Age validation of quillback rockfish (*Sebastes maliger*) using bomb radiocarbon

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Abstract—Rockfishes (*Sebastes* spp.) support one of the most economically important fisheries of the Pacific Northwest and it is essential for sustainable management that age estimation procedures be validated for these species. Atmospheric testing of thermonuclear devices during the 1950s and 1960s created a global radiocarbon (^{14}C) signal in the ocean environment that scientists have identified as a useful tracer and chronological marker in natural systems. In this study, we first demonstrated that fewer samples are necessary for age validation using the bomb-generated ^{14}C signal by emphasizing the utility of the time-specific marker created by the initial rise of bomb-^{14}C. Second, the bomb-generated ^{14}C signal retained in fish otoliths was used to validate the age and age estimation method of the quillback rockfish (*Sebastes maliger*) in the waters of southeast Alaska. Radiocarbon values from the first year's growth of quillback rockfish otoliths were plotted against estimated birth year to produce a ^{14}C time series spanning 1950 to 1985. The initial rise in bomb-^{14}C from prebomb levels (~ −90‰) occurred in 1959 [±1 year] and ^{14}C levels rose relatively rapidly to peak $\Delta^{14}C$ values in 1967 (+105.4‰) and subsequently declined through the end of the time series in 1985 (+15.4‰). The agreement between the year of initial rise of ^{14}C levels from the quillback rockfish time series and the chronology determined for the waters of southeast Alaska from yelloweye rockfish (*S. ruberrimus*) otoliths validated the aging method for the quillback rockfish. The concordance of the entire quillback rockfish ^{14}C time series with the yelloweye rockfish time series demonstrated the effectiveness of this age validation technique, confirmed the longevity of the quillback rockfish up to a minimum of 43 years, and strongly confirms higher age estimates of up to 90 years.

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Rockfishes (*Sebastes* spp.) comprise one of the most commercially important fisheries in the northeast Pacific Ocean. Some rockfish species possess life history characteristics, such as long life, slow growth, late age at maturity, low natural mortality, and variable juvenile recruitment success, all of which make them particularly vulnerable to overfishing (Adams, 1980; Archibald et al., 1981; Leaman and Beamish, 1984; Cailliet et al., 2001.). Rockfish population biomass and size composition have declined to very low levels today in part because of continued high exploitation rates (Love et al., 2002). Prevention of further population declines is a management imperative. Sustainable management of marine fisheries requires accurate life history information, of which validated age and growth characteristics can be one of the most important aspects.

Underestimated age can lead to inflated estimates of total allowable catch for a fishery that is unsustainable at that level of exploitation (Beamish and McFarlane, 1983; Campana, 2001). For example, underestimated longevity and improper management allowed overfishing that accelerated the decline of the Pacific ocean perch (*Sebastes alutus*) of the northeastern Pacific Ocean (Beamish, 1979; Archibald et al., 1983). Reliable estimates of age are also essential for understanding life history traits, such as age at maturity, rate of growth, longevity, and reproduction frequency (Beamish and McFarlane, 1983). For production (large-scale) aging purposes, age validation is especially important because it provides a standardized basis for ongoing aging efforts to identify strong and weak cohorts (Campana, 2001).

The most common method of age estimation of bony fishes is counting growth zones in their calcified inner ear bones, or otoliths (Chilton and Beamish, 1982; Beamish and McFarlane, 1987). A pair of translucent and opaque growth zones is often assumed to represent one year of growth (Williams and Bedford, 1974). By counting growth zones an estimate of fish age is possible; however, growth patterns are not easily discernible for all species. Age interpretations in long-lived species can be particularly difficult and subjective because of the compression of growth zones within the otolith (Munk, 2001). Therefore, it is necessary to validate the periodicity of growth zones in otoliths with an independent and objective method. Despite the importance of accurate age estimates for understanding and managing fish populations, validated age and growth characteristics are often not available (Beamish and McFarlane, 1983; Campana, 2001). Traditional age validation techniques, such as captive rearing, mark-recapture, and tag-recapture, can be difficult or impractical for long-lived and deep-dwelling fishes.

An alternative technique to traditional age validation methods uses radiocarbon (^{14}C) produced by the atmospheric testing of thermonuclear devices in the 1950s and 1960s as a time-specific marker (Kalish, 1993). This established method of validating otolith-derived age estimates of fishes involves relating the discrete temporal variation of ^{14}C recorded in otoliths to an established ^{14}C chronology. Otoliths are closed systems, accreting calcium carbonate throughout the life of the fish and this calcium carbonate is conserved through time. The measurement of bomb-produced ^{14}C in otoliths of fishes is considered one of the best objective means to validate otolith-based age estimates in long-lived fishes (Campana, 2001).

This technique is most reliable for fishes that inhabit the surface mixed layer of the ocean, at least during a portion of their life history. Uncertainty regarding mixing rate at depth and limited data on the ^{14}C signal in deeper waters make it difficult to use this technique for organisms that live below the mixed layer throughout their lives (Kalish, 1995, 2001). Studies indicate that the main source of carbon (70–90%) for otoliths is from dissolved inorganic carbon (DIC) in seawater and that the remainder (10–30%) is dietary (Kalish, 1991; Farrell and Campana, 1996; Schwarcz et al., 1998). An understanding of the life history of the fish (in particular diet, movement, and habitat) and the regional oceanography of the area are integral for interpreting otolith ^{14}C data. One caveat of this technique is that it must use otoliths with birth dates, including the period of initial increase in ^{14}C (mid-1950s to mid-1960s; Kalish, 1995). Consequently, this technique is well suited for age validation of long-lived species or species for which there is an archived otolith collection with birth years that span this period. The application of bomb ^{14}C for age validation of long-lived species is advantageous, in that it provides a minimum longevity and verifies the periodicity of growth zones in otoliths with only a small amount of material and with a high degree of precision (Kalish, 1993; Campana, 2001). However, the high cost of ^{14}C analysis (~$400–$500 per sample) has been a limiting factor in the widespread application of this technique.

The quillback rockfish (*Sebastes maliger*) is a commercially important rockfish that represents a portion (~8%) of the demersal shelf rockfish assemblage landings in the Gulf of Alaska (O'Connell et al.[1]). Species within the demersal shelf group are considered long-lived, late maturing, and sedentary as adults, making them highly susceptible to fishing pressure (O'Connell et al.[1]). Estimated exploitation rates are low; once exploited beyond a sustainable level, recovery is slow (Leaman and Beamish, 1984; Francis, 1985; O'Connell et al.[1]). Longevity estimates for the quillback rockfish are wide ranging, from 15 to 90 years (38 years, Barker, 1979; 55 years, Richards and Cass, 1986; 15 years, Reilly et al.[2]; 76 years, Yamanaka and Kronland, 1997; >32 years, Casillas et al., 1998; 90 years, Munk, 2001), and no age validation has been performed for this species to date.

Quillback rockfish are found associated with rocky substrate in relatively shallow continental shelf waters (9 to 146 m)—their abundance decreasing with increasing depth below 73 m (Kramer and O'Connell, 1995). As juveniles, quillback rockfish inhabit nearshore benthic habitat. Tagging studies confirmed that they do not demonstrate migratory behavior and are residents in their shallow-water habitat (Matthews, 1990). Because 1) most longevity estimates indicate that some present-day adult quillback rockfish were born in the prebomb era, 2) quillback rockfish in the juvenile stage are found in the ocean mixed layer, and 3) a suitable ^{14}C time series exists for the waters off southeast Alaska (previously determined from yelloweye rockfish [*S. ruberrimus*] otoliths [Kerr et al., 2004]), the quillback rockfish is an ideal candidate for ^{14}C age validation.

The objectives of our study were 1) to develop a method for determining the minimum number of samples required for bomb ^{14}C age validation to minimize cost, 2) to validate both age and age estimation methods of the quillback rockfish by measuring ^{14}C in aged otoliths and to compare the timing of the initial rise in ^{14}C with

[1] O'Connell, V. M., D. W. Carlile, and C. Brylinsky. 2002. Demersal shelf rockfish assessment for 2002. Stock assessment and fishery evaluation report for the groundfish resources of the Gulf of Alaska, 36 p. North Pacific Fishery Management Council (NPFMC), P.O. Box 103136, Anchorage AK 99510.

[2] Reilly, P. N., D. Wilson-Vandenberg, R. N. Lea, C. Wilson, and M. Sullivan. 1994. Recreational angler's guide to the common nearshore fishes of Northern and Central California. California Department of Fish and Game, Marine Resources Leaflet, 57 p. Calif. Dep. Fish and Game, 20 Lower Ragsdale Drive, Suite 100, Monterey, CA 93940.

the chronology determined for the waters of southeast Alaska (i.e., yelloweye rockfish), and 3) to analyze ^{14}C in aged quillback rockfish otoliths, spanning the pre- to postbomb era, in order to examine the complete ^{14}C time series and demonstrate the effectiveness of using the timing of the initial rise in ^{14}C as an age validation method.

Materials and methods

Sample size assessment

Because of the considerable cost of accelerator mass spectrometry (AMS) analyses, the minimum number of ^{14}C samples required to validate the aging method of the quillback rockfish was mathematically determined from a previously determined yelloweye rockfish otolith ^{14}C time series for the waters of southeast Alaska (Kerr et al., 2004). To assess minimum sample size, estimated years of initial rise in ^{14}C levels (and associated errors) were determined for different numbers of data points (n=3, 5, 7, 9, and 11) subsampled from the bomb-rise region of the yelloweye rockfish data set. The estimated years of initial rise from each subsample set were then compared to the initial year of rise and error determined from all bomb-rise yelloweye rockfish ^{14}C samples (n=23). Because the error associated with the yelloweye rockfish bomb-rise data set is limited by the uncertainty associated with age estimates for yelloweye rockfish, a maximum error of ±2 years for fish with birth years during the bomb rise (1956 to 1971; Kerr et al., 2004) was our precision criterion for defining the minimum number of quillback rockfish otolith samples.

Twenty-three yelloweye rockfish otolith ^{14}C values with birth years from 1956 to 1971 were divided into data sets of 3, 5, 7, 9, and 11 data points. A stratified sampling approach was applied by creating bomb ^{14}C linear regressions from repeated selection of 3, 5, 7, 9, and 11 data points at uniform intervals from 1956 to 1971. Random selection of data points was not practical because it is established that the careful choice of sample year during the rapid rise in ^{14}C is required for this technique (Baker and Wilson, 2001). The year of initial rise in ^{14}C, and associated error, was determined from the bomb ^{14}C regressions. The year of initial ^{14}C rise was calculated with the following formula:

$$x = (y - b)/m,$$

where x = year of initial rise in ^{14}C values;
y = average prebomb ^{14}C value;
m = slope of the line; and
b = y-intercept.

The error associated with the year of initial rise in ^{14}C values (σ_x) was calculated by using the delta method (treating b as a scaler; Wang et al., 1975):

$$\sigma_x = \sigma_y / \sigma_m,$$

where σ_y = error associated with average prebomb ^{14}C value
σ_m = error associated with the slope of the line.

Radiocarbon analysis

Sagittal otoliths of quillback rockfish were collected from a random subsampling of catches from commercial longline fishing vessels in the coastal waters off southeast Alaska by the Alaska Department of Fish and Game (ADFG), Juneau, AK in 2000 (Fig. 1). A single otolith from a pair taken from each fish was aged by using the break-and-burn method developed by researchers at the Mark, Tag, and Age Laboratory, ADFG in Juneau, AK, and the corresponding intact otolith was analyzed for ^{14}C. Whole and broken-and-burned otoliths were stored dry in paper envelopes. Year of capture, estimated final age, assigned year class, readability code, and reader identification information were archived and provided by ADFG for each sample.

Fifteen quillback rockfish otoliths, with estimated birth years ranging from the prebomb 1950s to the postbomb mid-1980s were selected for ^{14}C analysis. The core of each otolith, which constitutes the first year of growth, was analyzed for ^{14}C. From life history information, it is known that the core was formed while the fish inhabited the ocean mixed layer during its early growth stage (Yoklavich et al., 1996). To determine the average length and width, and minimum depth of the core, whole and broken-and-burnt otoliths from adult quillback rockfish were examined under a Leica® dissecting microscope with an attached Spot RT® video camera and were measured using Image Pro Plus® image analysis software (version 4.1 for Windows, Media Cybernetics, Silver Spring, MD). Cores were extracted with a milling machine with a 1.6-mm (1/16″) diameter end mill. To minimize the extraction of material deposited after the first year of growth, length, width, and depth parameters of the otolith core were used to guide coring. Because the first year of growth in quillback rockfish otoliths is clearly visible from the distal surface of the otolith we were able to visually correct for individual variability in otolith core size. The core (first year of growth in the otolith) was reduced to powder, collected, and weighed to the nearest 0.1 mg.

For ^{14}C analysis, otolith calcium carbonate ($CaCO_3$) was converted to pure carbon in the form of graphite (Vogel et al., 1984, 1987) and measured for ^{14}C content by using AMS at the Center for Accelerator Mass Spectrometry, Lawrence Livermore National Laboratory. The ^{14}C values were reported as $\Delta^{14}C$ (Stuvier and Polach, 1977).

The ^{14}C values measured in quillback rockfish otolith cores were plotted with respect to corresponding birth years assessed from break-and-burn age estimates, taking into consideration the potential variation of the age estimate (coefficient of variation=2.6%, rounded to the nearest whole number; Chang, 1982). The ^{14}C time series for the waters of southeast Alaska established from the otoliths of the age-validated yelloweye rockfish

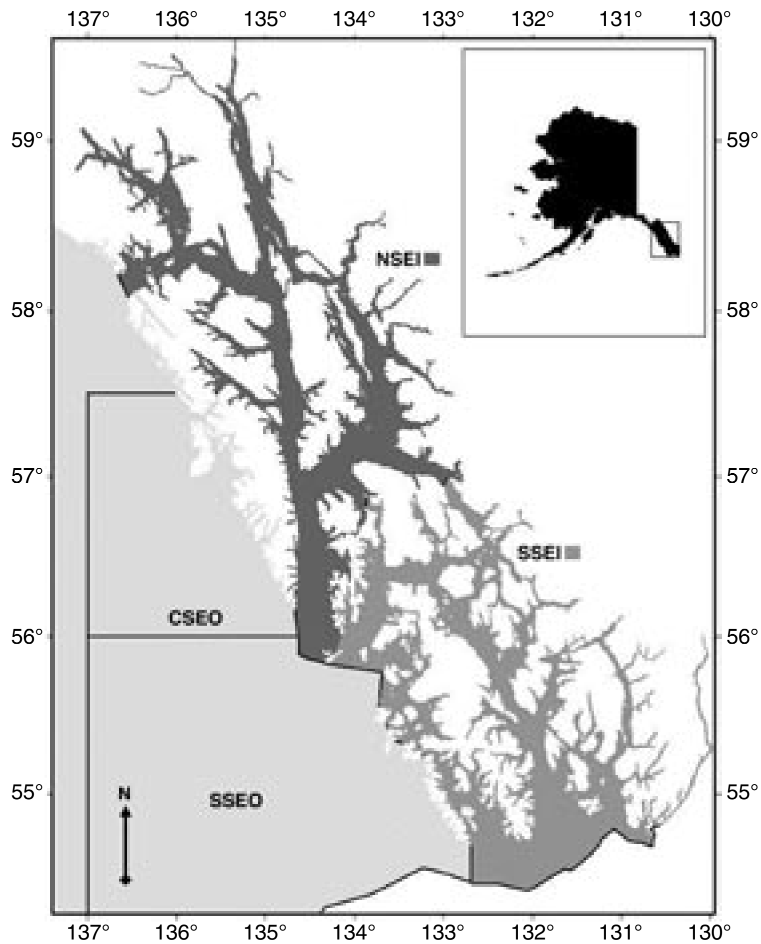

Figure 1

Map of southeast Alaska with regions where quillback rockfish (*Sebastes maliger*) used for otolith radiocarbon analyses were captured. Quillback rockfish were collected from random subsampling of catches from commercial longline fishing vessels in the coastal waters off southeast Alaska (CSEO: Central Southeast Offshore (outside), SSEI: Southern Southeast Inshore, SSEO: Southern Southeast Offshore, and NSEI Northern Southeast Inshore (inside)) by the Alaska Department of Fish and Game, Juneau, AK, in 2000. Note that the specific geographic location for individual fish during the first year of life is unknown; however, life history information indicates that quillback rockfish are not migratory and exhibit residential behavior in shallow-water habitat. Hence, the general location of the fish collected and used in this study may be useful in a broad context.

(n=43) was used for temporal calibration of the quillback rockfish record (Andrews et al., 2002; Kerr et al., 2004). The level of concordance between the years of initial rise in ^{14}C in the two time series was the basis for validating the otolith-based age estimates of the quillback rockfish. The degree of agreement between the ^{14}C time series, spanning the pre- to postbomb era, for the quillback and yelloweye rockfishes was examined to demonstrate the effectiveness of determining the year of initial rise in ^{14}C as an age validation method, and whether the entire time series for the quillback provided any further information relevant to age validation. To do this, the yelloweye rockfish ^{14}C time series was divided into three intervals (prebomb, bomb rise, and postbomb) and fitted with confidence intervals. The prebomb era ^{14}C values (1950–57) were fitted with an average (±2 SD); the bomb rise (1959–71) and postbomb era values (1966–85) were fitted with a linear regression and corresponding 95% prediction intervals. A qualitative comparison of the quillback rockfish ^{14}C record was made with other existing marine records: two Hawaiian Islands coral records—Oahu (Toggweiler et al., 1991)

Table 1

Range of the year of calculated initial rise in radiocarbon and the associated range of error calculated for bomb radiocarbon regressions. Each regression comprised varying numbers of yelloweye rockfish radiocarbon data points (n=3, 5, 7, 9, and 11) and was compared to the year of initial ^{14}C rise and error was determined from all bomb-rise yelloweye rockfish ^{14}C samples (n=23, last row) to determine the minimum number of quillback rockfish otolith samples sufficient to achieve the desired degree of precision (±2 years).

Number of data points in regression	Number of regressions	Range of the year of calculated initial rise in ^{14}C	Error range (± years)
3	8	1954.1–1960.3	0.8–6.8
5	5	1956.0–1959.4	1.3–2.9
7	4	1956.5–1957.9	1.0–2.5
9	3	1957.1–1957.3	0.9–1.8
11	2	1957.0–1957.8	1.2–1.5
23	1	1957.3	n/a

and Kona (Druffel et al., 2001)—and two otolith-based northern hemisphere ^{14}C records—for northwest Atlantic haddock (Campana, 1997) and the Barents Sea Arcto-Norwegian cod (Kalish et al., 2001).

Results

Sample size assessment

The estimated years of initial rise in ^{14}C calculated for the bomb-^{14}C regressions, composed of 3, 5, 7, 9, and 11 yelloweye rockfish data points spanning 1956 to 1971, converged towards the calculated year for all 23 data points as the number of samples comprising the regressions increased (Table 1). In parallel, the errors associated with the estimated years of initial rise in ^{14}C decreased as the number of ^{14}C samples increased (Table 1). The degree of precision within the quillback rockfish record was limited by the uncertainty associated with age estimates for yelloweye rockfish (a maximum error of ±2 years based on growth zone counts for fish with birth years from 1956 to 1971; Kerr et al., 2004). Examination of the error (years) associated with the year of initial rise in ^{14}C for the number of data points comprising each regression in relation to our ±2 year criterion indicated that a sample size of nine data points resulted in error values that ranged below 2 years (Table 1). Therefore, it was concluded that nine ^{14}C samples spanning 1956–71 would be sufficient to provide a suitable degree of precision in the quillback rockfish record. In addition, a limited number of samples, in this case 4, were required to establish an average prebomb level for the intercept year.

Radiocarbon analysis

The ^{14}C measured in 15 previously aged quillback rockfish otoliths with presumed birth years from 1950 to 1985 varied considerably over time (Table 2). Otoliths from quillback rockfish with birth years 1950–57 contained prebomb ^{14}C levels. Although there was more variation in these prebomb values than expected from ^{14}C uncertainties, the level was relatively consistent over time, averaging −90.7 (±11.5)‰ (mean ±SD). A sharp rise in otolith ^{14}C values was evident in 1959 (±1 year);

Table 2

Summary of fish and otolith data from quillback rockfish collected off the coast of southeast Alaska. Resolved age is the final age estimate given by Alaska Department of Fish and Game. Birth year is the collection year (2000) minus the resolved age. Age error is the uncertainty associated with the age estimate (CV=2.6%; year rounded to the nearest whole number). Radiocarbon values in the otolith cores of yelloweye rockfish are expressed as $\Delta^{14}C$ with the AMS analytical uncertainty.

Resolved age (years)	Birth year (± age error)	$\Delta^{14}C$ (‰)
50	1950 ±1	−76.9 ±3.3
46	1954 ±1	−104.8 ±3.2
45	1955 ±1	−89.0 ±4.0
43	1957 ±1	−92.2 ±3.8
41	1959 ±1	−66.9 ±3.3
40	1960 ±1	−54.7 ±4.2
39	1961 ±1	−57.8 ±3.7
37	1963 ± 1	−49.1 ±3.3
35	1965 ±1	28.2 ±3.7
33	1967 ±1	105.4 ±4.2
31	1969 ±1	19.4 ±4.0
30	1970 ±1	47.5 ±3.6
25	1975 ±1	43.9 ±4.0
20	1980 ±1	76.3 ±5.5
15	1985 ±0	15.4 ±3.7

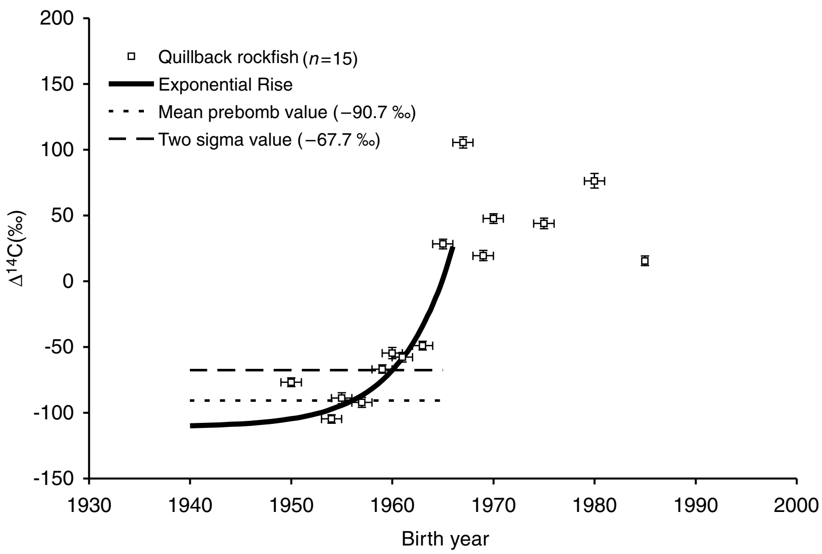

Figure 2

Radiocarbon ($\Delta^{14}C$) values for quillback rockfish (*Sebastes maliger*) otolith cores (n=15) in relation to estimated birth year. Horizontal error bars represent the age estimate uncertainty from growth zone counts (CV=2.6%, year rounded to the nearest whole number) and vertical error bars represent the 1−σ AMS (accelerator mass spectometry) analytical uncertainty. The solid line represents the exponential curve fitted to the data that was used to determine the year of initial rise in ^{14}C levels from prebomb levels (the fitted function had the form $Y=A+B\exp(CX)$ with $Y={}^{14}C$, X=birth year, and A, B, and C as fitted parameters). The dashed line represents the +2 SD level (−67.7‰) associated with the average prebomb ^{14}C value (−90.7 ±11.5‰; dotted line); the intersection of the +2 SD line and the curve was used to define the year-of-initial-rise in ^{14}C values.

this sample was the first to have a ^{14}C value (−66.9 [±3.3]‰) that was above prebomb radiocarbon levels with a +2 SD criteria (upper limit of −67.7‰). This first indication of a rise in ^{14}C related to the rise of the bomb was in agreement with the exponential fit of the quillback rockfish ^{14}C times series (Fig. 2). The ^{14}C record for quillback rockfish otoliths peaked in 1967 with a maximum ^{14}C concentration of +105.4 (±4)‰. This peak was followed by a generally declining, but inconsistent, trend in ^{14}C values to 1985 (last birth year sampled).

The ^{14}C values measured in quillback rockfish otoliths plotted against estimated birth years produced a characteristic increasing and decreasing curve representative of bomb-generated ^{14}C changes over time (Fig. 3). The quillback rockfish ^{14}C record was synchronous with a ^{14}C time series for southeast Alaskan waters determined from yelloweye rockfish otoliths (Kerr et al., 2004); the average prebomb ^{14}C values for the quillback rockfish were in close agreement with the average yelloweye rockfish prebomb levels (−102.2 [±9.3]‰ [mean ±SD]). The year of initial rise in the quillback and yelloweye rockfish records (1959 [±1 year] *cf.* 1958 [±2 years]) and peak in ^{14}C values (1967 *cf.* 1966) for these two species coincided within one year, a period encompassed within the uncertainty associated with break-and-burn age estimates. Furthermore, the postbomb decline in quillback rockfish ^{14}C values was similar to that of the yelloweye rockfish. In addition, thirteen of the fifteen quillback rockfish ^{14}C values fell within the confidence intervals of the yelloweye rockfish ^{14}C curve (Fig. 3).

The comparison of the quillback rockfish ^{14}C record with that for Hawaiian Islands corals (Toggweiler et al., 1991; Druffel et al., 2001) and two otolith-based northern hemisphere ^{14}C chronologies (northwest Atlantic haddock [Campana, 1997] and Barents Sea Arcto-Norwegian cod [Kalish et al., 2001]) revealed similarities in the year of initial rise and rate of rise of ^{14}C values, and differences in the pre- and postbomb eras that can be explained by regional oceanographic effects (Fig. 4).

Discussion

Sample size assessment

Although the ^{14}C technique has great potential for validating the age of many long-lived fishes, one of the main disadvantages has been the high cost of AMS ^{14}C analyses. By providing a means of defining the

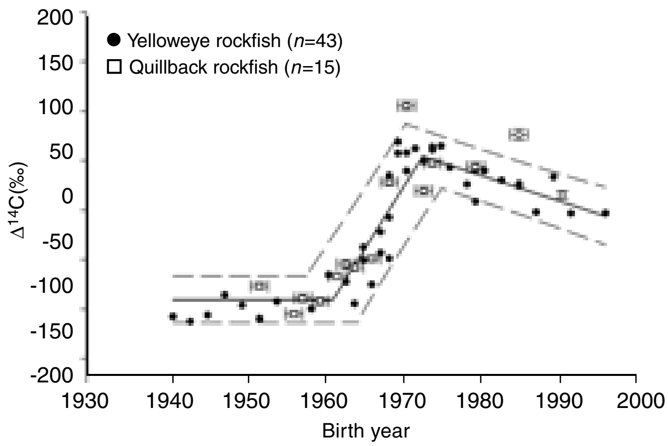

Figure 3

Radiocarbon ($\Delta^{14}C$) values from quillback rockfish (*Sebastes maliger*) otoliths and the yelloweye rockfish (*S. ruberrimus*) ^{14}C time series for the waters of southeast Alaska. The yelloweye rockfish ^{14}C data were divided into three intervals (prebomb, bomb rise, and postbomb) and fitted with confidence intervals. The prebomb era ^{14}C values (1950–57) were fitted with an average (±2 SD), and the bomb rise (1959–71) and postbomb era values (1966–85) were fitted with a linear regression and corresponding 95% prediction intervals.

minimum number of samples required to achieve the desired degree of precision, the present study takes a step toward reducing the number of prescribed samples, (i.e., 20–30 otoliths; Campana, 2001), effectively making age validation more affordable.

To determine the number of samples necessary for an age validation study, an assessment of the degree of precision is required. The degree of precision may be defined by the level of variation in the chronology or the uncertainty associated with age estimates. It can also be dependent on the estimated longevity of the fish and the resolution of age that is sufficient for the purposes of the study. For example, a resolution of ±5 years may be sufficient for a species estimated to live 100 years, but would not be satisfactory for a species estimated to live 20 years. The higher degree of precision, the greater the cost will be for a study. However, a maximum precision can be attained at a minimum cost by taking into consideration the precision of the ^{14}C time series, the error associated with age estimates, and the age resolution necessary to accomplish the goals of the study.

In our study, the ±2-year variation of the yelloweye rockfish ^{14}C time series limited the precision to which the age of the quillback rockfish could be determined through comparison. Stratified sampling of nine quillback rockfish ^{14}C values between 1956 and 1971 revealed an average year of initial rise in ^{14}C of 1959 (±1 year) that was in close agreement with the year of initial rise determined for the yelloweye rockfish time series. Thus, given the unique circumstances for this species, we have quantitatively reduced the number of samples required for age validation to 9 (given that some sampling or additional information is used to establish prebomb levels). It can also be envisioned that ^{14}C analysis of a single fish otolith could establish a minimum longevity for a species if the ^{14}C levels measured in the otolith core of an adult fish with a known capture year were consistent with established prebomb ^{14}C levels for the regional waters in which that fish spent its first year. This exercise illustrates the necessity of defining precision on a species-by-species basis prior to beginning a ^{14}C study. Despite the high cost of AMS analyses, the overall project cost may be lower and of shorter duration than traditional age validation studies because of the relatively short time required to prepare and process the minimum number of otoliths. Currently, the ^{14}C technique is considered one of the most effective methods for age validation of long-lived fishes (Campana, 2001) and as costs are minimized, future application of the bomb ^{14}C age-validation technique of marine fishes should increase.

Radiocarbon analysis

To interpret radiocarbon values recorded in marine organisms it is essential to put them in the context of the regional oceanography. The Alaska coastal current, driven by wind stress and enriched with freshwater runoff, is the driving force behind the coastal dynamics off southeast Alaska (Royer, 1982). The coastal environment off southeast Alaska is characterized by significant

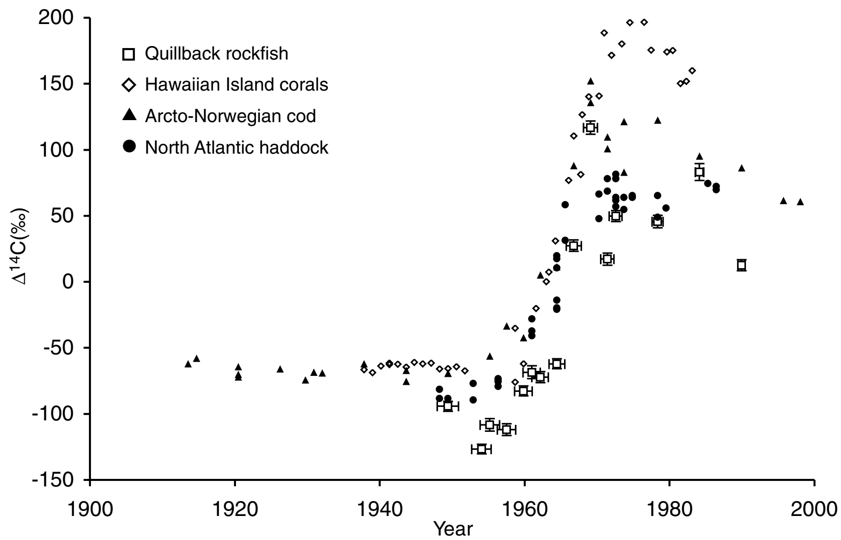

Figure 4

Radiocarbon data ($\Delta^{14}C$) from otolith cores of quillback rockfish (*Sebastes maliger*), Hawaiian hermatypic corals (Toggweiler et al., 1991; Druffel et al., 2001), and two age-validated fishes, the northwest Atlantic haddock (*Melanogrammus aeglefinus*; Campana, 1997) and the Arcto-Norwegian cod (*Gadus morhua*; Kalish et al., 2001). Note the strong agreement in the timing of the year of initial rise in ^{14}C values.

downwelling, high wind stress, eddies, and storm activity, resulting in a high degree of mixing. The rapid rise and early peak recorded in quillback rockfish otoliths, followed by a postbomb decline, indicated rapid ocean-atmosphere gas exchange in the shelf waters off southeast Alaska. Shallow continental shelf waters, such as the environment inhabited by juvenile quillback rockfish, have a thin mixed layer and relatively long surface residence time, resulting in a relatively fast response and build up of bomb-^{14}C from the atmospheric signal. In addition, low prebomb ^{14}C values in the quillback rockfish record may indicate the influence of upwelled ^{14}C-depleted waters on southeast Alaskan coastal surface waters. This is expected because surface waters sampled off the Alaskan Peninsula (GEOSECS; Ostlund and Stuvier, 1980) in 1973 had low ^{14}C values (+62‰) in relation to the subtropical Pacific (Oahu coral, +174.5‰ in 1973, Toggweiler et al., 1991), indicating the influence of upwelled ^{14}C-depleted waters.

A comparison of the ^{14}C time series determined from quillback rockfish otoliths to the established ^{14}C time series exhibited synchronicity with the global rise in radiocarbon. The quillback rockfish record and high latitude northern hemisphere records from Arcto-Norwegian cod and haddock exhibited nearly identical years of initial rise and rates of ^{14}C increase. Note that there are differences among these records in the prebomb and peak ^{14}C levels attained and the behavior of bomb-^{14}C after the peak, but it is irrelevant to the utility of the technique as an age validation tool. The quillback rockfish record was also temporally similar to a Hawaiian Island corals record (Oahu, Toggweiler et al., 1991; Hawaii, Druffel et al., 2001), both increasing rapidly from the late 1950s. However, as expected, the corals had higher prebomb levels (–50‰ *cf.* –90‰), a later peak (1971 *cf.* 1967) at a higher value (174‰ *cf.* 105‰), and the indication of a more rapid decline in the postbomb years. These differences are indicative of the different oceanographic influences on the subtropical waters (e.g., lesser relative influence of upwelled, ^{14}C-depleted, deep water).

Possible sources of error in the quillback rockfish ^{14}C record are the specific location of each fish during its first year of growth, possible inaccuracies in the method of extracting the core, age estimate uncertainty, and variable oceanographic conditions during the year of otolith formation. The unknown geographic location of individual fish during the first year of life is a potential source of ^{14}C variation. Although juvenile quillback rockfish occupy relatively limited regions, factors such as local bathymetry, coastal upwelling, and freshwater input are likely to impact the ^{14}C content of the local waters. Two of the quillback otolith samples (birth years 1967 and 1980) had considerably higher (~50‰) ^{14}C values when compared to the highest yelloweye rockfish value for that same year. These elevated ^{14}C values may indicate that the individuals resided in different water masses. The variability of otolith ^{14}C values from regional effects is evident in the observed ±11.5‰ (1 SD) associated with prebomb values, a higher variability than expected from the analytical uncertainties of the AMS ^{14}C measurements (~±3–4‰). Elevated ^{14}C levels have also been recorded in otoliths of the black drum (*Pogonias cromis*), known to reside in estuaries during the juvenile stage (Campana and Jones, 1998); these elevated values are attributed to the rapid exchange of atmospheric ^{14}C in the well-mixed estuarine environment and the influence of river input. Quillback rockfish are known to inhabit more nearshore waters than those inhabited by yelloweye rockfish (Love et al., 2002), which could explain the elevated ^{14}C levels.

The core-extraction method was designed to limit the inclusion of more recently formed material (older than age 1); however, the inclusion of some of this material may have inadvertently occurred, perhaps introducing error to the quillback rockfish ^{14}C record. This kind of error could alter the ^{14}C value from the actual core year value depending on the time of otolith formation in relation to the bomb ^{14}C signal. A small addition of material with ^{14}C content different from the core material, however, may not produce a significant change in the timing of the initial rise and the shape of the rise. We feel that in most cases this would lead to an underaging of the fish and provide us with a minimum age estimate.

Perhaps the most significant potential source of error is the uncertainty associated with age estimation methods (coefficient of variation=2.6%). Growth zone counting error could have contributed to variation in the quillback rockfish record; however, the otoliths used in our study were chosen specifically to provide clearly definable growth zones and the highest rank in age-estimate confidence. The samples chosen were best-case examples of precise age determinations.

Short-term regional-scale changes in oceanographic conditions, such as upwelling events, may have affected ^{14}C levels at the time of otolith formation. The variation in postbomb measurements exemplifies this factor.

Considering the discussions above and the similar biology, ecology, and distribution of the two rockfish species, we believe that the use of the yelloweye rockfish ^{14}C time-series (Kerr et al., 2004) as a means of temporal calibration for the quillback rockfish record is well supported. The year of initial rise in ^{14}C for quillback rockfish otoliths (1959 [±1 year]) is in agreement with the yelloweye rockfish record (1958 [±2 years]); this finding validates the age estimates of the quillback rockfish and the accuracy of the break-and-burn age estimation method. In addition, the concordance of the quillback time series (1950 to 1985) provides further support for the age validation. Note that the ^{14}C levels, timing of the peak, and the subsequent decline were similar between species. In addition, all but two of the quillback rockfish ^{14}C values (sample years 1967 and 1980) fell within the confidence intervals for the yelloweye rockfish ^{14}C curve, further supporting the concordance of the two rockfish records. If there had been consistent underaging or overaging of quillback rockfish otoliths, this discrepancy would have resulted in a chronology that was not in phase with the yelloweye rockfish time series (Campana et al., 2002).

This application of the bomb-^{14}C technique has confirmed the longevity of quillback rockfish to a minimum of 43 (±1) years. This minimum age estimate is based on the last individual fish sample (estimated birth year of 1957 from growth zone counting) to have prebomb levels, immediately preceding the significant rise in ^{14}C levels observed in 1959 (±1) year. These findings effectively refute previous longevity estimates less than 43 years (Barker, 1979; Reilly et al.[2]). In addition, it is reasonable to assume that the annual growth pattern continues throughout life; hence, these findings strongly support longevity estimates exceeding 43 years and ranging up to 90 years (Richards and Cass, 1986; Yamanaka and Kronland, 1997; Casillas et al., 1998; Munk, 2001).

Conclusions

It is our intention to not only validate the age and age estimation method for the quillback rockfish, but to determine the most effective number of samples for age validation with bomb radiocarbon. From our results, it appears that the concordance of the full ^{14}C time series is not entirely necessary for validating the age of fish, and perhaps of any other organism. Because the evolution and magnitude of the bomb-^{14}C rise from the prebomb to postbomb era is subject to variations due to the specific oceanography of the region, the ^{14}C time series are in fact regional and are not universally applicable to all validation studies. The agreement of the entire ^{14}C time series does not provide additional information relevant to age validation. Hence, we propose that the year-of-initial-rise method be considered an effective ^{14}C age validation approach. This method both reduces the number of samples required for age validation and effectively precludes the perceived need to establish a pre- to postbomb ^{14}C reference time series for every region of the world's oceans. Because the year of initial rise in ^{14}C levels in surface waters is well defined (1958 [±2 years]), it should be treated as a time-specific marker for organisms that inhabit the mixed layer of the oceans for some or all of their life cycle.

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