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Migrations of California Gray Whales Tracked by Oxygen-18 Variations in Their Epizoic Barnacles

Abstract. *Barnacles attached to the California gray whale have oxygen isotope compositions that serve as a record of changing ocean temperatures as the whale migrates between arctic and subtropical waters. The isotopic values for the barnacles can be used to track whale migrations and to reconstruct the recent movements of beached whales. The method may be useful for tracing the movements of other animals, living or fossil, and for reconstructing the voyages of ancient ships.*

Each year the California gray whale *Eschrichtius robustus* performs the longest migration of any mammal—a round trip of between 16,000 and 22,000 km (*1*, *2*). During the warm months of the Northern Hemisphere (late May through October), gray whales generally feed on the benthos in shallow waters of the Bering Sea, the Chukchi Sea, and the western Beaufort Sea as far north as the southern edge of the close pack ice. During the cold months, many of the whales are found in the warm lagoons and bays of Baja California, Mexico. The southward migration generally lasts from October through January. The whales swim south, roughly following the coastline until they reach Baja California. A few travel even farther south, and they winter in protected waters along the Gulf of California.

Deeply embedded in the skin of virtually all gray whales is the host-specific sessile barnacle *Cryptolepas rhachianecti*. This barnacle is closely related to the genus *Coronula* (*3*), which is frequently found on humpback whales (*2*, *4*). Although stable isotope studies of mollusk shells have been used to ascertain the range and succession of seasonal changes in temperature and physical processes (*5*), and to relate progressive changes in oxygen and carbon stable isotopes of benthopelagic fish otoliths to changes in their depth habitats (*6*), no detailed isotopic analyses have been performed on crustacean shells such as those of barnacles (Cirrepedia). I show here how temperature-related changes in $^{18}O/^{16}O$ ratios of the shell of *C. rhachianecti* can be employed as a tracking device to trace the migrations of the host animal.

The first specimen of *C. rhachianecti* that I analyzed was collected from the San Ignacio Lagoon, Baja California, where gray whales mate and calve. The shell (determined by x-ray diffraction to be pure calcite) was ultrasonically cleaned and treated with sodium hypochlorite. It was then broken in two across its diameter, and small samples were removed from the sequential growth lamellae of the sheath with a dental drill (0.5-mm diameter). Each sample (about 0.5 mg) was heated in a vacuum for 30 minutes at 250°C and then analyzed isotopically (*7*); the analytical precision was 0.07 per mil. Two other specimens of *C. rhachianecti* were treated and analyzed in a similar way. These had been removed from a small gray whale that had beached itself in October 1976 on Mission Beach, San Diego (*8*, *9*). Figure 1 gives a magnified view of one of these shells.

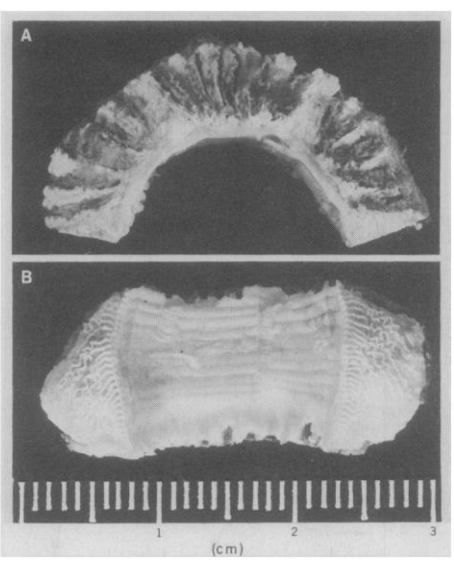

Fig. 1. Plan (A) and inside (B) views of half of the 28-mm barnacle from the beached whale. The inside view shows the sequential growth lamellae with the oldest (partly broken) sections at the top and the most recent growth (irregular toothlike protrusions) at the base.

Figure 2 shows the $\delta^{18}O$ (*10*) results for samples from the San Ignacio barnacle plotted against distance from the base of the shell (the terminal edge). There is a progressive decrease in $\delta^{18}O$ in the direction of shell growth, reflecting movement of the host animal from cold to warm waters. The $\delta^{18}O$ values can be used to calculate the temperature of the water from which the calcite precipitated by using a paleotemperature equation (*11*) that gives temperature as a function of the isotopic composition of the precipitated calcite and the isotopic composition of the water from which precipitation occurred. Conversely, expected calcite $\delta^{18}O$ values can be obtained if temperature and water $\delta^{18}O$ values are available. Estimates of the isotopic composition of the water can be made if the salinity is known (*12*).

From reported average values of salinity for the Arctic Ocean and the northeastern Pacific (*13*), I estimated ocean water $\delta^{18}O$ values and then used the paleoequation to calculate expected calcite $\delta^{18}O$ values for selected temperatures. Temperatures were estimated (*14*) at six points for a model in which a gray whale travels from Point Hope, Alaska (starting 15 October) to San Ignacio Lagoon (arriving 23 January, or 100 days later). Sequential points A to F (Fig. 2) are separated by 20-day intervals and correspond to expected locations during the migration (*1*).

Figure 2 shows the calculated $\delta^{18}O$ values and corresponding temperatures. The model migration agrees well with an actual migration as interpreted from the isotopic values for the barnacle. The average vertical growth rate of the *C. rhachianecti* shell during the migration south is indicated as 0.12 mm per day, and since the whale travels nearly 100 miles per day toward the end of its voyage south (where there is the greatest change of temperature with latitude), individual samples removed for analysis probably represent several days' growth.

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This may explain why the lowest $\delta^{18}O$ value determined for the barnacle was not as low as in the model (by about 2°C). The increase in $\delta^{18}O$ at the bottom edge of the barnacle can be explained by the sharp increase in salinity experienced by the barnacle after entering the San Ignacio Lagoon, which has no freshwater source and can attain salinities several parts per thousand higher than those of the open ocean (*15*).

The sharp change in the *C. rhachianecti* $\delta^{18}O$ curve between B and C in Fig. 2 is entirely consistent with the whale's having traveled from east of St. Lawrence Island in the Bering Sea and then followed the coastline before heading southwest toward the Unimak Pass. During this section of the journey, the whale would cross a sharp salinity gradient—entering waters near 20 per mil from waters of ~ 31 per mil and then recrossing the gradient en route to the Unimak Pass. This would be recorded in the oxygen isotopic signal as a decrease of ~ 0.7 per mil in $\delta^{18}O$, followed by a similar increase.

I conclude that *C. rhachianecti* records in its calcite shell the temperature and composition of water through which its host swims; hence the isotopic technique can be used as an accurate tracking device. As an example of the usefulness of this technique, Fig. 3 shows the $\delta^{18}O$ values obtained on the *C. rhachianecti* recovered from the whale beached in San Diego. Curve 1 shows the isotopic profile of the larger of the two barnacles; curve 2, the profile of the second barnacle analyzed in slightly less detail. The purpose of analyzing the second specimen was to demonstrate that two different barnacles attached to the same gray whale record similar $\delta^{18}O$ signals. Curve 1 is offset to the right of curve 2 by about 1.5 mm, presumably because the bottom 1.5 mm of the second barnacle was missing (it may have broken off during removal from the whale's skin).

The beached whale was 7.5 m long and, therefore, was probably a yearling (*2*). From the isotopic curves shown in Fig. 2, it is possible to plausibly reconstruct the movements of the whale in the last few months of its life. According to the reconstruction, the whale was in warm southern waters in midsummer (assuming a barnacle growth rate similar to that of the San Ignacio specimen), which suggests that the young whale had become lost. Instead of heading north in 1976 for summer feeding, it swam south as far as the Gulf of California, where a water temperature of 29°C and a salinity of 34.5 per mil are typical in August and correspond to the observed −2.9 per mil for $\delta^{18}O$. Possibly the long distances traveled by the whale without adequate nourishment led to its death.

To improve confidence in this tracking technique, it will be necessary to analyze isotopically a large number of specimens to learn more about the growth rates of barnacle shells in various temperature and salinity regimes (*16*). Clearly, useful historical information is contained in barnacles; these epizoic irritants have a redeeming value if they provide clues with which to increase our understanding of the life cycle of whales and perhaps of the reasons for whale mortalities. The ^{18}O tracking technique is applicable in principle to other species of whales and also to turtles, which carry barnacles on their shells. It may be possible to reconstruct the historical movements of fossil marine animals or ancient ships from the barnacle shells (or other calcareous shells) found in association with them.

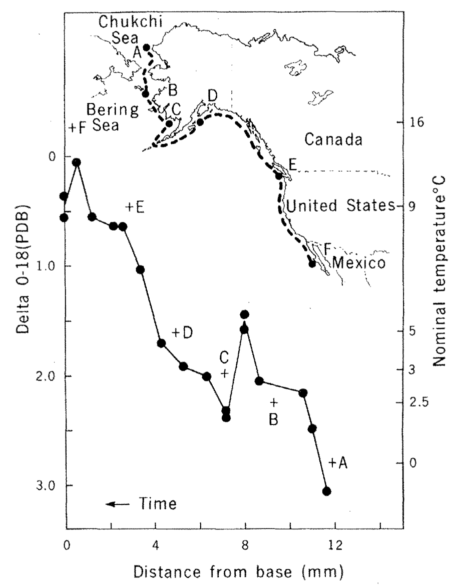

Fig. 2. Curve showing $\delta^{18}O$ variations in a *C. rhachianecti* shell from the San Ignacio Lagoon and map showing a model gray whale migration from Alaska to Mexico. Calculated $\delta^{18}O$ values correspond to nominal temperatures.

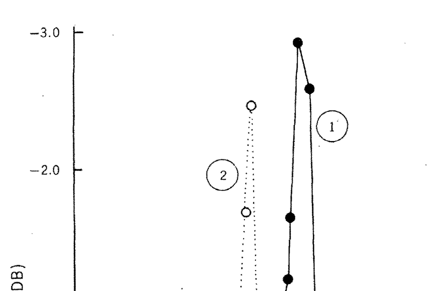

Fig. 3. Variations in $\delta^{18}O$ of a 28-mm diameter barnacle (solid line) and a 23-mm diameter barnacle (dotted line) from the beached whale.

J. S. KILLINGLEY

Scripps Institution of Oceanography, La Jolla, California 92093

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8. Barnacles were removed from this whale and stored in ethanol by R. Gilmore (*9*), who also measured the whale's length.
9. R. Gilmore, personal communication.
10. $\delta^{18}O$ (per mil) = $[(^{18}O/^{16}O)_{sample}/(^{18}O/^{16}O)_{standard} - 1] \times 1000$. Results are reported with respect to Pee Dee belemnite (PDB), calculated by the usual procedure [H. Craig, *Geochim. Cosmochim. Acta* **12**, 133 (1957)].
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14. Temperatures are estimated for an average swimming depth of about 30 m (*9*), where in general the temperature is 1° or 2°C lower than at the surface.
15. F. B. Phleger, personal communication.
16. Northbound gray whales have many small juvenile barnacles attached, which indicates that *C. rhachianecti* spawn predominantly in the warmer waters (*2*). The probability of obtaining a barnacle that has a record of several migrations is small because the large specimens are likely to be scraped from the whale or at least severely abraded when the host animal forages on the sea floor during the summer feeding period. Gray whales emerging from brackish lagoons in the Bering Sea carry no live barnacles, and *C. rhachianecti* can be killed experimentally by brief immersion in fresh or brackish water [B. A. Zenkovich, *Vestn. Akad. Nauk SSSR* **23**, 91 (1937)].

17. I thank R. Gilmore for providing barnacle specimens and valuable information on whale habits. Advice from W. H. Berger, J. L. Reid, W. C. Cummings, and W. A. Newman is appreciated. Supported by NSF (Oceanography) grant OCE78-25587.

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