005	.68 ± .04	.91 ± .12	120 ± 10	1.13 ± .04
765A	Key Largo limestone, Windley Key (coral)	4	2.66 ± .03	1.12 ± .01	.003	.61 ± .03	1.11 ± .09	95 ± 9	1.16 ± .02
801D	Key Largo limestone (coral)		2.98 ± .03	1.09 ± .02	< .005	.71 ± .04	.98 ± .09	130 ± 20	1.13 ± .03
801F	Key Largo limestone (coral)	< 1	3.01 ± .03	1.09 ± .01	< .001	.71 ± .03	.80 ± .08	130 ± 15	1.13 ± .02
801C	Key Largo limestone (coral)	3	2.59 ± .05	1.10 ± .02	< .001	.75 ± .03	.86 ± .09	140 ± 15	1.16 ± .02
744B	Key Largo limestone (coral)	90	1.56 ± .03	1.11 ± .02	.03	.90 ± .03	.98 ± .10	230 ± 30	1.21 ± .03
744A	Key Largo limestone (coral)	100	1.34 ± .04	1.14 ± .02	< .02	1.10 ± .04	.90 ± .10	>300	>1.32

er measurements with increased precision. This technique has definite promise as an aid in studying the late-Pleistocene history of the Florida Keys and the Bahaman Banks.

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Tritium and Phosphorus-32 in High-Resolution Autoradiography

Abstract. *The sensitivity of monolayers of Ilford L-4 nuclear emulsion to β^--particles is approximately 0.20 grain per particle emitted for H^3, and 0.025 grain per particle for P^{32}. The sensitivity for thick layers is 1.3 grains per tritium β^--particle emitted within the emulsion. In electron microscopic autoradiographs the maximum resolution is approximately 0.1 micron for H^3 and 0.3 micron for P^{32}.*

The energy of the charged particle emitted by a radioactive isotope affects both the resolution and the sensitivity of autoradiographs (*1*). As the energy of a β^--particle increases, so does its range in matter, thereby decreasing the resolution. Simultaneously, the rate of energy loss at the beginning of its trajectory is decreased, down to a minimum value obtained for approximately 1-Mev particles, and the particle has a lower chance of exposing a photographic grain near the source.

Tritium, one of the isotopes most commonly used in autoradiography, emits a β^--particle of 18-kev maximum energy, the lowest of any known isotope. It offers, therefore, excellent resolution and sensitivity. The maximum range of the H^3 β^--particle in dry Ilford emulsion is approximately 1.9 μ (corrected for curved path), and its rate of energy loss at the origin of the trajectory is 3.5 kev/μ (*2*). Phosphorus-32, also commonly used, has a β^--particle with a maximum energy of 1.72 Mev. Its maximum range in dry Ilford emulsion is of the order of 2100 μ, over 1000 times longer than tritium, and the rate of energy loss at the origin for the β^--particles of maximum energy is 0.53 kev/μ, almost seven times lower than tritium. Since the maximum ranges of almost all other common isotopes fall within these extremes, it is interesting to compare the sensitivity and resolution which can be achieved with these two isotopes. Thus limits can be established which will be useful in choosing a particular isotope.

The test objects were cells of *Escherichia coli* strain C, grown in M-9 minimal medium (*3*) supplemented with Casamino acids (0.5 g/lit.) and with uridine-H^3 (*4*) for at least seven generations, or in tris-glucose medium (*5*) supplemented with phosphate-free Casamino acids (0.5 g/lit.) (*6*) and with P^{32} (*7*) as inorganic phosphate. The specific activities were adjusted according to the amount of labeling desired. Cell concentrations were determined by means of Petroff-Hausser counter. Such determinations agreed with colony counts within 10 percent. Radioactivity measurements were made on planchets in a flow Geiger counter (*8*) operated with window for P^{32} and without window for H^3 (*9*) or in a scintillation counter (*8*). The efficiency for tritium counting was measured with a standard toluene-H^3 solution (*4*).

Autoradiographs were prepared as described previously (*10*). Ilford L-4 nuclear emulsion was used for both thick and thin emulsion layers. For examination under the light microscope the emulsion was developed for 5 minutes in D-19 at 20°C. For examination with the electron microscope the emulsion was developed for 1 minute at 20°C in the physical developer described by Caro and van Tubergen (*10*).

We first tried to establish the overall sensitivity of Ilford L-4 to β^--particles from tritium. Since our interest in quantitative autoradiography has been mostly with measurements of DNA in bacteria, it was convenient to use a DNA molecule of known molecular weight as a standard. Such a molecule is conveniently provided by the DNA of the bacteriophage lambda (*11*). We have measured, in the electron microscope, the length of this DNA molecule as 17.3 ± 0.6 μ, in agreement with the results of MacHattie and Thomas (*12*). The corresponding molecular weight, 33×10^6, was verified by measuring the thymine content per phage (*11*). Fully labeled phages were produced by infecting, in the presence of labeled thymidine, thymine-requiring *E. coli* cells, themselves previously labeled for seven generations. Thus all the thymine available to the phage was labeled and its specific activity known. Since the ratios of the bases in λ DNA is known (*13*), it is easy to calculate the number of disintegrations per phage.

After purification (*11*) the labeled phages were used to infect a culture of *E. coli* C, chosen because of its simple spherical shape. Infected bacteria, rather than phages, were used to provide a visual marker for the location of the phages on the slide. Ambiguities due to occasional clusters of background grains were thus avoided. Moreover, we were interested in measuring directly the efficiency obtained for DNA in bacteria, and high-resolution autoradiography showed (*14*) that soon after injection the λ DNA enters the bacterial nuclear region.

The average grain count per phage was obtained by fitting the observed grain count distribution over the labeled cells to a Poisson distribution (*15*). This average grain count increased linearly with time of exposure. The rate of increase, for thymidine-H^3 with a specific activity of 8.6 c/mmole, was 0.47 grain day^{-1} phage^{-1}. The calculated rate of emission of β^--particles was 16 per day per phage. The efficiency was thus 41 percent (0.41 grain per β^--particle emitted within a bacterium). The efficiency in terms of particles entering the emulsion was higher than 41 percent, because 50 percent of the β^--particles went toward the glass slide rather than the emul-