$^{210}Pb/^{226}Ra$ Determination of Longevity in Redfish

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Campana, S. E., K. C. T. Zwanenburg, and J. N. Smith. 1990. $^{210}Pb/^{226}Ra$ determination of longevity in redfish. Can. J. Fish. Aquat. Sci. 47: 163–165.

Examination of annular growth rings apparent in charred otolith cross sections is the basis for reports of extreme longevity in the rockfish genus *Sebastes*, but the interpretation of the annuli has long been disputed. We used a radiochemical assay of the otolith core to confirm our interpretation of annuli in Atlantic redfish, *Sebastes mentella*, to at least an age of 65 yr. Through measurement of the radioactive disequilibrium between ^{226}Ra and ^{210}Pb, it appears that redfish live to an age of at least 75 yr in the waters off of Nova Scotia.

Les données sur l'extrême longévité des sébastes du genre *Sebastes* proviennent de l'examen des anneaux de croissance annuelle visibles dans des coupes transversales d'otolithe brulées. Toutefois, l'interprétation des annuli a longtemps fait l'objet d'une controverse. Un examen radiochimique du noyau de l'otolithe a permis de confirmer notre interprétation des annuli chez le sébaste atlantique (*Sebastes mentella*) jusqu'à au moins 65 ans. D'après la quantification du déséquilibre radioactif entre Ra^{226} et Pb^{210}, il semble que le sébaste atteint au moins 75 an dans les eaux hauturières de la Nouvelle-Écosse.

Received April 27, 1989
Accepted August 23, 1989
(JA152)

Reçu le 27 avril 1989
Accepté le 23 août 1989

Several north temperate fish species are reputed to have lifespans over 60 yr (Power 1978; Beamish and Chilton 1982; Chilton and Beamish 1982; Beamish and McFarlane 1985), but the reported maximum ages have varied widely depending upon the choice of ageing methodologies and the interpretation of the investigator (Boehlert and Yoklavich 1984; Campana 1984). Recent findings indicate that annular growth rings apparent on scales and the surface of otoliths can underestimate the true age of old fishes by up to a factor of three (Beamish 1979; Casselman 1987). Such errors can confound any attempt at optimal management of a fish stock. Examination of charred otolith cross sections is now the preferred age determination technique for many species, but controversy concerning the interpretation of annuli remains (NAFO 1983; ICES 1984). Through recapture of tagged fish, annulus formation up to an age of 34 yr has been validated in the rockfish genus *Sebastes* (Leaman and Nagtegaal 1987). Unfortunately, the most controversial age determinations have usually been associated with fish that are much older. In a seminal study, Bennett et al. (1982) conducted a radiochemical assay of entire otoliths, concluding that *Sebastes diploproa* lived to considerably greater ages than was indicated by annuli visible on the otolith surface. In demonstrating the potential power of their age determination methodology, these authors highlighted the relative imprecision of $^{210}Pb:^{226}Ra$ ratios when applied to entire otoliths. We avoided a number of sources of potential error, and increased the precision of this geochronological technique by restricting the analysis to the extracted otolith core. Through use of a series of age-stratified samples, we used the $^{210}Pb:^{226}Ra$ ratio in the otolith core as a radiochemical clock to test our interpretation of annuli in Atlantic redfish, *Sebastes mentella*.

Materials and Methods

Redfish were collected from depths of 200–900 m along the edge of the Scotian Shelf in October, 1985 and 1986 (Zwanenburg and Hurley 1987). Sagittal otolith pairs ($n = 2775$) were extracted from fresh specimens and stored dry in paper envelopes. One otolith from each pair was cracked, charred, and coated with oil for the determination of fish age (Christensen 1964). Annuli were counted under 50× magnification at least twice by each of two independent readers, using criteria established by Beamish (1979). The remaining otolith from fish of age categories 6, 10–15, 20–25, 30–35, 40–45, 50–55, and 60+ yr were selected for core extraction and radiochemical analysis.

Otolith cores were extracted as rectangular blocks centred around the otolith nucleus. The location of the nucleus was assessed in relation to intact otolith morphology, and confirmed through sectioning of test samples. Block dimensions (6.3 × 3.2 × 0.94 mm) were derived from measurements of 5-yr old sagittae (length, width, and thickness, mean (SD) = 6.33 (0.12), 3.62 (0.51), and 0.95 (0.12) mm, respectively; $n = 18$). While a block is a crude approximation of otolith shape, the relatively large annuli in young otoliths imply that slight errors in measurement or extraction would have little effect on the mean age of the core. Cores were isolated with a low-speed, diamond-bladed saw, thinned with a metallurgical polishing machine, and cleansed of surface residue. Cores were subse-

TABLE 1. Radionuclide measurements on otolith cores. $^{210}P_o$ and $^{208}P_o$ tracer-plated silver discs were counted 3–4 wk in an alpha spectrometer to obtain the count statistics. The mean ^{226}Ra activity (five whole otolith samples, approximately 13 g each) was 0.033 ± 0.002 dpm/g. Data are given with 1 sigma counting uncertainties. Sample ages were derived from annulus counts of the otolith, and incorporated the time between sampling and radiochemical analysis.

Mean sample age (yr)	^{210}Pb (dpm/g)	$^{210}Pb/^{226}Ra$ (dpm/g)
8.4	0.0077 ± 0.0012	0.233 ± 0.039
14.1	0.0103 ± 0.0015	0.312 ± 0.049
24.8	0.0197 ± 0.0036	0.597 ± 0.115
33.8	0.0182 ± 0.0023	0.552 ± 0.077
44.8	0.0260 ± 0.0031	0.788 ± 0.105
54.2	0.0242 ± 0.0030	0.733 ± 0.101
65.0	0.0268 ± 0.0036	0.812 ± 0.120

quently pooled within age categories to form samples weighing approximately 1.0 g (21–28 cores).

The ^{210}Pb activity was determined by alpha spectrometric measurements of ^{210}Po, while ^{226}Ra was measured with a radon gas emanation technique (Smith and Walton 1980) as modified by Bennett et al. (1982) for otolith analyses. The ^{210}Pb blank was 0.0005 dpm and background counts were less than $1.0 \cdot d^{-1}$. ^{226}Ra analyses of both the core samples and 13 g whole-otolith samples ($n = 5$), revealed no significant differences in ^{226}Ra concentration between the two types of sample; therefore, the more precise whole-otolith ^{226}Ra values were used in calculations of ^{210}Pb ingrowth rates (Table 1). The otoliths were sufficiently old that ^{210}Po (half-life, 138 d) and ^{210}Pb would be in secular equilibrium, and sufficiently young for there to have been negligible decay of ^{226}Ra (half-life, 1608 yr).

To corroborate our annulus interpretations, we sent subsamples of our aged otoliths, stratified by age category, to three different age determination laboratories. All were experienced in interpreting *Sebastes* otoliths, and were given complete latitude in the criteria they adopted for age determination. The laboratories had no prior knowledge of our age assignments or categorization.

Results and Discussion

Otolith growth occurs through concentric accretions of calcium carbonate which show no evidence of resorption after deposition (Campana and Neilson 1985). The basis for radiochemical age determination is the incorporation of the calcium analogue ^{226}Ra into the accreting crystalline structure. Since ^{226}Ra decays radioactively to ^{210}Pb (half-life, 22.3 yr), the ratio of the two isotopes is an index of elapsed time since ^{226}Ra incorporation. The ^{210}Pb isotope is particularly suited to the determination of fish age due to the similarity between its half-life and the longevity of a typical fish.

In the only other study of this kind, Bennett et al. (1982) analyzed entire otoliths, and thus were forced to model the continued accretion of ^{226}Ra with otolith growth, through models of otolith mass growth rate. Further, they assumed constancy in the ratio of incorporated ^{210}Pb:^{226}Ra with age. We largely avoided these potential sources of error by extracting the core of the otolith, as defined by the first five annuli. Assuming negligible migration of radionuclides across annulus boundaries, radium decay in the otolith core should reflect elapsed time since its formation, and thus be unaffected by subsequent otolith growth.

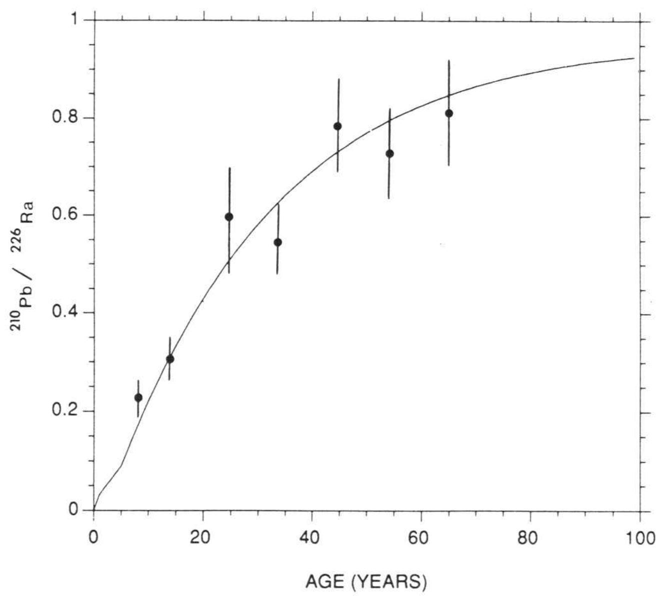

FIG. 1. Observed ^{210}Pb:^{226}Ra in otolith cores as a function of presumed otolith age. Error bars represent 1 SE. The decay curve expected of accurate age determinations represents simple first order ingrowth of ^{210}Pb with an initial ratio of zero. The first 5 yr of otolith growth were modelled assuming a linear increase in otolith mass with time and a constant radium incorporation rate.

Activity ratios of ^{210}Pb and ^{226}Ra, based upon simple ingrowth of ^{210}Pb in the fully-accreted otolith core, were used to estimate the age of the completed core. Assuming a linear increase in otolith mass through the period of core formation, the ratio, R_t, of the ^{210}Pb activity (A_{Pb}) to the ^{226}Ra activity (A_{Ra}) can be derived through integration of the standard rate equation for radioactive ingrowth and decay (Bennett et al. 1982), as in

$$(1) \quad R_{0 \leq t \leq 5} = \frac{A_{Pb}}{A_{Ra}}(t) = 1 - (1 - R^*)\frac{(1 - e^{-\lambda t})}{\lambda t},$$

where $0 \leq t$(years)≤ 5, λ is the radioactive decay constant ($0.031 \cdot yr^{-1}$) for ^{210}Pb, and R^* is the initial ^{210}Pb:^{226}Ra activity ratio in newly-formed otolith material. For $t > 5$ yr, R_t is given by

$$(2) \quad R_{5<t} = \frac{A_{Pb}}{A_{Ra}}(t) = (1 - e^{-\lambda(t-5)}) + R_{t=5}(e^{-\lambda(t-5)})$$

where $R_{t=5}$ is given by equation (1). The relationship between R_t and otolith age for $R^* = 0$ is illustrated in Fig. 1. From their results with juvenile *Sebastes*, Bennett et al. (1982) concluded that $R^* < 0.2$, while the results of this study are consistent with $R^* < 0.1$. While we assumed here that there was negligible uptake of ^{210}Pb from seawater ($R^* = 0$), values of R^* as high as 0.2 would not alter the conclusions of this study.

The ^{210}Pb:^{226}Ra activity ratios in the otolith cores were consistent with the otolith ages determined by annular counts (Fig. 1). Hence, the analysis supports our criteria, as outlined by Beamish (1979), for the interpretation of otolith annuli. These criteria have been widely accepted by those ageing Pacific fishes (Chilton and Beamish 1982), but have been rejected by those ageing Atlantic species as inducing age overestimation (NAFO 1983; ICES 1984). Corroboration of our annulus interpretations was provided by the three independent age determination laboratories, all of whom confirmed our interpretations for otoliths

TABLE 2. Comparison of mean annulus counts in redfish otoliths made by three independent laboratories. All otoliths were initially examined for this study; age-stratified subsamples ($n = 15$) were subsequently sent to the other laboratories for corroboration. Laboratories A and B used criteria for annulus interpretation similar to ours; laboratory C did not.

Age category (yr)	This study	Laboratory A	Laboratory B	Laboratory C
10–15	11.7	13.7	8.5	12.3
30–35	31.4	27.3	28.5	25.7
40–45	42.4	41.7	44.7	26.7
50–55	52.0	48.7	50.0	27.5
60–65	63.1	64.3	54.0	27.0

less than 25 yr old (Table 2). However, only the laboratories using Beamish's (1979) criteria confirmed our ages for the older fish. The consistency between the ages based upon these criteria and the radiochemical assay indicates that previous suggestions of longevity in Atlantic redfish of 70 yr or more are well founded (Sandeman 1961). Our examinations identified individuals that are 75 yr old. Our results also indicate that current age determination practices for Atlantic redfish, both scale- and otolith-based, are appropriate only to an age of approximately 25 yr. Little credence has been given to the validity of the outer, narrow annuli under this regime (NAFO 1983; ICES 1984). Since the NAFO/ICES practices are based upon validated ages in young fish (<15 yr) (Kelly and Wolf 1959; Mayo et al. 1981), our results underline the importance of age validation across the entire age range of the species (Beamish and McFarlane 1983). Use of underestimated ages in ecological or fisheries management contexts artifactually increases apparent growth and mortality rates, and could result in suboptimal management of the resource.

Acknowledgments

We sincerely thank B. Atkinson (Northwest Atlantic Fisheries Centre, St. John's, Nfld.), D. Kimura (Northwest and Alaska Fisheries Center, Seattle, WA), and G. McFarlane (Pacific Biological Station, Nanaimo, B.C.) for their cooperation in this study. J. Hunt offered helpful criticisms of the manuscript. J. Abriel, M. Huh, J. Simon, and G. Young provided expert technical assistance.

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