Reports

Sea-Level Lowering During the Illinoian Glaciation: Evidence from a Bahama "Blue Hole"

Abstract. *Stalagmites have been recovered from 45 meters below sea level in an underwater karstic cave ("blue hole") near Andros Island in the Bahamas. Uranium series ages, corrected for contamination of the sample by young marine carbonate replacements, show that the speleothem was deposited between 160,000 and 139,000 years before the present. This period corresponds to the Illinoian glacial event and demonstrates that sea level must have been lowered by at least 42 meters (allowing for subsidence) from its present position during this time.*

Worldwide changes in sea level due to variations in the continental ice volume are a well-known characteristic of the Pleistocene epoch. Fossil reef terraces found on tropical coastlines today remain as a legacy of high sea stands that occurred at warm intervals during this period. Uranium series and radiocarbon-dating methods have been used to determine the ages of these formations. Islands known to be tectonically stable, such as those in the Pacific and Indian oceans (*1*), Bermuda and the Florida Keys (*2*), and Oahu, Hawaii (*3*), consistently show an age of 120,000 to 130,000 years before the present (B.P.) for coral terraces lying up to 9 m above modern sea level. This period is taken as the time of the last interglacial maximum, when conditions were somewhat warmer than today. A more complete record of warm events in the Late Pleistocene is preserved in islands that are being uplifted at a rate fast enough to separate individual terraces but slow enough to provide a sufficient period of relatively static sea level for the substantial growth of coral. Two such islands, Barbados and New Guinea, have provided the first well-dated record of sea stands for the last 150,000 years (*4*).

Evidence of low sea stands is relatively scarce because related features are generally submerged at the present time. Submerged shorelines, beach levels, and valley entrenchments can indicate the amount of sea-level lowering, but such features cannot place it precisely on the Pleistocene time scale. Estimates for the maximum lowering of between 130 and 160 m have come from continental shelf terraces off eastern North America (*5*), the presence of littoral shells in cores taken off New Jersey and Argentina (*6*), and a submarine delta surface off the Huon Peninsula, New Guinea (*7*).

Recently, the oxygen isotopic composition of benthic foraminifera in deep-sea sediment cores has been interpreted as a direct measure of the isotopic variation of ocean water, which in turn is a measure of eustatic sea level (*8*). On the basis of a Wisconsin maximum depression of 120 m at 17,000 years B.P., an increase of 0.1 per mil in the oxygen isotopic ratio of foraminifera is equivalent to a decrease of 10 m in sea level. Extrapolation of these data (*8*) gives a lowering of about 145 m at 160,000 years B.P., corresponding to the Illinoian glacial event.

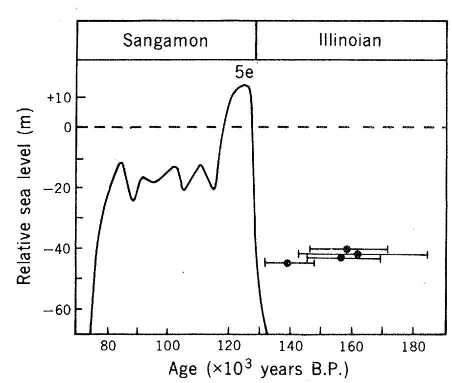

Fig. 1. Paleosea-level curve based on the work of Shackleton and Opdyke (*8*), showing the ages of speleothems that were determined and the inferred minimum depression of sea level.

Stalagmites recovered from submerged caves in Bermuda and the Bahamas have been used as indicators of low sea stand over the periods of 195,000 to 150,000, 120,000 to 100,000, 40,000 to <10,000 years B.P. (*9*), and at 22,000 years B.P. (*10*). However, these samples all grew at a depth of less than 12 m below the present sea level (less than 10 percent of the maximum estimated depression), and so relatively little of the glacial sea-level record can be obtained.

The "blue holes" found in shallow water off the eastern coast of Andros Island in the Bahamas are also thought to be evidence of sea-level lowering in the past. Their similarity to cave and pothole systems found today in continental karst regions suggests that they were formed by subaerial weathering and solutional processes. They consist of subhorizontal passageways and vertical pits extending to more than 100 m below sea level. Benjamin has located more than 100 blue holes in the Bahamas and has explored and mapped more than 60 of them (*11*). They cannot be simply explained in terms of a subaerial karst topography that is rapidly submerging as a result of tectonic processes, because correlations between depth and stratigraphic age in a borehole at Stafford Creek on Andros Island have shown the submergence to be proceeding at only about 0.2 m per 10,000 years (*12*).

Proof of the freshwater origin of blue holes has been given by the discovery of speleothems (*13*) in passageways leading from the bottom of one blue hole in South Bight, Andros Island (see cover photograph) (*11, 14*). Stalagmites up to 6 m long were found in a grotto approximately 45 m below the sea surface. In recent dives, Benjamin recovered five samples of stalagmite from this grotto (samples BH, 76015, 76016, 78032, and 78033). All the samples were already broken off, presumably as a result of visits by other divers since the initial exploration. The samples are thought to be from three stalagmite columns, although their stratigraphic relationship is unknown because none were in situ when collected. Samples 76015 and 76016, although lacking suitable growth layers for orientation, are believed to be the upper and lower sections, respectively, of a single columnar stalagmite. Samples BH, 78032, and 78033 are probably fragments of two other deposits.

The stalagmite sections are between 15 and 25 cm long and 12 to 15 cm in diameter. Each consists of an outer

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Table 1. Results of dating samples BH, 76015, and 76016 without prior removal of traces of aragonitic deposits.

Sample number	Location	U (ppm)	$^{234}U/^{238}U$	$^{230}Th/^{232}Th$	$^{230}Th/^{234}U$	Age ($\times 10^3$ years B.P.) $\pm 1\sigma$ error	Notes
BH-M	Center portion	0.26	0.943	49	0.765	161.6 ± 21.1	
BH-L	Lower portion	0.35	0.987	54	0.691	127.8 ± 8.9	
76015-3	Top of upper (?) block	0.32	1.019	26	0.618	104.1 ± 10.2	
76015-1a	Replicates of base of	0.29	0.993	155	0.678	123.1 ± 9.1	
76015-1b	upper (?) block	0.28	1.016	61	0.666	118.5 ± 9.3	
76016-3	Top of lower (?) block	0.28	1.019	>1000	0.608	101.1 ± 7.5	
76016-4	Middle of lower (?) block	0.31	1.031	81	0.591	96.5 ± 6.8	8 percent yield of U
76016-1a	Replicates of base of	0.26	1.028	70	0.698	128.8 ± 11.6	8 percent yield of Th
76016-1b	lower (?) block		1.031	96		$122.3\ ^{+38.4}_{-27.3}$	$^{231}Pa/^{230}Th$ date
76015-7	Outer aragonitic deposits	1.30	1.143	>1000	0.098	11.1 ± 1.1	5 percent yield of Th

marine deposit surrounding and replacing a central clear calcite core whose thickness ranges from 10 cm to zero where complete replacement has occurred. The calcite cores appear to be single crystal deposits, and intact growth layers can be seen in the larger samples (samples 78032 and 78033). The marine deposit consists of a calcite-aragonite matrix of annelid tubes, fungal filaments, bivalves, bryozoans, and polychaete borings (*15*). In the smaller samples (BH, 76015, and 76016) the calcite core is permeated by polychaete borings, the holes containing small but significant quantities of aragonitic deposits.

We used a pneumatic drill to chip out samples of the calcite core; we then analyzed for isotopes of uranium and thorium according to methods described in (*16*). The radiometric age is determined from the ratios $^{230}Th/^{234}U$ and $^{234}U/^{238}U$ in the speleothem sample. To give reliable age measurements, the sample must satisfy the following criteria. (i) It must remain a closed system after formation with respect to the migration of radionuclides. (ii) There must be no ^{230}Th incorporated at the time of growth. Therefore, the detrital content should be low and the $^{230}Th/^{232}Th$ ratio should be high. (iii) Measured ages must lie in stratigraphic sequence. (iv) Chemical recovery of radionuclides should be high to minimize reagent contamination and memory effects. In general, samples should contain >0.1 part per million (ppm) of uranium.

The first samples that we analyzed generally complied with these requirements (Table 1) except that regular stratigraphic ordering was not always found. The outer aragonitic deposits were significantly younger and richer in uranium than the calcite core (sample 76015-7, Table 1). We therefore thought that the poor stratigraphic ordering of ages was due to the incorporation of minor amounts of these deposits present in the worm tubes that pass through the calcite. To test this hypothesis, we leached crushed samples from two levels of sample 76016 with dilute nitric acid. Biogenic deposits, if present, should dissolve faster than the host calcite. We analyzed each leach fraction radiometrically as usual. Both leaches produced a sequence of increasing dates, but the limiting ages were quite different (Table 2a). Analysis of the magnesium and strontium contents in the younger sequence and comparison with those for pure calcite showed that even the last fraction must have contained significant aragonite and high-magnesium calcite. Extrapolation to the magnesium and strontium values for pure speleothem (Table 2b) suggests an age for sample 76016-9 of about 130,000 years B.P. Presumably sample 76016-5c represents the pure calcite end-member, which is mixed with varying amounts of marine deposit (typified by sample 76015-7) in all other determinations.

To avoid this problem of contamination, we carefully picked pure crystals from a sample of the crushed calcite core. Each crystal was rinsed in dilute acid before its complete dissolution to remove adhering powder. Sample 76016-9 (Table 2b) confirms the higher age of pure calcite from this stalagmite and also confirms that its magnesium and strontium contents fall within the error limits for the pure calcite analysis (these limits include both analytical error and the larger natural variation of trace elements within the sample).

From these results and the older dates from the initial work (presumably corre-

Table 2. Results of two approaches to the elimination of age-biasing marine deposits in speleothem calcite: (a) by progressive acid leaching of crushed calcite samples, with changes in the magnesium and strontium contents used to monitor leaching, and (b) by the analysis of cleaned handpicked calcite crystals. Also included for comparison are the results of magnesium and strontium analyses of spot samples of pure calcite and marine deposits for three of the speleothems (c).

Sample number	U (ppm)	$^{234}U/^{238}U$	$^{230}Th/^{232}Th$	$^{230}Th/^{234}U$	Age ($\times 10^3$ years B.P.) $+ 1\sigma$ error	Mg* (ppm)	Sr† (ppm)
			(a) Leaching experiments				
76016-5A	0.17	0.978	6	0.129	15.0 ± 2.0		
76016-5B	0.20	0.961	13	0.254	31.9 ± 2.6		
76016-5C	0.36	1.023	49	0.767	156.5 ± 11.0		
76016-9A	0.59	1.067	12	0.235	28.9 ± 10.8	9465	1815
76016-9B	0.38	1.030	28	0.527	81.0 ± 8.4	4205	1190
76016-9C	0.31	1.103	38	0.655	115.1 ± 11.0	3505	1100
76016-9D	0.27	1.013	>1000	0.658	115.9 ± 6.3	1955	1050
			(b) Analysis of selected calcite crystals				
76016-9	0.23	1.000	24	0.768	158.3 ± 12.6	1377	1080
78032-5	0.26	0.994	85	0.722	139.2 ± 8.0		
			(c) Analysis of pure calcite				
76016						1280	990
78032						1200	950
BH						2110	1130
			Analysis of marine deposits				
76016						41700	2800
78032						40860	2030
BH						36350	3095

*Error, ± 10 percent. †Error, ± 20 percent.

sponding to the least contaminated samples) we obtain a range of ages from 139,000 to 160,000 years B.P. Although this range lies within the statistical error limits of the individual determinations, it may in fact be real because each sample dated has a separate stratigraphic location and stalagmites of such dimensions usually require a period of at least this duration to develop (*17*).

The maximum estimated tectonic submergence (*12*) of this site in 150,000 years is about 3 m; therefore, sea level was at least 42 m below its present level during this period (Fig. 1). It is likely that a lowering of more than 42 m took place because there has been sufficient time for cave passages to develop and integrate and large speleothems to form. It is tempting to suggest that rising sea level at the end of the Illinoian glaciation may have terminated growth of these stalagmites, but unfortunately the younger (outer) layers of the stalagmites, which might demonstrate this effect, have been totally replaced by marine deposits. Neumann and Moore (*18*) have observed a high sea stand on Andros Island at +6 m above sea level, which correlates with the maximum sea level of the last interglacial (isotopic stage 5e, see Fig. 1). Correcting for tectonic submergence, sea level on the Bahamas platform must have risen at the end of the Illinoian at no less than 3.2 m per 1000 years. Further, deeper dives into these blue holes may allow us to establish a time scale for a large part of glacial sea-level lowering.

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13. Speleothems are the familiar stalagmites and stalactites formed by the loss of carbon dioxide from groundwaters entering a cave, with the concurrent precipitation of calcium carbonate (usually as calcite). Speleothems consisting of clear detritus-free calcite can only have formed under vadose conditions from percolating freshwater.
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Isolation of a Deep-Sea Barophilic Bacterium and Some of Its Growth Characteristics

Abstract. *A bacterium, a spirillum, has been isolated from a deep-sea sample and has been found to grow optimally at about 500 bars and 2° to 4°C. These conditions are similar to those prevailing at the 5700-meter depth from which the sample was collected. The organism grows at these pressures and temperatures with a generation time of between 4 and 13 hours; at atmospheric pressure and 2° to 4°C, the generation time is about 3 to 4 days.*

Barophilic bacteria are those that "grow preferentially or exclusively at high hydrostatic pressures" [(*1*), p. 771]. ZoBell and Morita (*2*) have described some characteristics of an obligately barophilic bacterium that functioned slowly at 700 bars, and they have found other probably barophilic bacteria associated with deep-sea animals. Recent efforts to isolate barophilic bacteria, let alone obligately barophilic ones, have been less successful. Schwarz *et al.* (*3*) and Jannasch and his colleagues (*4, 5*) have found only barotolerant bacteria. We report here the isolation and some growth characteristics of a barophilic deep-sea bacterium.

Amphipods (crustaceans) that had been retrieved alive (*6*) were maintained at deep-sea temperatures and pressures; after they died, deep-sea conditions of temperature (2° to 4°C) and pressure (580 bars) were maintained in the trap for 5 months. During that time autolytic and microbial processes led to the disintegration of the amphipod tissues. We then decompressed and opened the trap and found that it contained clear seawater overlaying a turbid suspension; an examination of this suspension with phase microscopy revealed the presence of bacteria. This suspension was used as the inoculum for the cultivation of bacteria. The deep-sea bacteria in this inoculum could have originated from the exterior of the dead animals (*7*), from the seawater, or from the gut of the amphipods (*8*).

We grew colonies of bacteria at high pressure in silica gel (*9*) containing nutrient medium. The silica-gel medium was inoculated at 2°C and atmospheric pressure, and it gelled within 10 minutes. Test tubes containing the gelled medium were sealed, placed in pressure vessels, and incubated at 570 atm and 2° to 4°C. After 3 weeks, the vessels were decompressed; four colonies were randomly selected and were used to inoculate more pour tubes. We examined these tubes after 5 days and found that they contained colonies. Such a rapid appearance of colonies suggested that the bacteria had a rapid doubling rate (*10*). One of these colonies was found to contain axenically a spirillum-like organism that did not grow into colonies in pour tubes incubated at atmospheric pressure for several weeks—the organism was apparently barophilic. The morphology of the cells is shown in Fig. 1. Cultures established from this colony served as the inocula for the experiments described below.

The data in Fig. 2 show the amount of growth (increase in cell numbers) observed in separate cultures that were begun with parts of the same starting culture and that were incubated at different pressures for the same amount of time (7 days). The curve shows that growth occurs at pressures between atmospheric pressure and somewhat above 825 bars. We calculate a maximum doubling time of 86 hours at atmospheric pressure. The optimum pressure for growth, about 500 bars, was not accurately determined by this experiment, probably because the incubation was too long (7 days). The growing cells were thus able to reach the concentration of 2×10^8 to 3×10^8 cells per milliliter, which is the maximum cell yield possible under these growth conditions. This pressure dependence has