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Growth rate and potential climate record from a rhodolith using ^{14}C accelerator mass spectrometry

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Abstract

Rhodoliths, free-living calcareous red algae, create large and diverse habitats worldwide. Although these plants are abundant and ecologically important, little is known about their growth rate. We determined the growth rate for an individual rhodolith, *Lithothamnium crassiusculum*, from the southern Gulf of California through ^{14}C analysis using accelerator mass spectrometry (AMS) to be 0.6 mm yr^{-1}. This growth rate suggests large *L. crassiusculum*, which have been found with radii in excess of 6 cm, may live over 100 yr. Declines in the $\Delta^{14}C$ record associated with the large El Niño events of 1957, 1982, and 1992 indicate ^{14}C analysis may lead to identification of important climate events in the more distant past. The ability to determine changes in past ocean circulation related to changes in past climatic conditions through AMS ^{14}C analysis of rhodoliths would increase the geographic range of available climate records from the tropical oceans to the entire global ocean and potentially allow for the determination of past climate conditions from rhodoliths in fossil beds.

Rhodoliths, red, nongeniculate calcareous algae, occupy large areas of the world's oceans, forming the basis of diverse and ecologically important communities (Bosence 1983; Foster et al. 1997). However, little is known about the rate at which these communities develop, their rate of recovery after natural or anthropogenic disturbances, or their effects on the global carbon budget. Because some rhodoliths are long lived, they also have the potential to provide information on past oceanic conditions. As they grow, these plants deposit calcium carbonate, which should contain chemical and isotopic records reflecting environmental conditions. Previous isotopic studies on coral and mollusks found that the amount of ^{14}C deposited as a part of the total carbon in biogenic carbonate records the ^{14}C concentration in the ocean water surrounding the organism (e.g., Druffel and Linick 1978; Nozaki et al. 1978; Druffel and Suess 1983). This type of ^{14}C record should also be found in the carbonate of rhodoliths and can potentially be used as a record of climate variation.

Rhodoliths are found in many locations and environments around the world, ranging from polar deep water to tropical shallows (Bosence 1983). In the subtropical Gulf of California where the material was collected for this study, rhodoliths occur in a variety of habitats, including 10–30-m deep tidal channels and shallow, rocky areas with mild surf (Foster et al. 1997). Rhodolith beds in these varying locations can occur over many square kilometers, sometimes covering 100% of the subtidal habitat (Foster et al. 1997) and provide habitat for organisms that would not otherwise be present, especially other macroalgae, crustaceans, sea stars, anemones, and mollusks (Foster et al. 1997). Fossil rhodoliths also form extensive beds throughout the terrestrial portions of Baja California (Dorsey 1997; Foster et al. 1997).

Examination of longitudinal sections under a dissecting microscope shows growth patterns in the rhodolith in this study, *Lithothamnium crassiusculum* (Foslie) L. R. Mason, that are similar to those of related nongeniculate coralline red algae as described in Woelkerling (1988) (Fig. 1). In *L. crassiusculum,* all but the tips of branches appear to have determinant growth; branch width from the rhodolith center to outer surface remains constant at 0.5–1.0 cm, whereas the branch elongates and bifurcates. Calcification occurs as the monomerous filaments grow, providing a carbonate growth axis that can be analyzed for elemental and isotopic changes over the life span of the plant. The manner in which the thallus develops is well known, but the rates at which it and its carbonate matrix develop are poorly documented.

^{14}C can be used as a tracer to help determine details of the lives of carbonate-depositing organisms such as calcareous algae. Anthropogenic activities have contributed significantly to the dilution of, or addition to, naturally produced atmospheric ^{14}C since the beginning of the industrial revolution ca. 1850. The burning of fossil fuels decreased the net atmospheric ratio of ^{14}C to total carbon, whereas atmospheric nuclear weapons testing in the late 1950s and early 1960s increased the atmospheric levels of ^{14}C, result-

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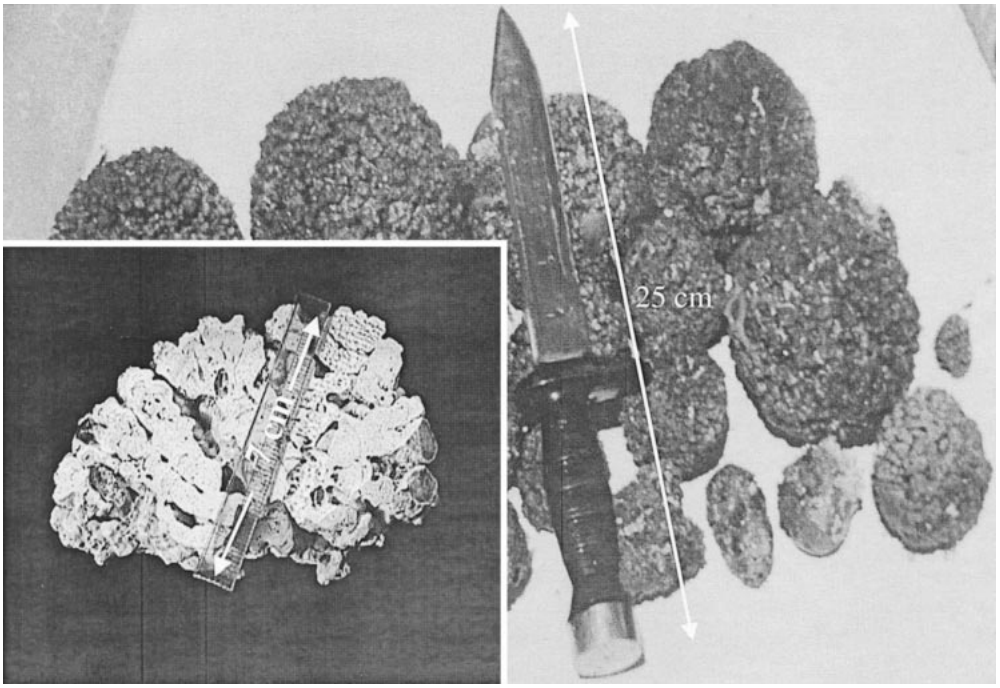

Fig. 1. Whole rhodoliths displayed with a dive knife for scale.

ing in a peak of ^{14}C in the atmosphere in the early 1960s (Levin et al. 1980). The initial stages of this bomb spike raised levels of ^{14}C in surface ocean waters as early as 1958 when ^{14}C from nuclear weapons tests began to enter oceanic surface water in the Northern Hemisphere (e.g., Druffel and Suess 1983). These anthropogenic activities provide isotopic benchmarks that can be used in deriving information on the growth histories of carbonate-depositing organisms.

In this study, we determined the growth rate of *Lithothamnium crassiusculum* using accelerator mass spectrometry (AMS) analysis of ^{14}C along a transect of the carbonate thallus to provide insight into its development and growth history. This determination also demonstrated the potential of rhodoliths to be used as indicators of past oceanographic conditions that are relevant to hemispheric climatic change.

Methods

To study the records of isotopic variations, 79 samples were analyzed from the rhodolith (radius ca. 5 cm) collected from the Gulf of California directly west of La Paz, Baja California Sur in October 1994 in approximately 4 m of water by a SCUBA diver. The rhodolith was on a rocky substrate exposed to open ocean conditions of the Gulf of California. All samples for isotopic analyses were taken from radial transects along the growth axes. Analysis for ^{14}C was performed on the rhodolith using AMS at Lawrence Livermore National Laboratory.

^{14}C measurements were performed on three separate branches. Samples from the first two branches were analyzed in pilot studies to identify the presence of prebomb and postbomb ^{14}C. The third branch was sampled every 1 mm to characterize ^{14}C changes over the plant's entire life. The latter sampling produced 52 samples extending from the proximal portion of the rhodolith (at the origin of growth) to the distal portion of the branch (living surface of the plant). Approximately 10 mg of $CaCO_3$ were removed at each sample position. Each sample was dissolved under vacuum with 85% H_3PO_4 and converted to CO_2 gas, which was used to prepare targets for ^{14}C analysis using AMS (Vogel et al. 1987).

All AMS ^{14}C samples were measured together with standards and ^{14}C-free materials. Oxalic Acid-1 (OX-1) was used as the primary reference standard for the measurements (Stuiver and Polach 1977), and background levels of radiocarbon were determined using ^{14}C-free calcite (TIRI-Calcite; Gulliksen and Scott 1995). Previous analyses of secondary standard materials show that ^{14}C measurements are accurate and precise within 4.1‰, with the majority of that error (2.5‰) accounted for in counting statistic (Roberts et al. 1997). Results of AMS measurements are reported as $\Delta^{14}C$, which is the expression of the fractional difference of the $^{14}C/C$ isotope ratio of the sample from $^{14}C/C$ of preindustrial atmosphere, in parts per thousand (Stuiver and Polach 1977).

Results

All three rhodolith branches showed prebomb and postbomb ^{14}C levels of the surface ocean from the Gulf of California that are consistent with Pacific surface ocean levels as measured in a Galapagos coral (Guilderson and Schrag 1998) (Fig. 2). Prebomb levels (less than -60‰) occurred 1–30 mm from the origin of growth. An abrupt increase of

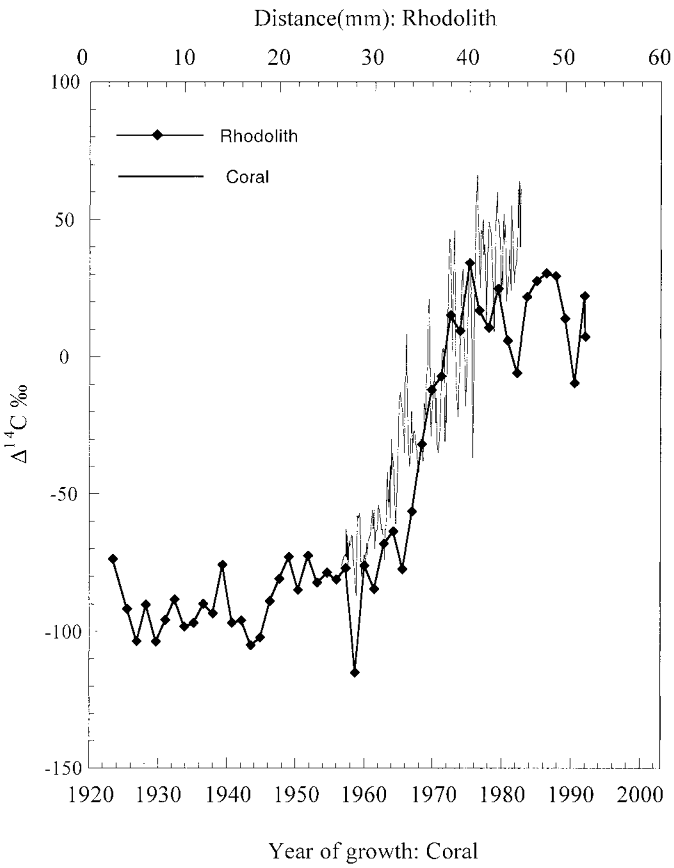

Fig. 2. $\Delta^{14}C$ record from a rhodolith collected near La Paz, Baja California Sur (solid diamonds) with sample interval (mm) on top *X*-axis and a $\Delta^{14}C$ record from Galapagos Islands coral with independent age chronology displaying the timing of the bomb ^{14}C increase due to nuclear weapons testing (Guilderson and Schrag 1998).

^{14}C peaking at +40‰ was observed between 31 mm and 40 mm, and postbomb levels extended from 40 mm to the rhodolith surface. Samples from 28, 45, and 51 mm (from the origin of growth) were analyzed twice to ensure the reliability of low $\Delta^{14}C$ values, and gave the same results.

Growth rate determination

The initial rise in Pacific surface ocean ^{14}C levels became evident in corals between 1958 and 1966 (Druffel and Suess 1983; Guilderson and Schrag 1998). An abrupt increase of ^{14}C in the rhodolith began at 31 mm. Assuming the increase in $\Delta^{14}C$ observed in the rhodolith occurred during the same time span as in the corals (1958–1966) and given the collection date of 1994, the growth rate of the rhodolith is 0.6 ± 0.1 mm yr^{-1}.

Discussion

Using the growth rate determined above, the age of the rhodolith branch is about 86 yr. The largest individual so far found at the collection site was approximately 12 cm in diameter, which corresponds to a maximum age on the order of 100 yr. The growth rate reported in this study is in excellent agreement with a field growth study of *L. crassiusculum* tagged with Alizarin red from the same location (0.63 mm yr^{-1}) (Georgina-Rivera 1999), as well as growth rates for other nongeniculate coraline algae from several short-term laboratory and field experiments (0.3–0.7 mm yr^{-1}) (e.g., Adey and Vassar 1975; Potin et al. 1990).

Two previous studies using AMS ^{14}C dating of rhodoliths determined growth rates in the range 0.01–0.09 mm yr^{-1} with the majority around 0.03 mm yr^{-1} (Reid and MacIntyre 1988; Littler et al. 1991). Reid and MacIntyre (1988) and Littler et al. (1991) measured ^{14}C ages from discrete interior sections of several rhodoliths and calculated growth rates by dividing the distance between the sampled area and the rhodolith surface by the measured ^{14}C age. Neither of these investigations corrected the measured AMS ^{14}C results for the marine reservoir effect, which causes ^{14}C dates on marine organisms to have an apparent age older than coeval terrestrial samples (Stuiver et al. 1986; Stuiver and Braziunas 1993). Because the chronological age of the rhodoliths in these studies is hundreds of years younger than the measured ^{14}C age, the slow growth rates calculated by Reid and MacIntyre (1988) and Littler et al. (1991) are underestimates. In this study, we compare AMS ^{14}C measurements along a rhodolith growth transect directly with the historical record of invasion of bomb pulse ^{14}C into the surface ocean from a Galapagos coral, avoiding the reservoir correction problems associated with ^{14}C dating.

Rhodolith beds can be disturbed by human activities such as trawling and dredging (Potin et al. 1990; Foster et al. 1997), in addition to natural events such as storms, drastic changes in temperatures, and increased turbidity and sedimentation. In spite of our new, higher estimate, these growth rates indicate that the recovery of rhodoliths, the dominant habitat formers in these beds, may be very slow.

Also evident from the $\Delta^{14}C$ record obtained from *L. crassiusculum* are three pronounced minima that correlate with three large El Niño events in 1957, 1982, and 1992 (global ocean surface temperature atlas-sea surface temperature (a), http://ingrid.ldgo.columbia.edu) (Fig. 3). The normal source water for the southern Gulf of California is a 500-m deep layer that originates from tropical surface and subsurface water in the North Equatorial Current (Baumgartner and Christensen 1985; Bray and Robles 1991). During El Niño events the source waters switch from the tropical North Equatorial Current to the California Current and Pacific deep water. Thus, these El Niño events appear as minima in the rhodolith $\Delta^{14}C$ record because of upwelling of radiocarbon-depleted Pacific deep and intermediate water at the mouth of the Gulf of California (Bray and Robles 1991; Goodfriend and Flessa 1997).

Dynamic changes of $\Delta^{14}C$ and other trace elements in oceanic waters are recorded in calcium carbonate-depositing organisms. Because of their wide distribution, rhodoliths and other long-lived nongeniculate corallines are potentially valuable archives of past oceanographic conditions. The ability to provide long histories of oceanic conditions from a wide range of the world's oceans could contribute to better

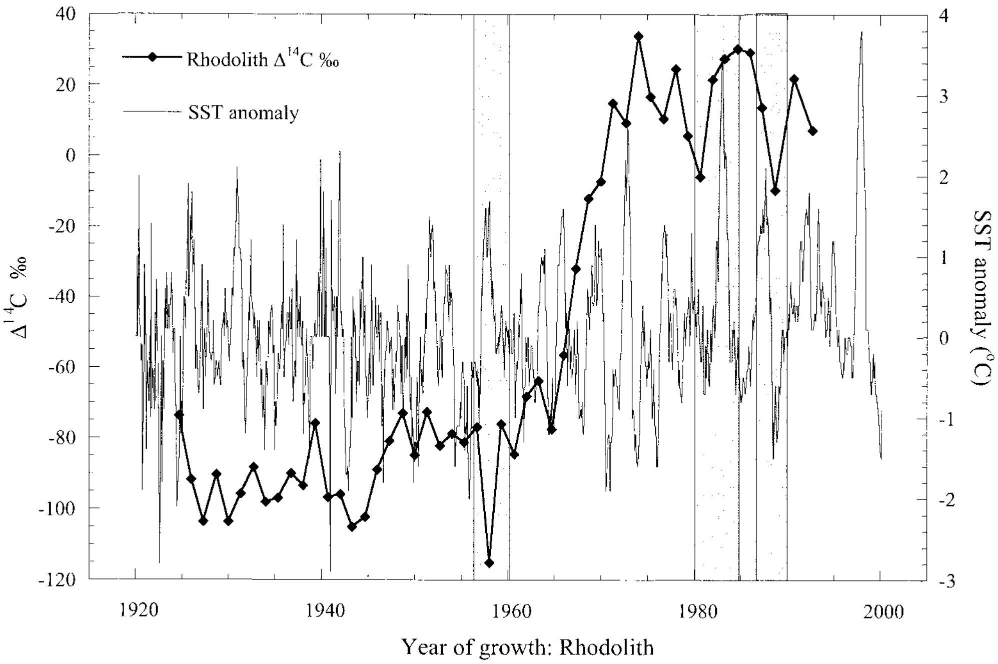

Fig. 3. $\Delta^{14}C$ record from a rhodolith with global ocean surface temperature atlas (GOSTA) ENSO 3 SST anomaly. Three large El Niño events shown (highlighted in gray) occurred coincidentally with three large declines in the $\Delta^{14}C$ record of the rhodolith.

documentation and understanding of how global climate has changed in the past, and to more accurate predictions of potential changes in the future. Additionally, the extensive occurrence of living and fossil rhodolith beds worldwide suggests that rhodoliths may be an important but overlooked component of present and past global carbon cycling and sequestration (Foster et al. 1997).

References

ADEY, W. H., AND M. VASSAR. 1975. Colonization, succession and growth rates of tropical crustose coralline algae (rhodophyta, cryptonemiales). Phycologia **14:** 55–69

BAUMGARTNER, T. R., AND N. CHRISTENSEN, JR. 1985. Coupling of the Gulf of California to large-scale interannual climatic variability. J. Mar. Res. **43:** 825–848.

BOSENCE, D. W. J. 1983. The occurrence and ecology of recent rhodoliths—a review, p. 225–242. *In* M. P. Tadeusz [ed.], Coated grains. Springer-Verlag.

BRAY, N. A., AND J. M. ROBLES. 1991. Physical oceanography of the Gulf of California, p. 511–553. *In* B. R. T. Simoneit and J. P. Dauphin [eds.], The Gulf of California and peninsular province of the Californias. Am. Assoc. Pet. Geol. Bull. 47.

DORSEY, R. J. 1997. Origin and significance of rhodolith-rich strata in the Punta El Baja section, Southeastern Pliocene Loreto Basin. Geol. Soc. Am. **65A:** 119–126.

DRUFFEL, E. R. M., AND T. W. LINICK. 1978. Radiocarbon in annual coral rings of Florida. Geophys. Res. Lett. **5:** 913–916.

———, AND H. E. SUESS. 1983. On the radiocarbon record in banded corals: Exchange parameters and net transport of $^{14}CO_2$ between atmosphere and surface ocean. J. Geophys. Res. **88:** 1271–1280.

FOSTER, M. S., R. RIOSMENA-RODRIGUEZ, D. L. STELLER, AND WM. J. WOELKERLING. 1997. Living rhodolith beds in the Gulf of California and their implications for paleoenvironmental interpretation. Geol. Soc. Am. **318:** 127–139.

GEORGINA-RIVERA, M. 1999. Edad y crecimiento de *Lithothamnium crassiusculum* (Foslie) Mason (Corallinales, Rhodophyta) en el suroesete del Golfo de California Mexico. Tesis, Universidad Autonoma de Baja California.

GOODFRIEND, G. A., AND K. W. FLESSA. 1997. Radiocarbon reservoir ages in the Gulf of California: Roles of upwelling and flow from the Colorado river. Radiocarbon **39:** 139–148.

GUILDERSON, T. P., AND D. P. SCHRAG. 1998. Abrupt shift in subsurface temperatures in the Eastern Tropical Pacific associated with recent changes in El Niño. Science **281:** 240–243.

GULLIKSEN, S., AND M. SCOTT. 1995. Report of the TIRI workshop, Saturday 13 August 1994. Radiocarbon **37:** 820–821.

LEVIN, I., K. O. MUNNICH, AND W. WEISS. 1980. The effect of anthropogenic CO_2 and ^{14}C sources on the distribution of ^{14}C in the atmosphere. Radiocarbon **22:** 379–391.

LITTLER, M. M., D. S. LITTLER, AND M. D. HANISAK. 1991. Deep-water rhodolith, productivity, and growth history at sites of formation and subsequent degradation. J. Exp. Mar. Biol. Ecol. **150:** 163–182.

NOZAKI, Y., D. M. RYE, K. K. TUREKIAN, AND R. E. DODGE. 1978. A 200-year record of carbon-13 and carbon-14 variations in Bermuda coral. Geophys. Res. Lett. **5:** 825–828.

POTIN, P., J. Y. FOC'H, C. AUGRIS, AND J. CABIOCH. 1990. Annual growth rate of the calcareous red alga *Lithothamnion corallioides* (Corallinales, Rhodophyta) in the Bay of Brest, France. Hydrobiologia **204/205:** 263–267.

REID, R. P., AND I. G. MACINTYRE. 1988. Foraminiferal-algal nodules from the Eastern Caribbean: Growth history and implications on the value of nodules as paleoenvironmental indicators. Palaios **3:** 424–435.

ROBERTS, M. L., AND OTHERS. 1997. The LLNL AMS facility. Nucl. Instrum. Methods Phys. Res. **B123:** 57–61.

STUIVER, M., AND T. F. BRAZIUNAS. 1993. Modeling atmospheric ^{14}C influences and ^{14}C ages of marine samples to 10,000 BC. Radiocarbon **35:** 137–189.

———, G. W. PEARSON, AND T. BRAZIUNAS. 1986. Radiocarbon age calibration of marine samples back to 9000 Cal Yr BP. Radiocarbon **28:** 980–1021.

———, AND H. A. POLACH. 1977. Discussion: Reporting of ^{14}C data. Radiocarbon **19:** 355–363.

VOGEL, J. S., D. E. NELSON, AND J. R. SOUTHON. 1987. ^{14}C Background levels in an accelerator mass spectrometry system. Radiocarbon **29:** 323–333.

WOELKERLING, W. J. 1988. The coralline red algae: An analysis of the genera and subfamilies of nongeniculate corallinaceae. Oxford Univ. Press.

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