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# Radiometric age validation of the yelloweye rockfish (*Sebastes ruberrimus*) from southeastern Alaska

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*Abstract.* The yelloweye rockfish (*Sebastes ruberrimus*), a dominant component of an important deep-water rockfish fishery of the Gulf of Alaska, is thought to be long-lived with an estimated longevity exceeding 100 years. For the purpose of monitoring stocks, age is routinely estimated by counting growth zones in otolith cross-sections using the break-and-burn technique; however, such age estimates for this species have remained unvalidated. To evaluate these age data, age estimations from the break-and-burn technique were corroborated by comparing results from transverse sectioning of otoliths. The agreement between the techniques was excellent and each technique had a very low coefficient of variation (3.6% and 4.5%). Radiometric age validation of these estimates was performed on the otolith core material (first three years of growth) of pooled age groups having an average estimated age of 27.4–101.4 years. Agreement was variable and somewhat subjective, but radiometric data support ages estimated from otolith growth zone counts. The strongest support for age that exceeds 100 years comes from the observation that as age derived from growth zones approached and exceeded 100 years, the sample ratios measured ($^{210}$Pb:$^{226}$Ra) approached equilibrium. The radiometric results of our study validate the estimates derived from growth zones and the age estimating procedures, which confirms that the longevity of yelloweye rockfish exceeds 100 years.

## Introduction

Rockfishes (*Sebastes* spp.) of the north-eastern Pacific Ocean support one of the most economically important fisheries of California, Oregon, Washington, Alaska, and British Columbia in Canada (Yamanaka and Kronlund 1997; Fritz *et al.* 1998; Bloeser 1999). The yelloweye rockfish (*S. ruberrimus*) fishery is a deep-water fishery that has been commercially important for several decades. Yelloweye rockfish has been the dominant component of landings for British Columbia, and most of the fish taken in recent years in both Canadian and Alaskan waters were captured with longline gear (Yamanaka and Kronlund 1997). It is the dominant by-catch species in the commercial halibut fishery and an important component of the directed long-line fishery for demersal shelf rockfishes in the eastern Gulf of Alaska. In the commercial long-line fishery for demersal shelf rockfishes, yelloweye rockfish accounted for >90% of the targeted landings (O'Connell and Carlile 1993; O'Connell *et al.* 2000).

To properly manage a fishery, its age structure, growth characteristics and other life history parameters must be understood. Some life-history aspects of the yelloweye rockfish have been studied, but estimated longevity remained unvalidated (O'Connell and Funk 1986). Current longevity estimates derived from interpretations of otolith growth zones exceed 100 years for the yelloweye rockfish (O'Connell and Funk 1986; Yamanaka and Kronlund 1997); centenarian rockfish species may be more common than previously known, and the reasons for their great longevity are the subject of much speculation (Cailliet *et al.* 2001; Munk 2001).

Fisheries management strategies rely heavily on accurate age determinations. Fish age is typically determined by one of several techniques, but most commonly by quantifying growth zones in calcified structures (Chilton and Beamish 1982; Beamish and McFarlane 1987). The annual periodicity of growth-zone formation in these structures is often assumed and was rarely validated in the past (Beamish and McFarlane 1983). As a consequence, underestimated ages and over-fishing may have contributed to the decline of the Pacific ocean perch (*Sebastes alutus*) of the north-eastern Pacific Ocean (Beamish 1979; Archibald *et al.* 1983; McFarlane and Beamish 1995) and the orange roughy

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(*Hoplostethus atlanticus*) off New Zealand (Mace *et al.* 1990; Smith *et al.* 1995). The problem with conventional techniques for the validation of ages derived from growth zones (e.g. marking and recapturing) is that they are difficult to conduct on deepwater or long-lived fishes (Macdonald 1987; Mace *et al.* 1990; McFarlane and Beamish 1995). One technique that can be used is radiometry of the disequilibrium of $^{210}$Pb and $^{226}$Ra in otoliths as a natural chronometer (Smith *et al.* 1991). Estimates of age and growth reported for at least 20 fish species have been validated by this technique (Fenton 1992; Burton *et al.* 1999; Andrews *et al.* 1999*a,* 2001; Kastelle *et al.* 2000).

Radiometric ageing is a process that uses naturally occurring radioisotopes in calcified structures to determine age. In fishes, this technique relies on the incorporation of $^{226}$Ra, a naturally occurring radioactive isotope that is a calcium analogue, from the environment into the calcium carbonate matrix of otoliths and skeletal structures. Once $^{226}$Ra is incorporated into the structure, it decays through a series of short-lived daughter isotopes to the more stable isotope $^{210}$Pb. Because the half-life of $^{226}$Ra (1622 years) is much greater than the half-life of $^{210}$Pb (22.26 years), $^{210}$Pb will build into secular equilibrium with $^{226}$Ra over time, where the activity ratio of $^{210}$Pb:$^{226}$Ra asymptotically approaches a ratio of 1.0 (Ivanovich and Harmon 1992). Hence, the disequilibrium of $^{210}$Pb relative to $^{226}$Ra in the oldest part of the calcified structure, in this case the otoliths, can be used to determine age (Smith *et al.* 1991).

The goals of this study were to describe and validate the growth of the yelloweye rockfish. Growth was described using existing age data from archived otoliths, which were aged by the break-and-burn technique, and fitted to the von Bertalanffy growth function. Age estimates derived from the break-and-burn technique were corroborated by an otolith-sectioning technique, and these age estimates, along with their procedures, were validated by the disequilibria of $^{210}$Pb and $^{226}$Ra in otolith cores of adult yelloweye rockfish.

## Materials and methods

The Alaska Department of Fish and Game (ADFG) in Juneau, AK, provided archived yelloweye rockfish otoliths and their records from off southeastern Alaska. The collection years 1984, 1991, 1992 and 1994–98 contained enough samples for a comprehensive study that would cover the age range of the species, with several old age groups that were near or above 100 years in age. Sexes were not separated because there was no evidence for sexual dimorphism in yelloweye rockfish (O'Connell and Funk 1986). Of the otolith pair collected for each fish, one otolith was previously aged by the ADFG Mark Tag and Age Laboratory in Juneau, using a traditional ageing technique (break-and-burn). The other otolith was used for radiometric age determination at Moss Landing Marine Laboratories (MLML).

To corroborate the break-and-burn age estimates, we selected a separate series of otolith samples, which were chosen by age, ranging from young ages to old ages ($n = 45$). These samples were transversely sectioned with a Buehler® Isomet low-speed bone saw with two Norton low-density diamond blades separated by 2 acetate spacers (total 0.5 mm). Sections were mounted to glass microscope slides and polished to an optimal viewing thickness on a Buehler® Ecomet III lapping wheel with 600–1200 grit silicon-carbide wet/dry sandpaper. Polished sections were viewed with a dissecting microscope, and the magnification necessary to count growth zones was from 16 to 40 times. Growth zones were defined as a set of light and dark bands or rings. To make the growth zones visible in the sections, the angle of the light being transmitted through the otolith had to be varied because clarity changed along the count transect. The total number of growth zones counted along each transect was used as an estimate of age. The findings from this technique were compared with the break-and-burn technique used on the other otolith at ADFG by use of a one-to-one plot and a regression significance *t*-test. A von Bertalanffy growth curve and parameters for yelloweye rockfish (O'Connell *et al.* 2000) provided context to this study.

To obtain enough material for radiometric analysis it was necessary to pool otoliths into age groups. Age groups were formed from the archived otoliths by searching for batches of otoliths with a similar or narrow age range (e.g. 50–55 years). Based on previous studies it was known that approximately 10–40 otoliths would be needed to gather enough core material for analysis. Radiometric analysis of the age groups involved the use of well established protocols, developed and refined at MLML, described below and in Andrews *et al.* (1999*b*).

The application of the radiometric age determination method, without making assumptions regarding constant accumulation rates within the otolith (Campana *et al.* 1990), requires that the younger, outer portion of the otoliths be removed from adult fishes. Thus, the disequilibrium of $^{210}$Pb to $^{226}$Ra measured is contained within the portion formed during juvenile growth. Otolith core size was determined by measuring the dimensions of the first 3 years of growth in the core region of adult otoliths (no otoliths from fish aged 3 year were available). The average dimensions of the first 3 years of growth from 42 transverse and 10 frontal sections were approximately 4.0 mm long by 3.0 mm high by 0.7 mm thick. To get to the oldest part of the otolith, adult otoliths were cored by hand by grinding the whole otolith to the core dimensions. Coring was performed on a Buehler Ecomet III lapping wheel with 120 to 300-grit silicon-carbide paper. In addition to the core dimensions, core weight was used as a measure of coring consistency (~0.025 g). Trace-metal precautions during sample cleaning and processing (Linn 1988; Fabry and Delaney 1989; Watters 1995) preceded radiometric analysis of juvenile and adult age groups (after coring), because of the extremely low levels of $^{210}$Pb and $^{226}$Ra. All acids used in radiometric procedures were double distilled (GFS Chemicals®) and dilutions used Millipore® filtered Milli-Q water (18 M$\Omega$ cm$^{-1}$).

When samples had been rigorously cleaned and dried to constant weight (Andrews *et al.* 1999*b*), they were first analysed for $^{210}$Pb. Due to the relatively low activity and low $\beta$-emission energy of $^{210}$Pb, the detection of $^{210}$Pb was accomplished by proxy, the autodeposition and $\alpha$-spectrometric determination of its daughter, polonium–210, $^{210}$Po (Flynn 1968). To ensure that all of the $^{210}$Po activity was due to ingrowth from $^{210}$Pb and that $^{210}$Po:$^{210}$Pb was in secular equilibrium, all samples were collected at least 2 years prior to processing. Samples prepared for $^{210}$Po analysis were spiked with a yield tracer, $^{208/209}$Po, and calibrated against NBS and geological standards (Williams 1988).

Spiked samples were dissolved in ~50 mL of 0.5N HCl on a hot plate (90°C). The $^{210}$Po and $^{208/209}$Po-tracer were autodeposited onto a purified silver planchet (99.999%, A.F. Murphy Die and Machine Co.) held in a rotating Teflon holder over a 4 h period (Flynn 1968). Planchets were analysed using both silicon surface barrier detectors and ion implant detectors in eight Tennelec TC256 alpha-spectrometers interfaced with a multi-channel analyser and an eight-channel digital multi-plexer. Counts were collected with Nucleus® software on an IBM-PC. The sample remaining after polonium autodeposition was dried and used for $^{226}$Ra analysis.

Activity of $^{210}$Po was calculated in the following manner. Counts collected by α-spectrometry for $^{210}$Po and $^{208}$Po were corrected for background and reagents by subtracting the amount of counts calculated to occur for counting time by reference to the rates measured for reagent blanks. Errors reported represent those propagated for all known sources including count statistics (pipetting error, yield-tracer uncertainty, etc.). $^{210}$Po activity can be determined from the corrected $^{210}$Po:$^{208}$Po activity ratio. Because the activity of $^{210}$Po was in secular equilibrium with $^{210}$Pb, the activity of $^{210}$Po was equal to the $^{210}$Pb activity. After $^{210}$Po was plated for each sample, $^{226}$Ra was measured from the remaining plating solution. Subsequent $^{226}$Ra analysis on the plating solution proceeded according to the methods of Andrews *et al.* (1999*b*).

Radiometric age was determined by applying the measured $^{210}$Pb and $^{226}$Ra activities to equations based on the secular equilibrium model (Smith *et al.* 1991). Because the activities were measured on the same sample, the calculation is independent of sample mass. A graphical comparison of the measured $^{210}$Pb:$^{226}$Ra ratio for each age group with the expected ratio from ingrowth was plotted to illustrate the trend observed. Radiometric age for each group was corrected for $^{210}$Pb ingrowth from the time of capture of the fish to autodeposition by subtracting the time elapsed between capture and plating. The age-group range was widened by a coefficient of variation determined from the uncertainty in otolith reading, from both break-and-burn and section ageing. A linear regression of these data was compared with a line of agreement or one-to-one using a regression significance *t*-test. A paired two-sample *t*-test was also used to determine whether a significant difference existed between the age determinations. From these comparisons, the validity of the age estimates derived from growth zones was determined.

## Results

The transverse otolith sections from the series of otoliths (young to old) were relatively easy to read and many had growth zones that were clearly defined (Fig. 1). Growth zones seen in sections were broad at first (first 5–10 years) and rapidly became thin and compressed toward the edges in old adult fishes, especially the centenarians.

The comparison between the two traditional ageing techniques, break-and-burn *v.* transverse sectioning, revealed no significant difference between the two techniques (paired two-sample *t*-test: df 44, $t$ = 0.715, $P$ = 0.478; Fig. 2). Between the two methods, 40% of the readings were within ± 1 year, 62% were within ± 2 year, and 89% were within ± 5 year. Only one specimen differed greatly (24 years) between the techniques. The range of ages used in this comparison was 15–117 years. For the transverse-section ageing, the overall CV was 4.5% with an average error of 2.6% for the three readers at MLML. For break-and-burn age estimates, the overall CV was 3.6% with an average error of 2.0% for three readers at ADFG. The figure for break-and-burn age estimates applies to all otoliths used in the radiometric portion of this study because they were pooled on the basis of age determined at ADFG.

Fitting the von Bertalanffy growth curve to the age and length data from O'Connell *et al.* (2000) revealed a growth

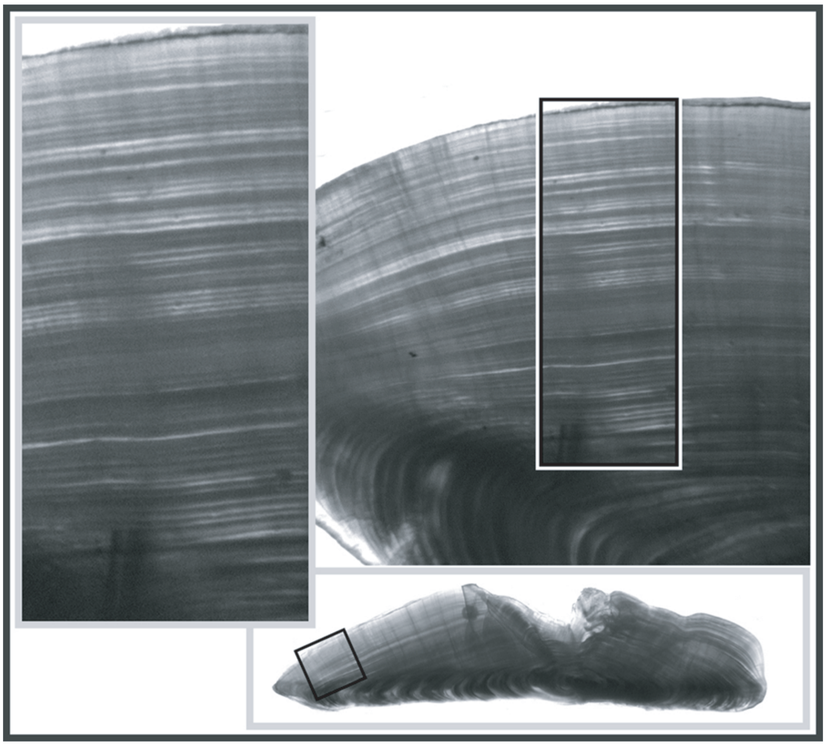

**Fig. 1.** Transverse cross section of an otolith from a yelloweye rockfish (*Sebastes ruberrimus*) showing the well defined growth zones at three different magnifications (approximately 10×, 32×, and 50×) with transmitted light. Thickness of section ~0.5 mm. Estimated age of fish 106 years.

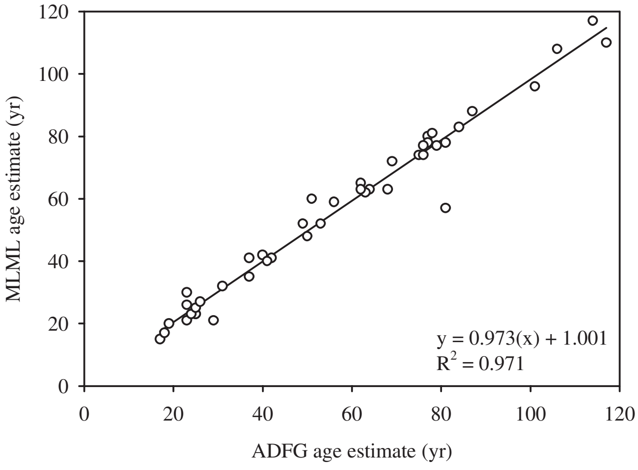

**Fig. 2.** Strong agreement between the two traditional ageing techniques used for yelloweye rockfish. Break-and-burn estimates at ADFG and estimates for transverse sections at MLML used otoliths from the same fish.

pattern that was similar to that of many long-lived fishes, with attainment of maximum or asymptotic length late in life at about 30–50 years (Fig. 3). Once maximum length is reached, growth appears to slow or cease as the fish approaches an age exceeding 100 years. The highest estimate of age for these data was for a female at 105 years, and growth parameters for combined sexes ($n = 2203$) were 644 mm fork length (FL) for asymptotic length ($L_\infty$) with a growth coefficient ($k$) of 0.0459. Results for separate sexes (not plotted, for clarity) were as follows: males had an asymptotic length of 643 mm FL and a growth coefficient of 0.0512 ($n = 1112$); females had an asymptotic length of 659 mm FL and a growth coefficient of 0.0372 ($n = 1091$).

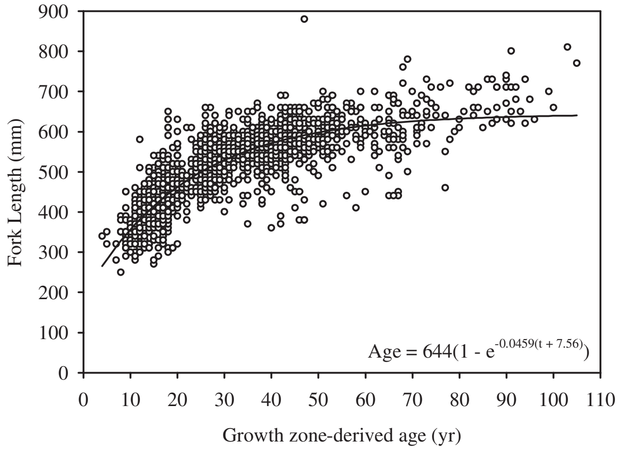

**Fig. 3.** Von Bertalanffy growth curve fitted to the data used for the yelloweye rockfish (*Sebastes ruberrimus*) stock assessment (O'Connell *et al.* 2000). Age of fish was based on growth-zone-derived estimates using the break-and-burn technique.

Otolith cores from twelve age groups of fish aged at ADFG were selected and processed for radiometric age determination. Age groups derived from growth zones ranged from 27.4 to 101.4 years (mean age), with each group spanning 6–10 years (Table 1). Most age groups were from collections made in 1984 and three from the 1990s. The capture date composition was kept as narrow as possible, usually within 1 year, but two age groups exceeded 1 year in order to obtain a large enough sample (Y9 and Y10). Fork-length composition for the age groups ranged from 410–610 mm (529 ± 43 mm average) for the youngest group to 630–770 mm (694 ± 54 mm average) in the oldest group. Total number of otoliths in each age group ranged from 9 in one of the oldest age groups to around 40–50 in the more plentiful younger age groups. Samples Y2 and Y3 were a gravimetric split of one dissolved sample, an age group composed of 50 otolith cores. Overall, sample weight ranged from 0.2224 to 1.2010 g and the average core weight was very consistent at about 0.025 g per core.

All twelve samples were processed for $^{210}$Pb and $^{226}$Ra, which resulted in measurable activities (Table 2). For $^{210}$Pb determination, samples were processed by α-spectrometry by proxy of its daughter product, $^{210}$Po; samples were counted on the α-spectrometer for periods greater than 30 days. $^{210}$Pb activities increased, as predicted, with increasing age from 0.02089 ± 5.1% dpm $g^{-1}$ for the youngest to 0.03558 ± 7.8% dpm $g^{-1}$ for the oldest age groups. The activity of $^{226}$Ra ranged from 0.02761 ± 1.4% to 0.03468 ± 1.2% dpm $g^{-1}$. $^{210}$Pb:$^{226}$Ra activity ratios for ten of the twelve samples were defined (0.7567 to 0.9588); a ratio between zero and one is required for age determination because a ratio exceeding one becomes undefined. The ratio for the remaining two samples, however, was very close to 1.0 (1.0684 and 1.0966), indicating that the samples were near equilibrium and must have been approaching the maximum age detectable by this method (~120 years).

Radiometric age was determined for ten of the twelve samples and ranged from 30.5 to 94.6 years (Table 3). The margin of error associated with each radiometric age determination either overlapped or fully encompassed the age range estimated from counts of growth zones (including 4% CV for estimated age) in all ten samples. The split sample (35–40 years) should have yielded the same age for each determination, but did not. One closely agrees with the age derived from growth zones, but the other overlaps and ranges higher. The upper limit on the radiometric age range determined for each sample exceeded 100 years for two samples and was undefined for five samples. The undefined limit was caused by a calculated $^{210}$Pb:$^{226}$Ra ratio that exceeded 1.0 for those samples. The lower limit on samples with a defined radiometric age ranged from 24.6 to 58.5 years. The two samples that had a measured $^{210}$Pb:$^{226}$Ra ratio that exceeded 1.0 had lower limits of 134 years and 157 years.

Regressions were fitted to the two different age-data sets for comparison, one for the samples with a defined

**Table 1. Detailed summary of data for pooled otolith age groups for yelloweye rockfish**

Range of age groups is based on growth-zone-derived age estimates from ADFG using the break-and-burn technique. Capture dates and total length (with average FL length ± s.d. in parentheses) are also listed for comparison. The number of otolith cores equals the number of fish

| Sample | Age group (years) | Average age (years) | Capture date range (span years) | Fork length (mm) | No. otolith cores | Sample weight (g) |
|---|---|---|---|---|---|---|
| Y1 | 25–30 | 27.4 | 11 Mar.–27 Nov. 1984<br>(0.71) | 410–610<br>(529 ± 43) | 39 | 0.9389 |
| Y2 | 35–40 | 37.6 | 17 Mar.–17 Dec. 1984<br>(0.75) | 430–566<br>(566 ± 49) | ~25 | 0.6402 |
| Y3 | 35–40 | 37.6 | 17 Mar.–17 Dec. 1984<br>(0.75) | 430–566<br>(566 ± 49) | ~25 | 0.6598 |
| Y4 | 50–55 | 52.7 | 11 Mar.–17 Dec. 1984<br>(0.77) | 490–700<br>(615 ± 47) | 47 | 1.1238 |
| Y5 | 60–65 | 61.9 | 11 Mar.–17 Dec. 1984<br>(0.77) | 490–730<br>(616 ± 58) | 52 | 1.2010 |
| Y6 | 70–75 | 72.2 | 11 Mar.–17 Dec. 1984<br>(0.77) | 530–720<br>(623 ± 54) | 29 | 0.6782 |
| Y7 | 80–88 | 83.0 | 11 Mar.–1 May 1984<br>(0.14) | 510–770<br>(629 ± 55) | 39 | 0.9423 |
| Y8 | 89–95 | 91.6 | 11 Mar.–23 Apr. 1984<br>(0.12) | 570–730<br>(635 ± 48) | 19 | 0.4933 |
| Y9 | 97–100 | 98.1 | 19 Feb. 1991–16 Dec. 1992<br>(1.82) | 560–710<br>(646 ± 38) | 14 | 0.3805 |
| Y10 | 98–107 | 101.4 | 4 Jan. 1995–19 Nov. 1996<br>(1.88) | 630–770<br>(694 ± 54) | 17 | 0.4416 |
| Y11 | 97–106 | 101.0 | 17 Mar.–28 Apr. 1984<br>(0.11) | 540–750<br>(642 ± 62) | 9 | 0.2224 |
| Y12 | 97–107 | 100.8 | 11 Jan.–8 Aug. 1994<br>(0.57) | 600–710<br>(657 ± 35) | 11 | 0.3033 |

radiometric age and another taking into consideration the lower limit of the samples with an undefined age. The slope of the regression for the defined age samples ($n$ = 10) was 0.546 with a fairly good fit ($R^2$ = 0.523), which seemed to indicate that age derived from growth zones was overestimated for the oldest fish. This slope was tested for a difference from a hypothetical slope of 1 (line of agreement) using a $t$-test and was found to be significantly different (df 9, $t$ = 2.46, $P$ <0.05). A paired-sample $t$-test, however, indicated that there was no difference between the individual age estimates (df 9, $t$ = 0.657, $P$ = 0.528). The other regression, taking into consideration the defined lower limit of the samples with an undefined radiometric age ($n$ = 12), had a slope of 0.980 ($R^2$ = 0.530), which was in close

**Table 2. Radiometric results for each age group**

| Age group (years) | Sample weight (g) | $^{210}$Pb (dpm g$^{-1}$) ± % error[A] | $^{226}$Ra (dpm g$^{-1}$) ± % error[B] | $^{210}$Pb:$^{226}$Ra activity ratio | $^{210}$Pb:$^{226}$Ra (low) | $^{210}$Pb:$^{226}$Ra (high) |
|---|---|---|---|---|---|---|
| 25–30 | 0.9389 | 0.02089 ± 5.1 | 0.02761 ± 1.4 | 0.7567 | 0.7074 | 0.8074 |
| 35–40 | 0.6402 | 0.02754 ± 6.2 | 0.03126 ± 1.3 | 0.8820 | 0.8167 | 0.9489 |
| 35–40 | 0.6598 | 0.02633 ± 5.6 | 0.03424 ± 1.1 | 0.7684 | 0.7170 | 0.8210 |
| 50–55 | 1.1238 | 0.03098 ± 4.4 | 0.03347 ± 1.3 | 0.9255 | 0.8731 | 0.9793 |
| 60–65 | 1.2010 | 0.03069 ± 4.2 | 0.03214 ± 1.8 | 0.9547 | 0.8988 | 1.0126 |
| 70–75 | 0.6782 | 0.03158 ± 4.9 | 0.03468 ± 1.2 | 0.9106 | 0.8554 | 0.9672 |
| 80–88 | 0.9423 | 0.03040 ± 4.6 | 0.03313 ± 1.5 | 0.9176 | 0.8616 | 0.9753 |
| 89–95 | 0.4933 | 0.02981 ± 5.4 | 0.03309 ± 1.2 | 0.9007 | 0.8413 | 0.9617 |
| 97–100 | 0.3805 | 0.02697 ± 7.6 | 0.02813 ± 1.9 | 0.9588 | 0.8693 | 1.0518 |
| 98–107 | 0.4416 | 0.03212 ± 6.5 | 0.03007 ± 1.2 | 1.0684 | 0.9864 | 1.1524 |
| 97–106 | 0.2224 | 0.03214 ± 8.6 | 0.03425 ± 3.5 | 0.9384 | 0.8283 | 1.0565 |
| 97–107 | 0.3033 | 0.03558 ± 7.8 | 0.03244 ± 1.8 | 1.0966 | 0.9937 | 1.2032 |

[A] Calculation based on standard deviation of $^{210}$Pb activity, the delta method (Wang *et al.* 1975; Knoll 1989).

[B] Calculation based on TIMS analysis routine (± 1 s.e.) and the delta method (Knoll 1989).

**Table 3. Comparison of growth-zone-derived ages and radiometric ages for yelloweye rockfish**

A Coefficient of Variation (CV) of 4% extended the age group range by a few years. Average age of groups was based on growth-zone-derived age estimates. Radiometric age calculations were based on the measured ratio of $^{210}$Pb:$^{226}$Ra in each sample. Radiometric age range was based on low and high activity ratios from analytical uncertainty calculations. The degree of age-range agreement is noted where the radiometric age range either overlapped or fully encompassed the age-group age range with the 4% CV

| Age group (years) | Age group (CV = 4%) | Average age (years) | Radiometric age (years) | Radiometric age range (years) | Age range agreement |
|---|---|---|---|---|---|
| 25–30 | 24–31 | 27.4 | 30.5 | 24.6–38.0 | Overlaps |
| 35–40 | 34–42 | 37.6 | 53.8 | 39.6–80.7 | Overlaps |
| 35–40 | 34–42 | 37.6 | 32.1 | 25.7–40.4 | Overlaps |
| 50–55 | 48–57 | 52.7 | 68.6 | 51.5–109.7 | Overlaps |
| 60–65 | 58–68 | 61.9 | 84.3 | 58.5–Undefined | Overlaps |
| 70–75 | 67–78 | 72.2 | 62.3 | 46.9–94.5 | Encompasses |
| 80–88 | 77–92 | 83.0 | 65.0 | 48.3–103.7 | Encompasses |
| 89–95 | 85–99 | 91.6 | 59.0 | 43.9–89.5 | Overlaps |
| 97–100 | 93–104 | 98.1 | 94.6 | 57.2–Undefined | Encompasses |
| 98–107 | 94–111 | 101.4 | Undefined | 134.0–Undefined | Exceeds |
| 97–106 | 93–110 | 101.0 | 74.2 | 41.3–Undefined | Encompasses |
| 97–107 | 93–111 | 100.8 | Undefined | 157.1–Undefined | Exceeds |

agreement with a slope of 1.0 (df 11, $t = 0.069$, $P > 0.95$). In addition, a paired sample *t*-test indicated that there was no difference between the age estimates (df 11, $t = 0.563$, $P = 0.585$). In general, there was agreement between age derived from growth zones and radiometric age when the range for each radiometric age estimate was subjectively compared with the age range for each group (Table 3).

There was a strong concordance of the measured $^{210}$Pb:$^{226}$Ra ratios for the pooled otolith samples, plotted with respect to total sample age (age derived from growth zones, plus time since collection), with the expected $^{210}$Pb:$^{226}$Ra ingrowth curve (Fig. 4). The close proximity of the measured ratios to 1.0 indicated that the samples were near equilibrium. On the basis of this observation and the strong concordance of the measured ratios with the expected ingrowth curve, the oldest yelloweye rockfish samples processed in this study were >100 years old.

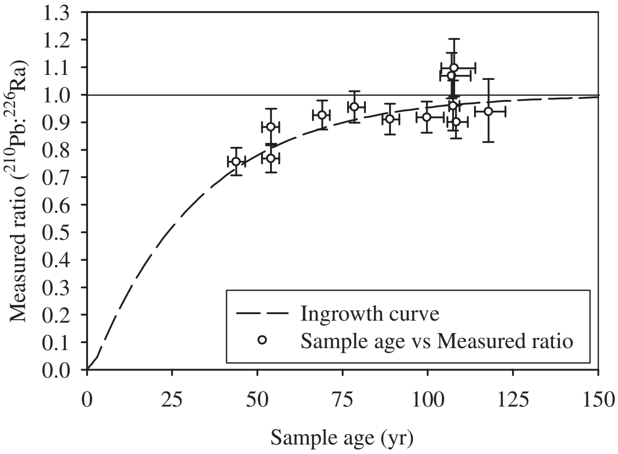

**Fig. 4.** Measured $^{210}$Pb:$^{226}$Ra ratios plotted with respect to total sample age (growth-zone-derived age estimates and the time since capture), with the expected $^{210}$Pb:$^{226}$Ra ratio (ingrowth curve) for the yelloweye rockfish. Horizontal error bars: growth-zone-derived age range with a 4% CV taken into consideration. Vertical error bars: analytical uncertainty (1 s.e.) associated with measuring $^{210}$Pb and $^{226}$Ra.

## Discussion

The landmark paper describing the disparity between researchers using the surface of the otolith and those using transverse sections to determine the age of Pacific ocean perch (*S. alutus*) established the now widely accepted view that surface estimates from otoliths can severely underestimate age (Beamish 1979). Thin transverse sections have proven to be a valuable means of age estimation because they allow fine discrimination of growth zones, preservation of the sample, and ageing of the same specimen by many readers. In routine production age determination, the break-and-burn method is used largely because of convenience, and it is the means by which the yelloweye rockfish samples used in this study were aged. Unfortunately, this method does not provide a preserved record of age because the broken and burnt section deteriorates within a short time. Because our study was aimed at validating the age estimations for the yelloweye rockfish, we decided to make a comparison between break-and-burn and transverse-section ages. There was remarkable agreement between the age estimations made at ADFG and MLML using two different techniques. Each technique had a very high precision, and agreement among readers was very good. This indicated that the growth-zone pattern quantified with each technique was similar and that otoliths of yelloweye rockfish were unambiguous and relatively easy to read. The sections made in this study have created a preserved record of age estimates for the yelloweye rockfish.

The range of age groups used in this study was unique because numerous samples were available at the oldest ages. Generally for fish collections, the oldest members of the population tend to be the least numerous and are often rare. This can be largely attributed to the fact that survivorship is low and there are few unexploited populations; exploitation can artificially reduce observed longevity (Craig 1985). The age data determined by ADFG for the yelloweye rockfish seemed to indicate that older fish were becoming less numerous because the maximum age observed had declined from the 1980s; however, this observation must be taken cautiously as this could easily be an artifact of sampling bias.

In previous studies, measurement of the $^{210}$Pb:$^{226}$Ra activity level in juvenile otoliths was used to determine whether an adjustment was necessary for any exogenous uptake of $^{210}$Pb (Andrews *et al.* 1999*a*; Kastelle *et al.* 2000). Because juvenile yelloweye rockfish were not available at a young enough age (preferably the age of the core; in this case 3 years) and in sufficient number to do a baseline determination of the initial $^{210}$Pb:$^{226}$Ra activity ratio, we assumed that the initial ratio was zero. On the basis of results for other rockfishes, it is possible that this assumption was invalid (Kastelle *et al.* 2000); however, assumption of an initial uptake ratio of 0.1 would have had little effect, reducing the radiometric ages by 3.4 years.

It is possible to attribute the undefined radiometric ages to contamination from lead sources while the material was stored for extended periods of time. Most of these samples were more than a decade old and had been stored in alcohol, most of which had dried since storage. An attempt was made to minimize any possible problems from storage conditions by removing otoliths that had adhering organic substances and avoiding the few that were still in alcohol. Because the otoliths were thick and the core region was buried deep within the otolith, it was thought that contamination from storage could be removed by grinding away the outer layers. The side of the otolith distal to the brain and opposite the sulcus (valley) of yelloweye rockfish otoliths, however, does not accrete as much material as other parts of the otolith. During the coring procedure, this side was not ground down as much as other surfaces, and it is possible that adsorbing $^{210}$Pb contamination made its way into the sample via this avenue. The activity of $^{226}$Ra was fairly constant among the core samples, which indicated that uptake from the environment for juvenile fish has varied little over a century (mean = 0.03204 ± 0.00235). This finding is similar to determinations made in a preliminary yelloweye rockfish study (mean = 0.0295 ± 0.0025; Andrews *et al.* 1999*b*).

The strongest support for age that exceeds 100 years comes from the observation that as age derived from growth zones approached and exceeded 100 years, the sample ratios measured approached equilibrium ($^{210}$Pb:$^{226}$Ra = 1.0). For these samples to attain a measured activity ratio near equilibrium, where minor variations due to analytical error or random error in counting statistics can explain the variations in the measured ratio, the age of the fish comprising these samples must have been near the limit of the radiometric method. Although it is uncertain what the exact sample age was, it is certain that the average age of the fish in these samples exceeded 100 years. The highest reported age estimate of 118 years (O'Connell and Funk 1986), which was recently increased to 121 years (Munk, unpublished), and the von Bertalanffy growth parameters determined for use in the yelloweye rockfish stock assessment (O'Connell *et al.* 2000), which are presented here, are valid descriptions of potential longevity, age and growth. The radiometric results of our study validate the age estimates derived from growth zones, support the estimating procedures, and confirm that the yelloweye rockfish has a longevity that exceeds 100 years.

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