# AGE, GROWTH, AND RADIOMETRIC AGE VALIDATION OF THE BLACKGILL ROCKFISH, *SEBASTES MELANOSTOMUS*

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By
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# AGE, GROWTH AND RADIOMETRIC AGE VALIDATION OF THE BLACKGILL ROCKFISH, *SEBASTES MELANOSTOMUS*

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As nearshore fish populations in the eastern Pacific Ocean become depleted, many commercial fishers shift their efforts toward deeper continental slope habitats to target fishes for which biological information is limited. One such fishery developed in the early 1980's for the blackgill rockfish, *Sebastes melanostomus*, a deep-dwelling (500-800 m) species that congregates over rocky pinnacles mainly from southern California to southern Oregon. Growth zone-derived age estimates from otolith thin sections were compared to ages obtained from the radioactive disequilibria of $^{210}Pb$, relative to its parent, $^{226}Ra$, in otolith cores of blackgill rockfish collected off the Pacific coast in 1985 and 1998-2000. Age estimates were validated up to at least age 41, with a strong pattern of agreement supporting longevity exceeding 90 years. Age and length data fitted to the Von Bertalanffy growth function indicate *Sebastes melanostomus* is slow-growing ($k = 0.045$) and that females grow slower than males, but reach a larger asymptotic length. Estimates of age at 50% maturity are 17 years for males and 21 years for females. Results of this study agree with general life history traits already recognized for many *Sebastes* species, such as long life, slow growth, and late age at maturation. These traits

may undermine the sustainability of blackgill rockfish populations when heavy fishing pressure, such as that which occurred in the 1980s, is applied.

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TABLE OF CONTENTS

## LIST OF TABLES

# LIST OF FIGURES

LIST OF APPENDICES

# INTRODUCTION

The blackgill rockfish, *Sebastes melanostomus*, is a deep-water rockfish, mainly occurring between 300 and 700 m depth (Cross 1987, Eschmeyer et al. 1983) off central and southern California (Fig. 1; Moser and Ahlstrom 1978). After a 3-7 month pelagic phase, juveniles settle to depths of approximately 185 m (Moser and Ahlstrom 1978); adults commonly are found near rocky outcrops in deeper water (Allen & Smith 1988, Butler et al. 1999). Blackgill rockfish reach a maximum reported total length of 61 cm (Eschmeyer 1983), are estimated to live at least 87 years from otolith increment counts, and reach full (100%) maturity at 13 to 26 years for females and 13 to 24 years for males (Butler et al. 1999). To date, these age and maturity estimates have not been validated.

The directed fishery for blackgill rockfish developed in the mid-1970s off southern California, where bottom topography and new deep-water fishing technologies allowed the commercial fleet to catch large aggregations of previously unexploited blackgill rockfish (John Butler, Southwest Fisheries Science Center, P.O. Box 271, La Jolla CA 92038, personal communication). Fishing effort, mainly with set nets, was concentrated around deep rocky pinnacles, where as many as 20,000 to 30,000 pounds (9-14 metric tons) of blackgill rockfish could be landed in a single haul (Butler et al. 1999).

In the early 1980s, the fishery for blackgill rockfish spread northward to areas off central California where other targeted species, such as the vermilion rockfish (*S. miniatus*), had declined (Butler et al. 1999). In the Monterey area, the method for fishing blackgill rockfish has been primarily bottom trawling, whereas the Point Conception area is dominated by rocky pinnacles, so hook and line gear is more common, with set nets used in calm weather. Juvenile blackgill rockfish are also taken occasionally as bycatch in the spot prawn trawl/trap fishery near Monterey Bay, California (Reilly and Geibel 2002).

Landings of blackgill rockfish peaked in 1983, with 1,112 metric tons (mt) caught in the Point Conception area and 1,346 mt caught coast-wide (Fig. 2). After several years of intensive fishing throughout the late 1970s and 1980s, dense aggregations of blackgills became harder for fishermen to find. By 1998, fishers rarely reported catches of blackgill rockfish greater than 500 pounds (Butler et al. 1999). In 2001, just 141 mt were reportedly landed along the entire West Coast (PacFIN 2002).

Under current federal and state management plans, blackgill rockfish are associated with the *Sebastes* complex termed "remaining rockfish" (Rogers et al. 1996). They are managed as a group without species-specific estimates of acceptable biological catch (ABC) and harvest guidelines (Butler et al. 1999). Because there are few data on population structure or validated age and growth information for this species, it is crucial that these parameters be determined to properly manage the fishery.

*Age determination*

Age determination is an essential tool of fisheries management. Accurate ages of fishes are critical for understanding their life cycle, population structure, and how fishing pressure may affect that structure. Fisheries biologists, therefore, determine age and growth characteristics of individual species by analyzing calcified structures present in the animal, such as scales, vertebrae, fin rays, and especially otoliths (earbones). Many of these structures, when viewed under proper conditions, exhibit repetitive growth patterns that portend the determination of age. In the field of marine fish ageing, most investigators have concentrated analyses on the largest otoliths, or sagittae, instead of scales or other structures that may be regenerated, therefore under-representing fish age.

In their efforts to determine the age structure of commercially important fishes, many earlier researchers quantified growth zones on the surface of whole otoliths. This method resulted in underestimation of longevity and inappropriate management of those fisheries. For example, underestimation of fish age (and subsequent age/size at maturity) led to unsustainably high quotas for Pacific ocean perch (*Sebastes alutus*) in the northeastern Pacific and orange roughy (*Hoplostethus atlanticus*) stocks off New Zealand (Beamish 1979, Archibald et al. 1983, Mace et al. 1990), causing severe declines in these fisheries. It was later discovered that otoliths of adult fish grow isometrically (more material is deposited on the medial side, near the brain), therefore, transverse sections, which elucidate all growth layers, are required to achieve an accurate account of adult fish age (Chilton and Beamish 1982). It is also important to note that some growth increments may not represent an annual event (i.e. checks; Chilton and Beamish 1982), further qualifying the need for validation of age estimates.

Age determination methods must be validated to predict age accurately from interpretation of growth zones apparent in hard parts of a fish (Beamish and McFarlane 1983, Campana 2001). Age validation has traditionally been achieved by mark-recapture studies, marginal increment analysis, or laboratory rearing (Chilton and Beamish 1982). Although these techniques may be feasible for short-lived species, they are difficult to apply to deepwater, long-lived rockfishes that may suffer fatal barotrauma when brought to the surface. A more appropriate technique is radiometric age validation (Bennett et al. 1982, Smith et al. 1991), which uses the disequilibria between two isotopes, radium-226 ($^{226}$Ra: 1,599 year half-life) and lead-210 ($^{210}$Pb: 22.3 year half-life), present in the otolith structure. This method has proven successful in validating age for over 15 species of rockfishes and other marine teleosts (see Burton et al. 1999 for review).

Radiometric age validation of fishes may be accomplished by determining the relative activities of $^{226}$Ra and its daughter, $^{210}$Pb. Radium-226 is a naturally occurring radioisotope and calcium analogue that is incorporated from the surrounding seawater into the aragonitic crystalline matrix of fish otoliths. Radium-226 then decays through a series of short-lived isotopes to $^{210}$Pb. Because the half-lives of these isotopes are known, the ratio of activity between them ($^{210}$Pb:$^{226}$Ra) gives a measure of elapsed time since initial $^{226}$Ra incorporation into the otolith (Campana 1990). Radium-226 decays very slowly (1,600 year half-life) relative to $^{210}$Pb (22 year half-life), allowing the latter to build into secular equilibrium (approach a 1:1 ratio) with its parent (Smith et al. 1991).

Based on this relationship, the $^{210}Pb$: $^{226}Ra$ isotope pair is suitable for age determination in fishes up 5 half-lives of $^{210}Pb$, or approximately 100 years of age (Andrews et al. 1999b, Campana 2001). It is therefore ideally suited to the blackgill rockfish, based on previous longevity estimates.

Three assumptions must be met to accept radiometrically determined ages (Bennett et al. 1982, Campana et al. 1990, Fenton et al. 1990). First, the structure to be aged must act as a closed system for $^{226}Ra$ and all of its daughter products ($^{222}Rn$, $^{218}Po$, $^{214}Pb$, $^{214}Bi$, $^{214}Po$, $^{210}Pb$). The second assumption is that $^{210}Pb$ is not incorporated during the formation of the otolith, but is produced solely from decay of $^{226}Ra$ within the otolith structure. In many marine fishes, minor $^{210}Pb$ incorporation is a possibility. As long as the initial $^{210}Pb$ activity is measured, it can be accounted for in age determination calculations. The third assumption is that the rate of $^{226}Ra$ incorporation is constant (relative to calcium) within the otolith as it grows. Reliance upon this assumption can be largely avoided by using cored instead of whole otoliths (Campana et al. 1990). Cored otoliths have had all growth layers removed but the first few (1-5) years of growth.

Because otolith cores weigh much less than whole otoliths (0.01-0.05 g), they must be pooled to attain measurable $^{210}Pb$ and $^{226}Ra$ activity. Earlier methods (e.g. radon emanation) required over 10 grams of material for activity determination (Kline 1996). The application of isotope-dilution thermal ionization mass spectrometry (TIMS) as described by Andrews et al. (1999b) reduces the required sample size for $^{226}Ra$

determination to approximately 0.5 gram of material per sample, or approximately 20-40 otoliths (10-20 fish), depending on core size. It is critical, then, to obtain many fish of equal age for use in one radiometric sample.

The objectives of this study were: 1) to estimate age from growth zone counts, 2) describe growth, and 3) validate the annual periodicity of growth zones used to estimate longevity for the blackgill rockfish using the radiometric ageing technique. Growth zones quantified in sectioned otoliths were used to estimate age, and growth was described using the Von Bertalanffy growth function ($L_0 = L_\infty \cdot (1 - e^{-k(t-t_0)})$). An ancillary objective was to create a reliable predictive relationship between average otolith weight and estimated age for use as a timesaving tool in the management of this species. Final age estimates were directly compared with radiometrically determined ages to evaluate agreement between the two methods and ultimately validate age estimation procedures, longevity, and age at maturity for this species.

# METHODS

A total of 1,210 blackgill rockfish sagittal otoliths was available for this study. Approximately 617 pairs were sampled by National Marine Fisheries Service (NMFS) workers from commercial vessels in 1985 at ports along the California coastline (Long Beach to Ft. Bragg; Fig. 2). Another 561 otolith pairs were collected during NMFS research surveys in 1998 to 2000 from central California to the Oregon/Washington border (lat 34° 53'N, long 124° 50'W) at depths from 257 to 602 m. Thirty-two juvenile blackgill rockfish, collected from spot prawn traps along the central California coast, were provided by Robert Lea of the California Department of Fish and Game (CDFG). Fish total length (TL; cm or mm), catch area (port or geographic location), and otolith weights (right and left, 1985 samples only) were provided. Extracted and cleaned otoliths were stored in either paper envelopes (1985) or glass vials (1998-2000). Individual fish weights were provided for only a small portion of samples ($n = 128$) and therefore could not be uniformly applied.

Otolith length (measured in a subsample of otoliths) and otolith weight (of all samples) was measured to the nearest 0.001 mm and 0.001 g, and total length was measured to the nearest 1 mm for all fish donated by CDFG. Otolith weights (left and right, male and female) were compared with $t$ tests to determine if significant differences existed between sides or sexes. Approximately 310 randomly selected otoliths, representing all available size ranges, were prepared for age estimation using the thin-sectioning technique. Final age estimates, along with their average otolith weight, were used to predict age for the remaining samples, which were considered for radiometric analysis. A total of 14 radiometric age groups (4 juvenile, 5 female, and 5 male), were analyzed for $^{226}Ra$ and $^{210}Pb$ activity.

*Age Estimation*

To develop a protocol for optimal viewing of growth zones, blackgill rockfish otoliths were examined in several ways. Preparations included whole, break and burn (including baking the otolith at high temperature before breaking), transverse sectioning (Chilton and Beamish 1982), and staining (Richter and McDermott 1990). Thin transverse sections (without staining or baking) resulted in the clearest growth zones.

The left sagittal otolith from each preselected fish was mounted onto the center of wax-covered cards with epoxy resin and allowed to dry for at least 24 hours. A 0.5 mm thick transverse section containing the nucleus was removed using a Buehler-Isomet low-speed bone saw with two Norton ® low-density diamond blades separated by acetate spacers (0.6 mm total; Cailliet et al. 1986). Sections were mounted onto labeled glass slides and covered with a clear coat of Cytoseal™, allowed to dry, and then ground to approximately 0.3 mm thickness on a Buehler-Ecomet III lapping wheel with 600 to 1,200 grit wet-dry grinding paper. Approximately 50 otoliths were damaged in the sectioning process (missed nucleus or over-grinding the slide), leaving 260 otoliths available for age estimation.

Three separate readers viewed otolith sections under magnification (25x and 40x) with transmitted or reflected light. An annual growth increment (annulus) was defined as one pair of translucent (winter-forming) and opaque (summer-forming) bands. Protocol observed by readers consisted of inspecting all available growth axes, choosing the most discernable axis, and reading it three times consecutively. After the third reading, the reader chose a final age based on their most confident estimate. Each section was rated from 1 (very confident) to 4 (unreadable), based on the quality of the preparation and the reader's confidence of the estimate. Unreadable otoliths were defined as lacking a consistent, discernable growth pattern along any axes. Otoliths fitting this description were removed from analysis, while those with a confidence rating score $\leq 2$ were used to create the growth and age prediction models.

Precision between and within readers was compared using average percent error (APE; Beamish and Fournier 1981), index of precision (D), and coefficient of variation (CV; Chang 1982). Percent agreement between final age estimates for readers was calculated, and age bias plots were used to determine if systematic differences in under or over-ageing among readers were present (Campana et al. 1995). Reader 1 (author) determined final age estimates for use in the growth model. Final ages were determined in the following way: if all three ages were within 5 years, reader 1 age was used. If two out of three estimates were within 5 years, the average of the two was used. If all estimates differed by more than 5 years, ages were resolved by reader 1 through re-examination of the section. Ages that could not be confidently resolved were removed from analysis.

Length and age estimates for males, females, and sexes combined were fitted to the Von Bertalanffy growth function (VBGF) using the software application "IGOR" (Cope 2000). This function was chosen due to its suitable fit, as well as the desire to compare parameters with results obtained in Butler et al. (1999). A portion of the final age estimates (43% of females, 30% of males) used in a preliminary stock assessment conducted by Butler et al. (1999) was also included in the VBGF and age prediction models. Estimates of age at 1%, 50%, and 100% maturity were calculated by inserting existing size at maturity data (Echeverria 1987) into the VBGF and solving for age (t).

*Age Prediction, age group determination and core extraction*

To define groups of otoliths to be pooled and conserve available material for radiometric analysis, final ages of fish whose otoliths were sectioned, along with their corresponding average otolith weight, were used to predict age for all remaining fish. Several sets of parameters were regressed to determine a predictive relationship between average otolith weight and estimated age. The following regressions were compared to estimated age using Kruskal-Wallis (non-normal) ANOVA: 1) average otolith weight, 2) otolith weight and fish length, and 3) otolith weight plus otolith length multiplied by otolith weight (as an interaction term). A power function was also investigated, but did not result in a greater biological fit than a simple linear regression (log and normal). A paired sample *t* test indicated a significant difference between male and female average otolith weight ($t = 4.54$, $P < 0.001$), so male and female age estimates were regressed separately. The final regression equations (male and female) were then applied to the average otolith weight for all remaining fish to obtain a predicted age.

Because otoliths were to be cored, fish of similar age and sex had to be pooled into discrete age groups to acquire the mass of material needed for radiometric analysis (~ 0.5 to 1 gram). The age range for each group was kept as narrow as possible while still permitting enough material for analysis; approximately 50 otoliths were needed at a target weight of 0.02 g per core. Ninety-five percent confidence intervals with respect to available fish and otolith parameters were used to eliminate potentially dissimilar fish from age groups. In addition to age and sex, groups were further defined by capture year and location. Only samples caught in the same year and similar geographic location (based on the majority of port locations to be within 300 miles) were included for each group.

Core size was determined by viewing several whole juvenile blackgill rockfish otoliths with estimated ages between 1 and 7 years. The first annulus was determined to be approximately 2 mm wide, and a 3 year-old core was estimated to be 3 mm wide, 4 mm long, and 1 mm thick, with a weight of 0.02 g. This age was chosen because its size could be easily extracted, yet was small enough to minimize the possible error associated with variable $^{226}Ra$ uptake in the first few years of growth. Otoliths were ground to the target core size using a lapping wheel and 80 to 120 grit silicon-carbide paper.

*Radiometric analysis*

The radiometric analysis was conducted as described in Andrews et al. (1999a,b). Because previous studies have revealed extremely low levels of $^{210}Pb$ and $^{226}Ra$ in otolith samples, trace metal precautions were employed throughout sample cleaning and processing (Bennett et al. 1982, Campana et al. 1990, Watters 1995, Andrews et al.1999a). Acids were double distilled (GFS Chemicals®) and all dilutions were made using Millipore ® filtered Milli-Q water (18MΩ $cm^{-1}$). Samples were thoroughly cleaned, dried, and weighed to the nearest 0.0001 g prior to dissolution. Once the cores in each sample were fully dissolved, they were analyzed for presence of $^{210}Pb$. Whole juvenile otoliths estimated to be aged 1 to 7 years were analyzed first to determine the presence, if any, of exogenous $^{210}Pb$.

Due to the low-level detection problems associated with (beta) $\beta$-decay of $^{210}Pb$, its activity was quantified through the autodepostion and (alpha) $\alpha$-spectrometric determination of its daughter proxy, polonium-210 ($^{210}Po$, half-life = 138 days; Flynn 1968). Ideally, all samples should be at least two years old to ensure that $^{210}Po$ is in secular equilibrium with $^{210}Pb$ (Andrews et al. 1999b). Ten of the juvenile otoliths used in the analysis were caught less than 2 years prior to processing. All remaining samples were caught in the year 2000 or earlier.

In preparation for $^{210}Po$ analysis, dissolved samples were spiked with a calibrated yield tracer, $^{208}Po$, estimated to be 5 times the activity of $^{210}Po$ in the otolith sample. Isotopes from the sample were autodeposited onto a purified silver planchet (A.F. Murphy Die and Machine Co.) held in a rotating Teflon holder over a 4-hour period (i.e. plating; Flynn 1968). The activity of $^{208}Po$ and $^{210}Po$ on the planchets was measured with ion-implant detectors in a Tennelec TC256 alpha-spectrometer interfaced with a multi-channel analyzer and an eight channel digital multi-plexer (Andrews et al. 1999a). Lead-210 activity was calculated in a series of equations that corrected for background and reagent counts (see Appendix A). The remaining sample was dried down and conserved for $^{226}Ra$ analysis.

Determination of $^{226}Ra$ employed an elemental separation procedure followed by isotope-dilution thermal ionization mass spectrometry (TIMS) as described in Andrews et al. (1999a,b). The sample was spiked with an amount of $^{228}Ra$ yield tracer estimated to produce a $^{226}Ra:^{228}Ra$ atom ratio close to one. The samples were then dissolved and re-dried repeatedly (~ 90-100°C) until the sample color was bright white, indicating most organic material had been removed. A three-step elemental separation procedure was used to remove calcium and barium, elements that interfere with the detection of $^{226}Ra$ in the TIMS process. Each step involved passing the samples through a cation exchange column containing a slurry of AG® (first and second column) or Sr® resin (third column; EiChrom Industries) in a highly acidic environment. As the sample settled into the resin, the acidity of the column was altered, preferentially separating different elements due to their elution characteristics (Andrews et al. 1999b).

Corrected values for adult activity of $^{210}$Pb and $^{226}$Ra were then used to calculate the age of the sample using the following equation:

$$t_{age} = \frac{\ln\left(\frac{1-\left(\frac{A^{210}Pb}{A^{226}Ra}\right)}{\left(\frac{1-e^{-\lambda T}}{\lambda T}\right)}\right)}{-\lambda} + T$$

where:

$t_{age}$ = radiometric age at time of capture

$A^{210}$Pb = the $^{210}$Pb activity at time of capture (dpm/g)

$A^{226}$Ra = the $^{226}$Ra activity (dpm/g)

$\lambda$ = the decay constant for $^{210}$Pb (ln(2)/22.26 years)

T = core age (3 years)

Uncertainty error associated with the corrected $^{210}Pb$ activity was based on the total counts (after correction) for background and reagents, while uncertainty for $^{226}Ra$ activity was determined instrumentally during TIMS analysis (Andrews et al. 1999a,b). The combined errors were then used to calculate high and low radiometric activities and ages (see Appendix B).

*Age estimate accuracy*

Measured $^{210}Pb$:$^{226}Ra$ activity ratios for each age group along with their total sample age (predicted age + time since capture) were plotted with the expected $^{210}Pb$:$^{226}Ra$ ingrowth curve. Agreement between the measured ratio and the expected ratio provided an indication of age estimate accuracy. Predicted age for each group also was compared directly to radiometric age through regression analysis and a paired sample *t* test to determine if a significant difference existed between the two ages for each group.

## RESULTS

### *Age Estimation*

Growth increments within otolith sections of most blackgill rockfish were difficult to interpret (Fig. 4a). Sections (~260) were examined several times to evaluate the growth pattern before actual estimates were recorded. The most consistent axis for interpretation was along either sulcus ridge, or along the dorso-ventral margin. Final age estimates were resolved for 174 fish, or approximately 67% of adequately sectioned otoliths. The two oldest fish were a 90-year-old male (450 mm TL) collected off the southern California coast in 1999 and an 87 year old female (546 mm TL) collected in 1985.

Difficulties associated with interpretation of growth were experienced from the nucleus to the otolith edge. The distinction between the nucleus (initial growth kernel) and first annulus was ambiguous, with wide and often inconsistent (noisy) band patterns during the first several (1 ~ 10) years of growth. After approximately 8-12 complete (annual) growth increments, band widths began to narrow, until after estimated age 20-40 years, the bands became extremely compressed and were often beyond optical resolution.

Agreement among readers was poor: age estimates differed by as much as 27 years, with a mean difference of 2.85 ± 4.02 years (Fig. 5). Approximately 24% of age estimates were within ± 1 year, 61% were within ± 5 years, and 87% were within ± 10 years. Among the three readers, APE was 10.68%, the D was 8.44%, and CV was

14.61% (n = 174; Table 1). Average percent error, D, and CV estimates were comparable within readers; reader 1 APE was 5.2%, D was 4.1%, and CV was 7.0% (Table 1). Age bias plots also indicated relatively large variance among readers, but there was no systematic under or over-ageing by one reader compared with others (Fig. 6).

Length (TL) and age data for blackgill rockfish fitted to the VBGF resulted in distinct growth curves between male and female blackgill rockfish (Table 2, Fig. 7). The growth coefficient, k, ranged from 0.04 (female) to 0.068 (male), and asymptotic length was 448 mm for males to 548 mm for females. The asymptotic length for females was 32 mm less than the largest female fish sampled (580 mm TL), and for males, was 74 mm less than the largest male sampled (522 mm TL). The fit for all three functions was satisfactory ($r^2 = 0.81, 0.87$; Fig. 7). Estimated ages at 1%, 50%, and 100% maturity, derived from inserting published estimates of size at maturity (Echeverria 1987) into the growth model for each sex, were 15, 21, and 22 years for females and 13, 17, and 28 years for males.

*Age prediction, age group determination and core extraction*

There was no statistical difference between regressions involving fish and otolith parameters (Kruskal-Wallis one way ANOVA on Ranks, $H = 4.834$, $P = 0.089$). A simple linear regression, with average otolith weight as the independent variable and growth zone estimates as the dependent variable, was sufficient to predict age ($r^2 = 0.83$

males, 0.85 females; Fig. 8). Log normalizing the regressions to stabilize the variance in older age estimates was unsuccessful (Cochran's test: $\alpha = 0.05$, 36 df, $C = 0.4748$, $P = 0.486$). The final regressions were:

| | | | |
|---|---|---|---|
| Females: | Age = (93.8 * length) + 0.175 | Adj. $r^2 = 0.85$ | (n = 165) |
| Males: | Age = (108.2 * length) – 2.653 | Adj. $r^2 = 0.83$ | (n = 151) |

A students' $t$ test for slopes indicated a significant difference between male and female regressions ($t_{crit} = 1.967$, $t = 2.87$, $P < 0.05$).

Based on the predicted ages of un-sectioned otoliths, 14 age groups, consisting of 4 juvenile and 5 male and female groups, were chosen for analysis (Table 3). Four age groups were collected from the year 2000, 3 from 1998 research surveys, and 7 from 1985 port samples. Available fish lengths ranged from 68 mm to 580 mm TL, with a predicted age range of 1 to 69 years. The number of otolith cores per age group ranged from 11 to 59, representing 7 to 32 fish per group (Table 3).

Whole otolith weight ranged from 0.041 to 0.842 g, and average core weight for each individual otolith core was between 0.023 g and 0.028 g. Total sample weight for each pooled age group ranged from 0.4649 g to 1.6424 g, depending on availability of otoliths in each age group, as well as the fact that some otolith cores were inadvertently destroyed in the grinding process, leading to smaller samples. Where extra material was available, it was utilized, as the analytical error associated with determination of $^{226}$Ra decreases as activity increases (Andrews et al. 1999b).

*Radiometric analysis*

Radiometric analysis of all age groups (n = 14) resulted in successful determination of $^{210}$Pb activity (Table 4). Activities of $^{210}$Pb increased fivefold between juvenile and adult age groups, from approximately 0.011 dpm/g in juvenile samples to 0.058 dpm/g for the age 56-59 group. Error associated with this measurement ranged from 3.7 to 9.2 % (1*s*). Conversely, $^{226}$Ra activity was not detected in 4 groups, and yields were extremely low in 3 others, with larger than expected analytical error (>10%; Appendix C).

Because 1) $^{210}$Pb activity in all groups was consistent with expected activity at age, and 2) juvenile $^{210}$Pb activity was low (~ 0.01 dpm/g) indicating that most $^{210}$Pb was due to ingrowth from $^{226}$Ra, average $^{226}$Ra activity for successful groups (0.06427 ± 0.0035 dpm/g, n = 7) was applied group wide to produce a more reliable estimate of $^{226}$Ra activity. The ratio of $^{210}$Pb:$^{226}$Ra increased as expected from 0.1723 dpm/g in a juvenile sample to 0.9120 dpm/g in a 56-59 age group sample. The oldest predicted age group (60-69) had an activity ratio of 0.8448 dpm/g.

*Age estimate accuracy*

Radiometrically determined ages agreed well with predicted ages, as evidenced by concordance of $^{210}Pb$:$^{226}Ra$ activity in otolith cores with expected ingrowth curves through time (Fig. 9), and by direct comparison to predicted ages ($r^2 = 0.88$; Fig. 10). Of the 14 pooled otolith groups, 3 had radiometric age ranges that fully encompassed the predicted age range, 10 resulted in overlapping age ranges, and 1 groups' radiometric age range exceeded predicted age (extended by ± 15% CV; Table 4). A paired sample *t* test indicated no significant difference between predicted age and radiometric age ($t = 1.265$, $P = 0.228$).

# DISCUSSION

*Estimation of age and growth*

Age estimates from transverse otolith sections indicate the blackgill rockfish reaches a maximum age of at least 90 years. The results of this study, therefore, agree with those of Butler et al. (1999), who estimated that blackgill rockfish live to at least 87 years. Since heavy fishing occurred in the years prior to sampling (1978 – 1984; Butler et al. 1999), it is possible that a majority of the oldest individuals may have been removed from the population and thus were not represented here. Given the extreme depth of occurrence for adults (300-700 m), the slow growth associated with depth (Childress et al. 1980, Cailliet et al. 2001), and the established trait for longevity approaching or exceeding 100 years in many rockfish species (Chilton and Beamish 1982, Munk 2001, Andrews et al. 2002), it is probable that blackgill rockfish attain ages older than 90 years.

Growth patterns present within the otoliths of blackgill rockfish were often difficult to interpret (Fig. 4a). Complications inherent to the blackgill rockfish pattern were: 'noisy' patterns up to age 10-15 (the point where otolith begins to thicken laterally), sudden transitions to slower growth, conflicting or ambiguous growth patterns, and poor resolution of extremely compressed zones in old aged fish. Irregular patterns may have led to enumeration of false bands (checks), while compressed growth zones may have concealed growth increments present in older fish. There were, however, some remarkably clear otoliths (Fig. 4b) in which our estimates of age were confident.

Because of the difficulty involved in interpreting growth patterns, ageing of blackgill rockfish otoliths involved a high degree of individual subjectivity, as evidenced by the relatively low precision (D = 8.4%) and large variation (CV = 15%) between readers (Table 1). Precision was finer within individual readers (5.2 - 5.8 %), suggesting that the reproducibility of an age estimate is more attainable within individual readers than between readers. Interpretation differences, however, showed very little bias for over or under-ageing with respect to other readers (Fig. 5). Bias would have been represented by a pair of reader ages forming a separate parallel or diverging line relative to the line of agreement (Campana et al. 1995), which was not visible here. Age estimates, therefore, were imprecise, but generally unbiased with respect to under or over-estimation.

The overall growth characteristics of the blackgill rockfish, as evidenced by the parameters of the VBGF, relate to the physiological characteristics of deep-sea (>200 m) marine fishes, many of which have adapted to low levels of food, light, and oxygen with a reduced metabolism and growth rate (Childress and Somero 1979, Childress 1995, Cailliet et al. 2001). The growth coefficient, k, is low (0.04-0.07; Table 2) when compared to shallower-dwelling rockfishes such as the bocaccio rockfish (*S. paucispinis*, k = 0.16 - 0.19; Andrews et al. *in prep*), but very similar to other deep-dwelling, long-lived rockfishes, such as the shortspine thornyhead (*Sebastolobus alascanus*, k = 0.02;

Kline 1996), yelloweye (*S. ruberrimus*, k = 0.0459; Andrews et al. 2002), and bank rockfishes (*S. rufus*, k = 0.041; Watters 1995).

The VBGF suggests male and female blackgill rockfish possess different patterns of growth (Table 2; Fig. 7). Like many other species of *Sebastes* (Love et al. 1990), female blackgill rockfish exhibited slower growth than males, but ultimately reached a larger asymptotic length. The opposite result was reported in female splitnose rockfish (*S. diploproa*), another deep-living species (to 578 m; Hart 1973). Boehlert and Kappenman (1980) found that females, especially in northern latitudes, grew faster than males. Females, however, were also reported to reach a larger asymptotic length.

It is interesting to note that the oldest aged blackgill rockfish in this study was a 90 year-old male that was only 450 mm total length, 160 mm less than the maximum reported for the species (Eschmeyer 1983). According Kristen Munk, "some of the oldest specimens [rockfish] are rarely the largest (lengthwise), and most, if not all, are males" (K. Munk, Alaska Department of Fish and Game, P.O. 25526, Juneau AK 99802, personal communication). While the reasons behind this pattern are beyond the scope of this work, the implications to stock dynamics and management deem it worthy of further study. Extraordinarily old ages in averaged size fish should not be dismissed as a simple anomaly, but perhaps be recognized in the literature as a distinctive growth characteristic of *Sebastes*.

*Age prediction and age group determination*

Predicting ages from otolith weight allowed greater availability of un-sectioned otoliths for use in the radiometric analysis, but prediction also amplified the uncertainty associated with the age estimate, especially in older fish. The variance around the regression line increased with otolith weight; log normalizing the data did not eliminate this problem. Older predicted ages, therefore, were more uncertain than younger ages. For example, a fish whose average otolith weight was between 0.041 and 0.317g (3 - 42 years) had a standard deviation (with respect to age) of ±7.98 years, while fish whose average otolith weight was between 0.493 and 0.842g (38-87 years) had a standard deviation of ±11.3 years.

It was hoped that the entire estimated age range for blackgill rockfish would be represented by available otoliths. Otoliths from fish with predicted ages greater than 70 years, however, were not present in sufficient numbers to allow their radiometric age determination. This was surprising, given that over 600 of the 1,000 otolith pairs obtained for this study were sampled directly from commercial fishing vessels in 1985 along the coast of central and southern California where the bulk of the fishery occurred. Since fishers are known to target adult aggregations, the absence of these older individuals may be an indication that the population was already experiencing depletion of older age classes at the time of sample collection.

*Radiometric analysis*

The use of TIMS requires less processing time, allows for a much smaller sample size than previously possible with radon emanation (Watters 1995, Kline 1996), and reduces the error associated with $^{226}Ra$ determination to 1.5% in ideal analyses (Andrews et al.1999b). Normally, $^{210}Pb$ analytical uncertainty is the limiting factor in radiometric ageing (Andrews et al. 1999a) due to its indirect detection through $^{210}Po$ decay. In this study, uncertainty associated with detection of $^{210}Pb$ activity was generally less than that of $^{226}Ra$. Error associated with low-yield detection of $^{226}Ra$ was much greater than 1.5% in most samples (up to 19.11%), and was likely due to interfering quantities of barium ($Ba^{2+}$), calcium ($Ca^{2+}$), and possibly otolin (an organic component of the otolith) that were not successfully eliminated during processing. Error also may have occurred from improper mixing of nitric acid ($HNO_3$) during the third column separation. These errors caused spurious $^{226}Ra$ activities in 7 out of the14 age group samples, whereas the other 7 samples had $^{226}Ra$ errors within an acceptable range of uncertainty (subjectively set at <10%). Among those successful samples, activity was fairly consistent (0.06427 ± 0.0035 dpm/g). Because previous radiometric studies on Pacific rockfishes have resulted in consistent $^{226}Ra$ activities for those species (Bennett et al. 1982, Kastelle et al. 2000, Andrews et al. 2002), average $^{226}Ra$ activity for all successful age group samples was assumed to be a more accurate estimate of the true environmental condition, and would thus produce a more accurate estimate of the true age of pooled otolith cores.

Radium-226 activities of blackgill rockfish otolith cores were generally greater than those found in many other rockfish and thornyhead species living in similar depths along the continental shelf of the West Coast. For example, adult splitnose rockfish (*S. diploproa*) whole otoliths had a mean $^{226}$Ra activity of 0.043 ± 0.009 dpm/g (Bennett et al. 1982); yelloweye rockfish (*S. ruberrimus*) cored otoliths had a mean $^{226}$Ra activity of 0.0316 ± 0.002 dpm/g (Andrews et al. 2002); whole juvenile and adult shortspine and longspine thornyhead (*Sebastes alascanus and S. altivelis*) otoliths had $^{226}$Ra activities averaging 0.043 ± 0.006 and 0.045 ± 0.002 dpm/g, respectively (Kline 1996). Other rockfishes, such as the rougheye rockfish (*S. aleutianus*), have similar $^{226}$Ra activities averaging 0.065 ± 0.015 dpm/g (Kastelle et al. 2000). Because the concentration of $^{226}$Ra in seawater increases with depth in the Pacific Ocean (Koczy 1958, Chung and Craig 1980), it is possible that the greater activity in cores of blackgill rockfish is a result of their deeper settlement depth (> 200 m; Moser and Ahlstrom 1978). Uptake ratios of $^{226}$Ra relative to calcium (and other elements) are also related to a suite of internal physiological factors such as metabolism, activity levels, and stress (Radtke and Shafer 1992), as well as environmental factors such as temperature, pH, salinity, and pressure (Polikarpov 1966).

*Assumptions*

Of the three assumptions conditional to the radiometric ageing technique, only two need be addressed when using cored otoliths. The assumption of minor $^{210}$Pb uptake has been addressed in this study by analyzing juvenile otoliths, which represent the core of all otoliths used from adult fish. Initial $^{210}$Pb activity for these groups was measured and found to be close to zero (0.0127 ± 0.0019, n = 4). The main argument against the third assumption that the otolith acts as a closed system is that radon-222 ($^{222}$Rn, 3.83 day half life), an intermediate daughter of $^{226}$Ra, is an inert gas and thus may diffuse out of the otolith matrix. Gauldie and Cremer (1998) concluded 8.9% $^{222}$Rn loss from otoliths of orange roughy (*Hoplostethus atlanticus*) using gamma spectrometry, which they suggested invalidates radiometric ages for this species. Baker et al (2001) also found $^{222}$Rn loss in otoliths of red snapper (*Lutjanus campechanus*; ≤4.1%) and red drum (*Sciaenops ocellatus*; ≤0.6%), although loss was minimal. Conversely, Whitehead and Ditchburn (1995) concluded that $^{222}$Rn loss was negligible for orange roughy, while Kastelle and Forsberg (2002) suggested $^{222}$Rn was conserved in Pacific halibut (*Hippoglossus stenolepis*) otoliths because radiometric ages closely agreed with estimated ages. It is doubtful that a significant $^{222}$Rn loss occurred in this study, based on the previous studies mentioned, and because radiometric ages closely agreed with predicted ages. If loss of $^{222}$Rn did occur, it would not necessarily invalidate ages, but would cause a slight underestimation of age.

*Accuracy and Uncertainty*

The most critical sources of error involved in age estimation, prediction, and radiometric determination are: 1) age estimate accuracy, 2) regression error associated with predicted ages, 3) core age accuracy and 4) analytical uncertainty associated with the radiometric ageing technique (TIMS and alpha spectrometry). In this study, we experienced larger than normal analytical error associated with $^{226}$Ra detection, causing some radiometric ages to be less exact. Another factor may have been an incorrect core age for the dimensions used, although this would only affect ages by 1 to 2 years at most. Age prediction error follows directly from age estimation error, and because blackgill rockfish otoliths were generally difficult to interpret, over- or underestimation of age likely occurred, leading to less than accurate assignment of age groups (as represented by the error bars in Figs. 9 and 10).

Even though a considerable amount of error was present, radiometric activities determined for blackgill rockfish otoliths generally agreed with expected activity ratios for $^{210}$Pb and $^{226}$Ra (Fig. 9), and confirm the validity of growth zone derived age estimates. Unfortunately there were not enough of the oldest aged otoliths (70 – 90) to analyze radiometrically. If assessed, radiometric ages may have proven that estimated age, if anything, had been underestimated slightly, due to the extremely compressed nature of growth zones in otoliths of old individuals. When plotted directly with radiometric age, underestimation of predicted age was apparent in a three samples (Fig.

radiometric age, underestimation of predicted age was apparent in a three samples (Fig. 10), further supporting the idea that older age estimates were underestimated to some extent.

*Management Implications*

Fishery managers face a great challenge to create sustainable fishery management plans for increasingly sparse fish populations that will balance the environmental needs of the marine ecosystem with the economic and consumptive needs of society. In recent years an increasing number of fisheries have collapsed under the weight of heavy fishing pressure caused by overcapitalization of a technologically advanced fleet (Moore 1999, Koslow et al. 2000, Roberts 2002). The West Coast groundfish fishery, of which many rockfish species are an integral part, was declared a "fishery disaster" by the federal government on 19 January 2000 (NOAA 2000). Most recently (July 2002), the Pacific Fishery Management Council closed a significant portion of the continental shelf along the entire West Coast (from the Washington border with Canada to California border with Mexico) to groundfish fishing in order to protect 4 species of severely overfished rockfish (bocaccio, *S. paucispinis*; darkblotched, *S. crameri*; canary, *S. pinniger*; and yelloweye, *S. ruberrimus* rockfishes; PFMC 2002). Clearly, management of rockfishes and other long-lived species is a difficult task that will require reliable science to understand the dynamic nature of fish populations.

The purpose of this study was to elucidate key characteristics in the life history of a commercially important deep-water rockfish so that the information could be applied to better manage the fishery. Generally, rockfish otoliths are difficult to interpret, so conducting age and growth studies for rockfish is time-intensive and costly. The formulation of a reliable predictive relationship between average otolith weight and estimated age, followed by confirmation of the validity of those ages, provides managers with an effective tool for future age and growth studies of this and other rockfish species.

Although a longevity of 90 years may seem extremely long for lower vertebrates, it is actually an intermediate age for the rockfishes. While the bocaccio rockfish was determined to live up 46 years (Munk et al. 2001, Andrews et al. *in press*), the maximum age for an individual rougheye rockfish (*S. aleutianus*) was recently estimated to be 205 years (Munk 2001), and age estimates to 118 years (Munk 2001) were recently validated for the yelloweye rockfish (*S. ruberrimus*; Andrews et al. 2002). Cailliet et al. (2001) reported a general trend of increasing longevity with depth and latitude in scorpaenids, and suggested that longevity is associated with the physiological pressures of deep-sea living, such as low temperature, high pressure, low light and oxygen levels, and minimal or patchy food resources. Based on its known maximum depth of occurrence (768 m; Eschmeyer 1983, Love et al. 2002) and the longevity observed in this study, the blackgill rockfish also would agree strongly with this trend.

Longevity in the rockfishes has been central to its evolutionary success relative to other marine teleosts. As a reproductive strategy, longevity serves to propagate genetic material across several generations, as well as diffuse the mortality associated with each reproductive event (Leaman 1991). In this sense, longevity may act to buffer the species against long-term environmental change (El Nino, Pacific decadal oscillations) and the stochasticity inherent in natural systems. The trade-off of course is slower growth, which could limit the survival of the individual by increasing its chances of predation from larger animals. It has been suggested, however, that in the presence of fishing pressure, survival and growth rates are inversely correlated (Leaman 1991), meaning that a faster-growing fish in an exploited stock may recruit to the fishery sooner and thus incur greater mortality. So, in the absence of fishing pressure, the genetic contribution of a slow-growing, longer-lived species may be more conserved in the collective species' gene pool (K. Munk, Alaska Department of Fish and Game, P.O. 25526, Juneau AK 99802, personal communication). This issue has far-reaching implications concerning the recovery of overfished rockfish populations. If too much genetic material is lost through elimination of the oldest fish, full recovery of the species may be unattainable.

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Williams, R.W. 1988. Uranium and thorium decay series disequilibria in young volcanic rocks. Ph.D. thesis. University of California, Santa Cruz.

Yoklavich, M.M and G.W. Boehlert. 1987. Daily growth increments in otoliths of juvenile black rockfish, *Sebastes melanops*: an evaluation of autoradiography as a new method of validation. Fishery Bulletin. 85(4): 826-832.

Table 1. Comparison of reader agreement among and between 3 independent readers. Average percent error (APE), index of precision (D) and coefficient of variation (CV) are listed. Final ages from each reader were based on the most confident estimate. Agreement among readers from Butler et al. (1999) is shown for contrast between studies.

| Group | APE (%) | D (%) | CV (%) | Percent Agreement ± 1 | Percent Agreement ± 2 | n |
|---|---|---|---|---|---|---|
| Reader 1 | 5.2 | 4.1 | 7.0 | 38% | 51% | 60 |
| Reader 2 | 5.3 | 4.1 | 7.2 | 36% | 50% | 60 |
| Reader 3 | 5.8 | 4.6 | 7.9 | 27% | 42% | 60 |
| All Readers | 10.7 | 8.44 | 14.61 | 23.1% | 39.3% | 180 |
| Butler et al. (1999)[a] | 6.9 | 3.9 | (N.R.) | (N.R.) | (N.R.) | 229 |

[a] Final age for each fish was assigned by taking the mean of three readers' ages.

N.R. Not reported.

Table 2: Comparison of von Bertalanffy growth function parameters for this study and that of Butler et al. (1999; in parentheses), for combined sexes, females and males. All lengths are in total length (mm).

| | Combined sexes | Females | Males |
|---|---|---|---|
| $L_\infty$(mm) | 509 (524[a]) | 548 (554) | 448 (467) |
| 95% CI | 491 – 528 (N.R.) | 520 – 576 (N.R.) | 434 – 462 |
| (N.R.) | | | |
| k | 0.05 (0.04) | 0.04 (0.04) | 0.07 (0.06) |
| 95% CI | 0.038 - 0.052 | 0.033 – 0.047 | 0.058 – 0.078 |
| $t_0$ | -4.857 (-5.018) | -4.485 (-4.66) | -2.369 (-2.98) |
| 95% CI | -6.597 to -3.116 | -6.297 to -2.672 | -3.551 to - |
| 1.186 | | | |
| n | 314 (335) | 165 (98) | 151 (78) |
| $r^2$ | 0.81 (0.79) | 0.87 (0.90) | 0.87 (0.92) |

[a] Total lengths from some samples in Butler et al. (1999) were estimated from fork length (FL in mm) using an equation from Echeverria and Lenarz (1984).

N.R. Not reported.

Table 3. Summary data for 14 pooled otolith age groups of blackgill rockfish. The age range and sample weight of each age group was based on predicted age and otolith availability. Groups were confined by year of capture, and for 1985 samples, port location. Both otoliths were not available for every fish chosen. Mean total length (± 1 standard deviation) of individuals per group is provided.

| Sample # | Age group (yr) | Sex | Capture year | Mean length ± σ (TL mm) | Number of fish, otoliths | Sample weight (g) |
|---|---|---|---|---|---|---|
| BG1 | 1 - 3 | Juvenile | 1998 | 154 ± 26 | 7, 11 | 0.4649 |
| BG2 | 3.8 - 4.2 | Juvenile | 1998 | 200 ± 8 | 10, 18 | 1.1687 |
| BG3 | 4 - 5 | Juvenile | 1999 | 217 ± 9 | 15,19 | 1.663 |
| BG4 | 1-7 | Juvenile | 2000 | 119 ± 37 | 25, 36 | 0.7854 |
| BG5 | 29-31 | Female | 1985 | 400 ± 20 | 25, 46 | 1.251 |
| BG6 | 26-28 | Male | 1985 | 379 ± 19 | 22, 35 | 0.8866 |
| BG7 | 11-17 | Female | 1998 | 276 ± 20 | 22, 33 | 0.9018 |
| BG8 | 39-41 | Female | 1985 | 458 ± 22 | 31, 53 | 1.3332 |
| BG9 | 48-54 | Male | 1985 | 459 ± 21 | 25, 48 | 1.2491 |
| BG10 | 60-69 | Female | 1985 | 525 ± 30 | 19, 30 | 0.8254 |
| BG11 | 19-23 | Male | 1998 | 329 ± 16 | 21, 39 | 1.0313 |
| BG12 | 56-59 | Female | 1985 | 502 ± 28 | 13, 25 | 0.6989 |
| BG13 | 39-41 | Male | 1985 | 428 ± 24 | 31, 59 | 1.6424 |
| BG14 | 42-47 | Male | 1998 | 423 ± 26 | 32, 54 | 1.4267 |

Table 4. Summary of radiometric results for pooled otolith age groups. Samples are listed in order of increasing age group range. Activities are expressed as disintegrations per minute (dpm/g). Radium-226 activity was averaged among samples with low analytical error (<10%; n = 7) and was found to be 0.06427 ± 0.0035. This value was then applied to all samples to gain a superior estimate of $^{226}Ra$ activity (see Appendix C for true values). Agreement between radiometric age and predicted age is qualified by the degree of overlap between the two age ranges. Radiometric age incorporates the time between capture and analysis (delta t).

| Sample Number | $^{210}Pb$ activity (dpm/g) [a] | $^{210}Pb$:$^{226}Ra$ activity ratio | Radiometric Age (yr) | Radiometric age range (yr) | Predicted age group range [b] | Average age (yr) | Age range agreement[c] |
|---|---|---|---|---|---|---|---|
| BG1 | 0.0154 ± 8.57 | 0.23957 | 7.1 | 5.4 - 8.7 | 0 - 3 | 2 | Exceeds |
| BG2 | 0.0124 ± 6.74 | 0.19324 | 5.5 | 4.3 - 6.5 | 3.2 - 4.8 | 4 | Overlaps |
| BG3 | 0.0118 ± 5.45 | 0.18410 | 5.5 | 4.5 - 6.4 | 3.5 – 5.5 | 4.5 | Overlaps |
| BG4 | 0.0111 ± 9.22 | 0.17225 | 6.0 | 5.3 - 6.7 | 0 - 8 | 3.5 | Encompass |
| BG7 | 0.0300 ± 5.58 | 0.46700 | 18.0 | 15.2 – 21.4 | 9 – 19 | 14 | Overlaps |
| BG11 | 0.0276 ± 5.75 | 0.42998 | 15.7 | 13.2 – 18.7 | 16 - 26 | 21 | Overlaps |
| BG6 | 0.0440 ± 4.67 | 0.68395 | 22.3 | 16.2 – 30.3 | 22 - 32 | 27 | Overlaps |
| BG5 | 0.0439 ± 4.43 | 0.68282 | 22.1 | 16.2 - 30.3 | 25 - 35 | 30 | Overlaps |
| BG13 | 0.0481 ± 3.81 | 0.74910 | 29.3 | 21.8 – 40.4 | 33 - 47 | 40 | Overlaps |
| BG8 | 0.0494 ± 3.99 | 0.76930 | 32.1 | 23.7 – 45.1 | 33 - 47 | 40 | Overlaps |
| BG14 | 0.0499 ± 3.75 | 0.77699 | 45.8 | 37.3 - 59.1 | 36 - 54 | 45 | Overlaps |
| BG9 | 0.0560 ± 3.73 | 0.87136 | 50.7 | 35.8 – 85.1 | 41 - 62 | 51 | Encompass |
| BG12 | 0.0586 ± 4.72 | 0.91198 | 62.9 | 40.7-undef. | 48 - 67 | 57 | Encompass |
| BG10 | 0.0543 ± 4.38 | 0.84483 | 44.8 | 31.6 – 71.6 | 51 - 79 | 65 | Overlaps |

[a] Error calculation based on the standard deviation of $^{210}Pb$ activity (Wang et al. 1975).

[b] Predicted age range is extended by 15% coefficient of variation associated with growth zone derived age estimates.

[c] Definition of terms: Exceeds = radiometric age is greater than predicted age; Overlaps = radiometric age partially agrees with predicted age; Encompasses = radiometric age completely agrees with predicted age; Below = radiometric age is less than predicted age.

Figure 1. Blackgill rockfish (*Sebastes melanostomus*), photographed from a submersible at approximately 350 m near the head of Ascension Canyon, Monterey Bay, California. Blackgill rockfish are distinguished from other rockfishes by the black skin in the fold above the upper jaw, in the mouth, and inside the operculum. (Courtesy: Joe Bizzarro, Moss Landing Marine Laboratories, Moss Landing, California)

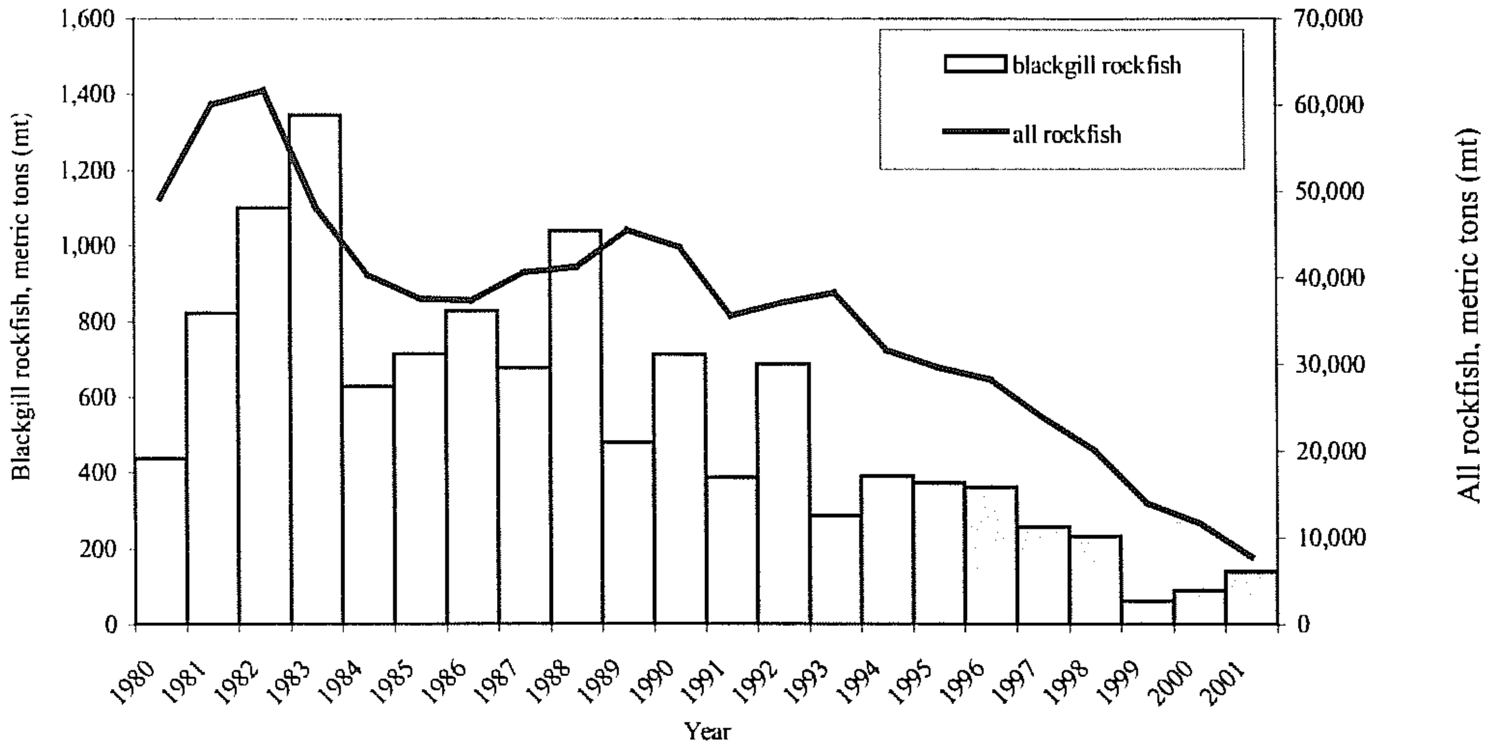


Figure 2. Landings of blackgill rockfish compared to all rockfish landed at West Coast ports from California to Washington, 1980-2001 given in metric tons (mt). Landings of blackgill rockfish only from 1980 to 1997 are reported from Butler et al. (1999) and are described as "imprecise estimates" (p. 11). From 1980 to 1996, approximately 84% of landings were from the Point Conception area of California and 16% were from the Monterey area, with less than 1% from areas north of Eureka, California. All other landings are reported from the Pacific Fishery Management Council database (PacFIN 2002). NOTE: Scales differ between landing axes.

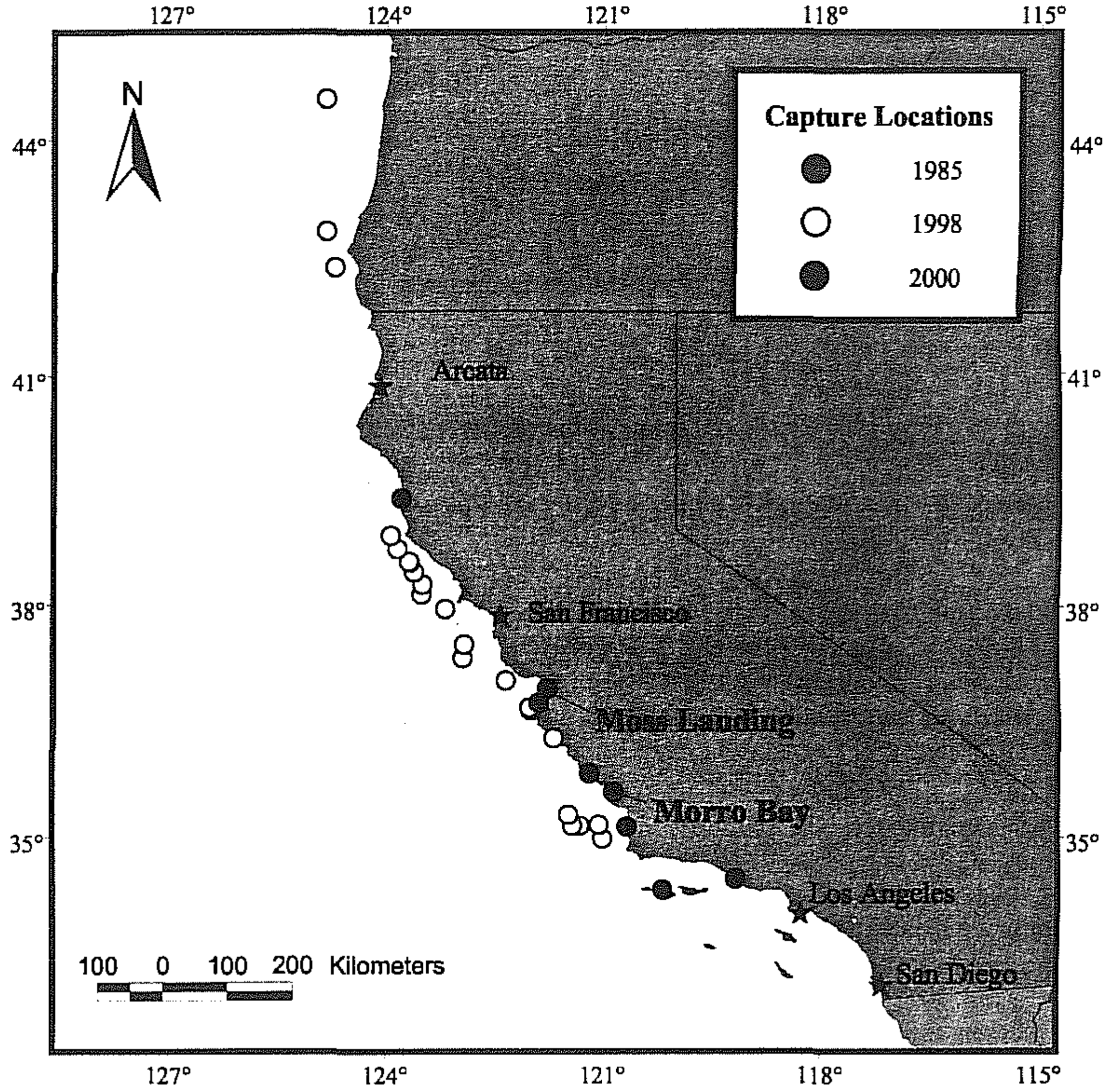


Figure 3. Capture locations for blackgill rockfish used in this study. Symbols represent either NMFS research trawl locations (1998, 2000) or port locations (1985) where NMFS workers removed otoliths from commercially caught fish.

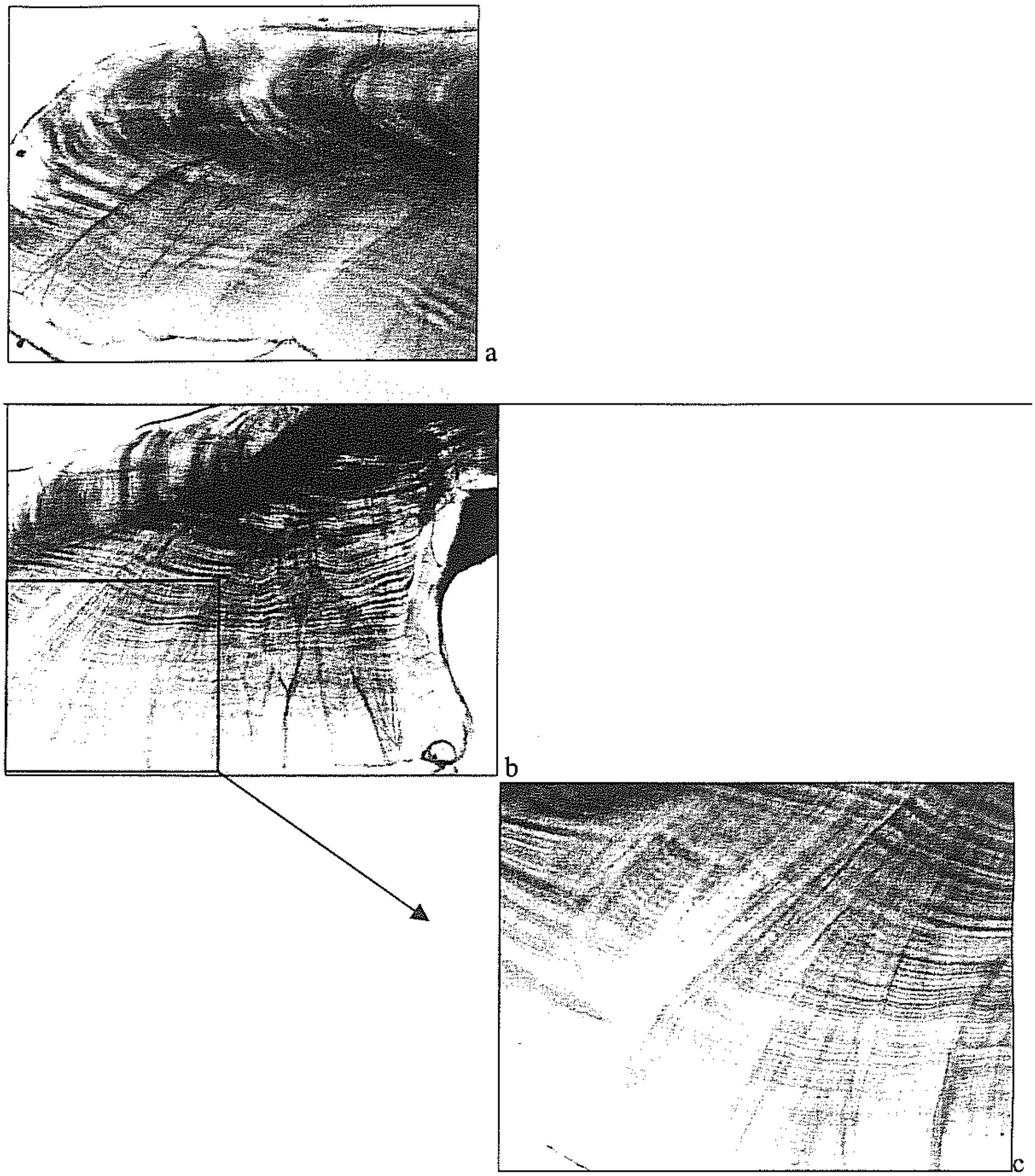

Figure 4. Transverse section of blackgill rockfish otolith, viewed under transmitted light at various magnifications. a) Example of difficult otolith section, 25x magnification b) example of clear section, 40x, and c) 80x magnification, aged at 90 years.

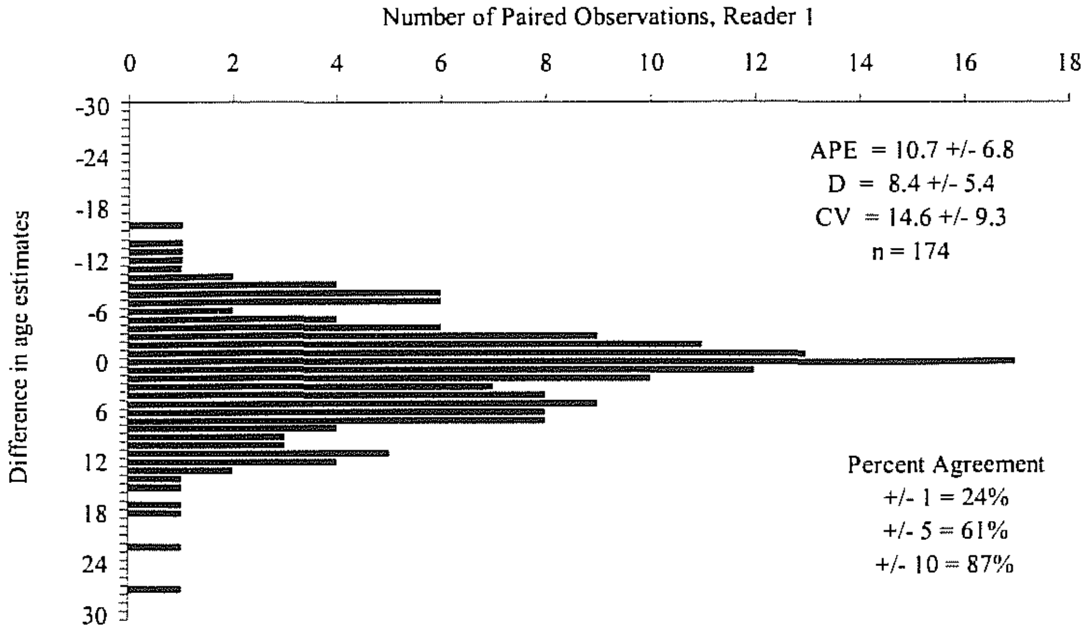


Figure 5. Precision of reader 1 age estimates of *Sebastes melanostomus*, compared to readers 2 and 3. The histogram represents the difference (as a percentage of paired age estimates differing by years) between readings. The average percent error (APE, %), index of precision (D, %), and coeffiecient of variation (CV, %) among readers is listed for reference, and the sample size (n) represents the number of aged otolith sections. Unreadable otoliths were not included in the analysis.

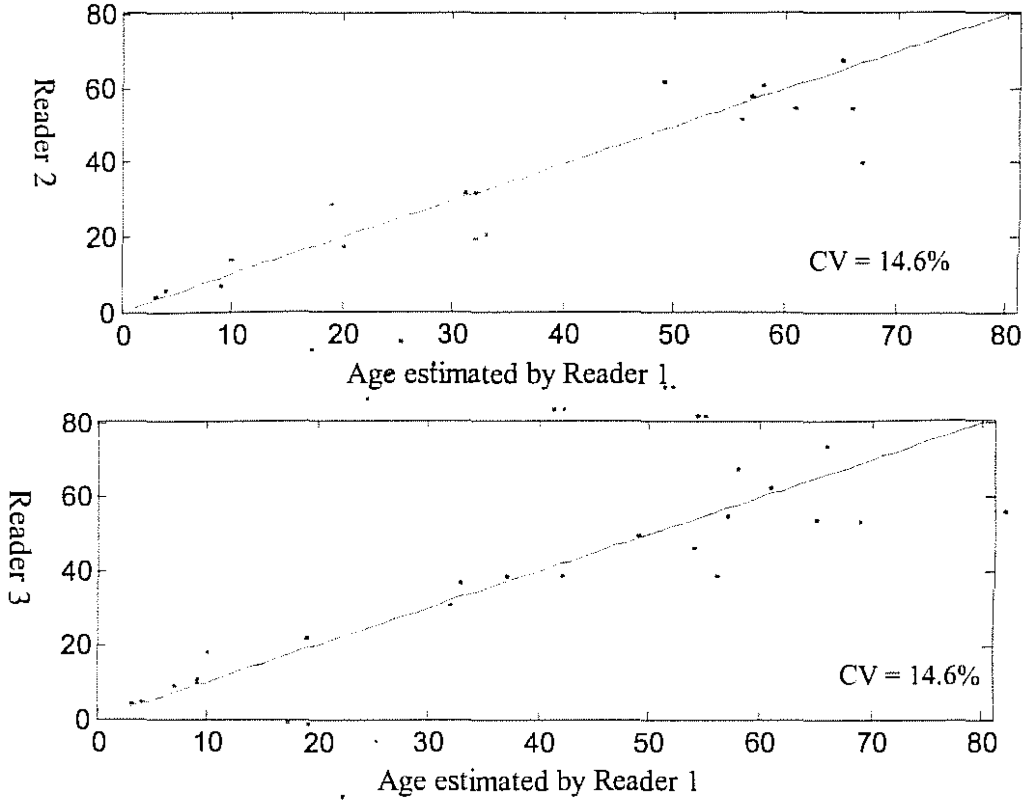


Figure 6. Age bias plots, comparing each reader against reader 1 (author). The 45° line is the line of agreement between the readers. The error bars represent variance around the average age estimates for the reader being compared with the primary reader (reader 1). Any ages that are above or below the line (data points) may be considered an aging bias of one reader (y-axis) versus the primary reader (x-axis).

Correction for page 49

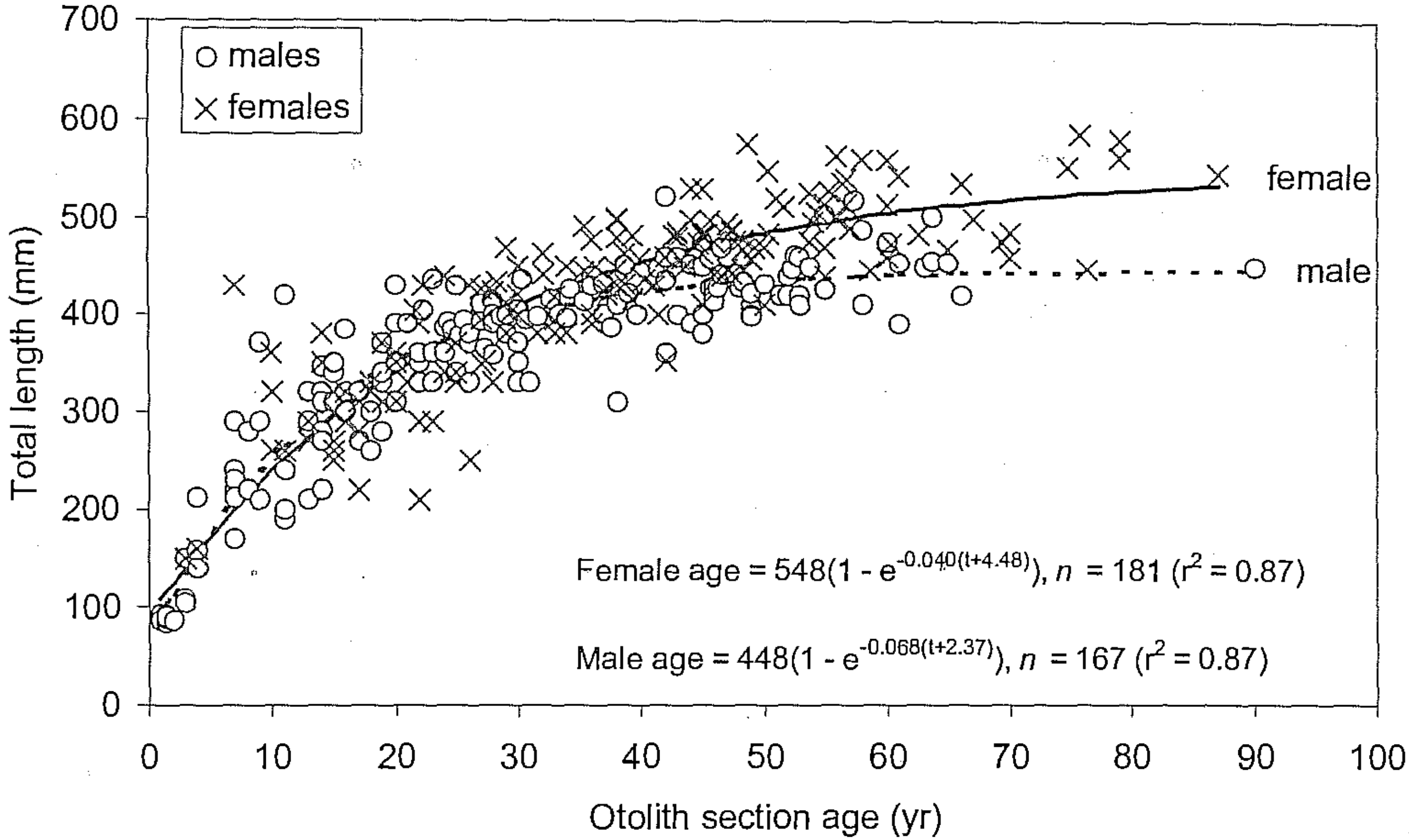


Figure 7. Blackgill rockfish von Bertalanffy growth functions plotted for males and females. Observed and expected values, as well as the parameters of the equations, are given. Note that the same juvenile samples ($n = 16$) were included in both male and female equations.

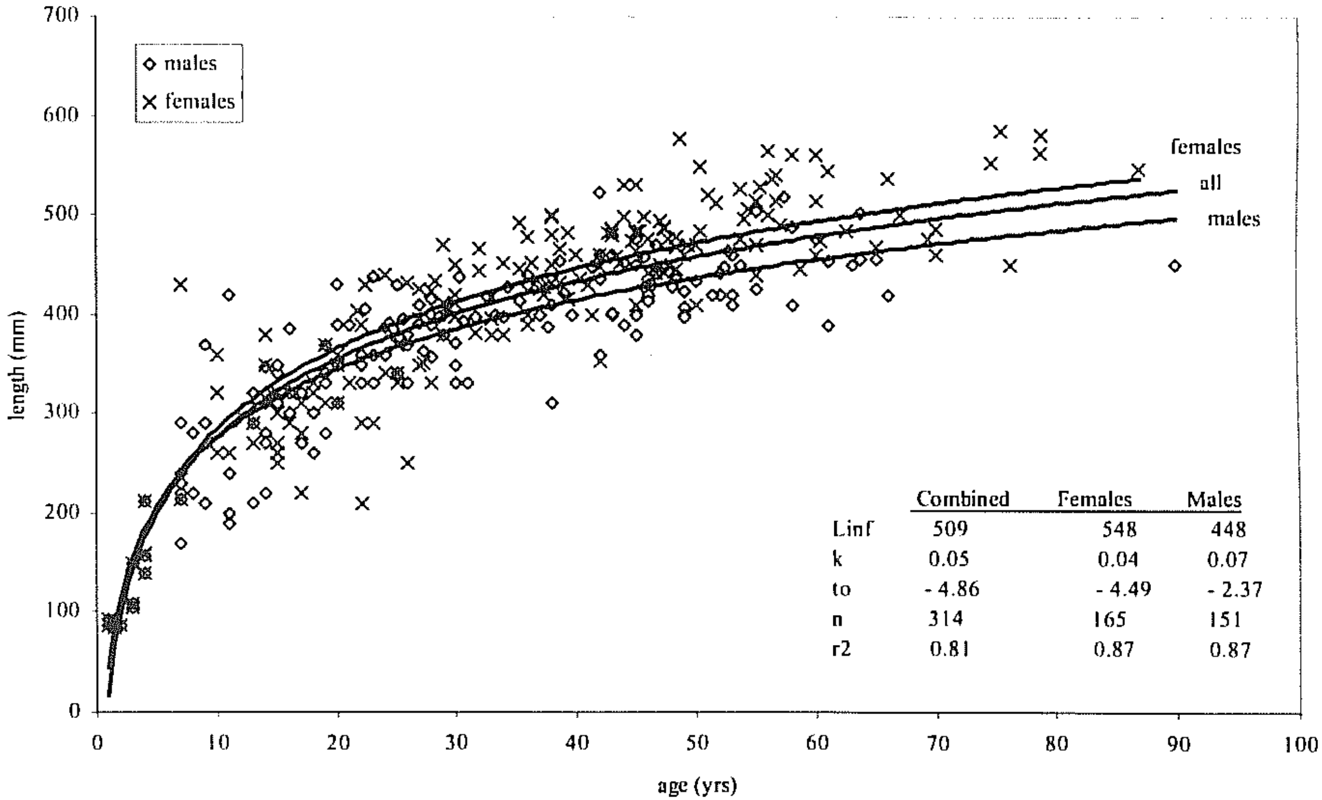


Figure 7. Von Bertalanffy growth function plotted for males, females and combined sexes of blackgill rockfish. Observed and expected values, as well as the parameters of the equation, are shown.

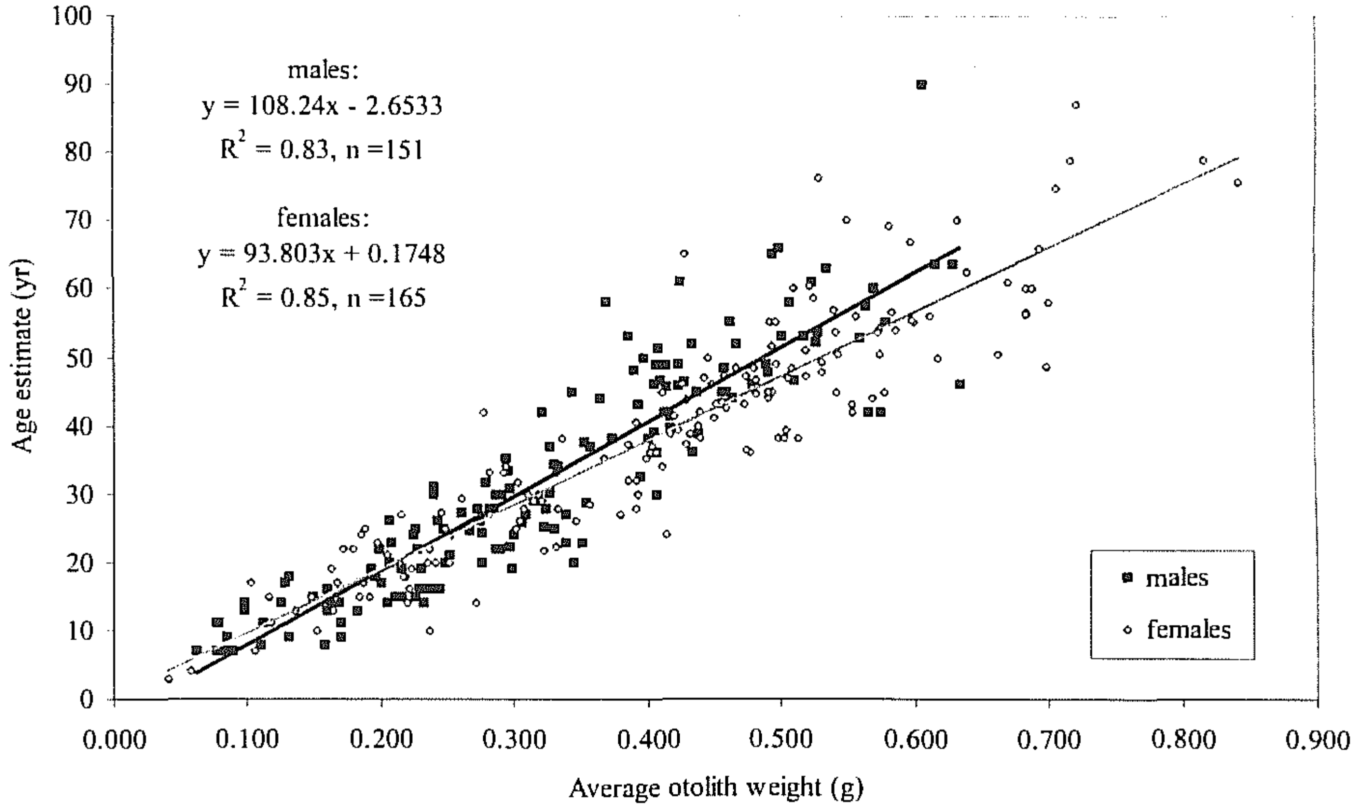


Figure 8. Predictive relationship between average otolith weight and estimated age for blackgill rockfish. These regression equations were then used to predict age of fish whose otoliths were reserved for radiometric analysis.

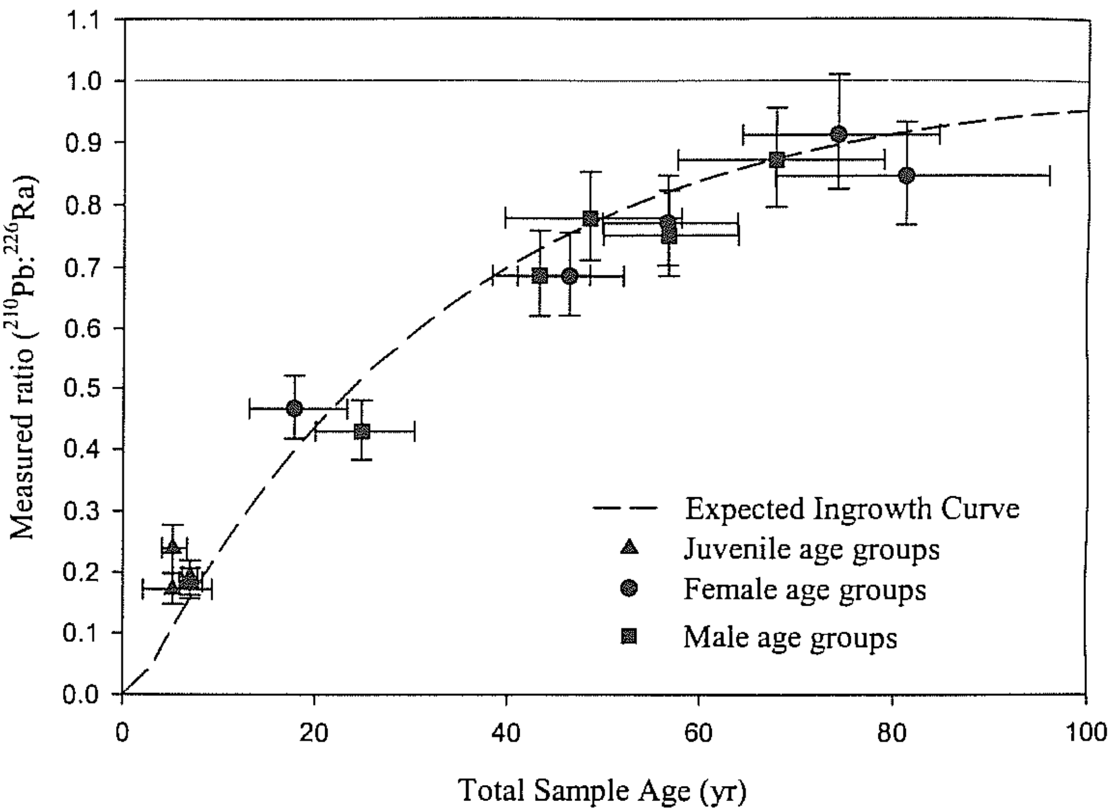


Figure 9. Measured $^{210}$Pb:$^{226}$Ra ratio plotted against total sample age (predicted age plus time since capture), with respect to the expected $^{210}$Pb:$^{226}$Ra activity ratio (ingrowth curve). Horizontal error bars represent the predicted age range (based on growth zone derived age estimates plotted against average otolith weight; Fig. 8) extended by 15% (CV). Vertical error bars represent high and low activity ratios, based on the analytical uncertainty associated with $^{210}$Pb and $^{226}$Ra measurements.

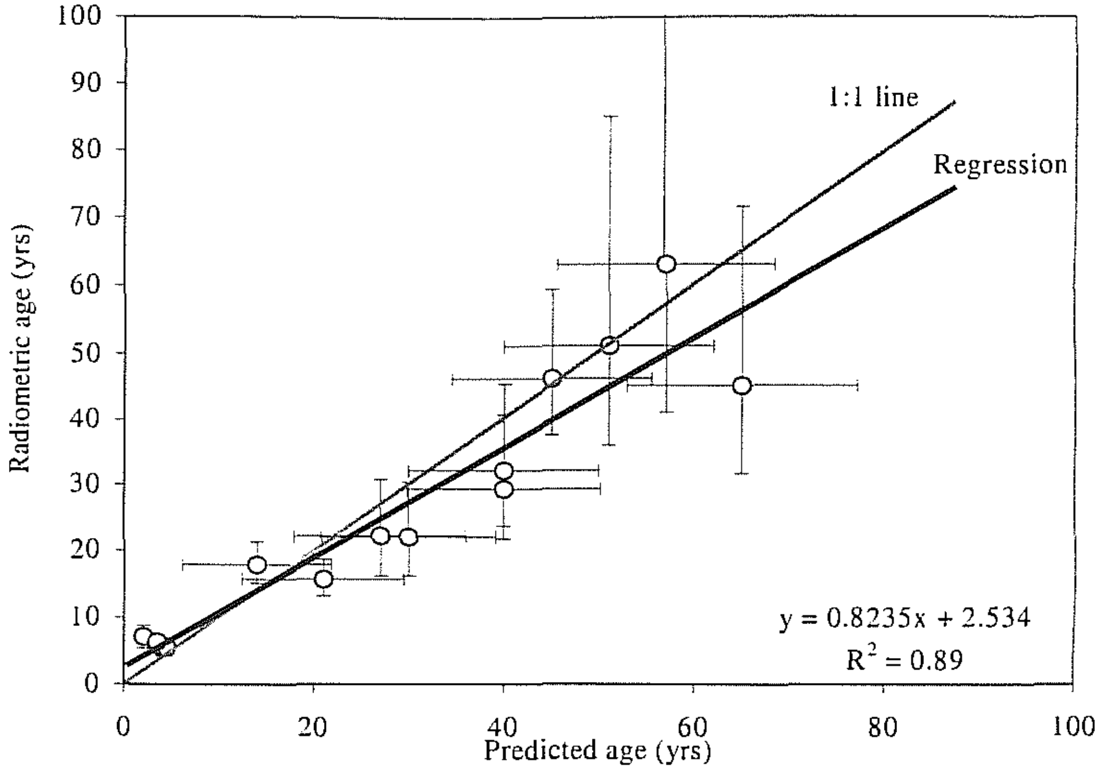


Figure 10. Direct comparison of mean predicted age and radiometric age for 14 pooled otolith age groups for blackgill rockfish. Regression and 1:1 agreement lines are included for comparison. Horizontal error bars represent the uncertainty in age estimates (D, the index of precision) and the standard error of the regression (1*s*), which was used to predict age for radiometric samples. Vertical error bars represent high and low radiometric age estimates, based on the analytical uncertainty associated with $^{210}Pb$ and $^{226}Ra$ measurements.

APPENDIX A: $^{210}$Pb Activity Calculation (from Andrews et al. 1999a)

Activity of $^{210}$Pb was determined by auto-deposition and alpha-spectrometry of its daughter, $^{210}$Po. Polonium-208 was used as a yield tracer; $^{210}$Po and $^{208}$Po were corrected for background and reagent counts as follows:

$$t_{mid} = \frac{\ln\left(\left(1 + e^{\left(-\lambda^{2xx} Po * t_{fin}\right)}\right)\right)}{2} * \left(-\lambda^{2xx} Po\right) ,$$

where $t_{mid}$ was the midpoint in each interval, for each isotope, where counts collected before and after were equal; $\lambda^{2xx}$Po was the decay constant for $^{208}$Po (ln(2)/2.898 yr) or $^{210}$Po (ln(2)/0.3789 yr); and tfin was the time from autodepostition to the end of the counting interval. Tmid was then used to calculate the $^{210}$Po and $^{208}$Po counts, corrected for decay since autodeposition,

$$Cts^{2xx} Po_{ta} = \frac{Cts^{2xx} Po_{m}}{\left(e^{\left(\left(-\lambda^{2xx} Po\right) * t_{mid}\right)}\right)} ,$$

where $Cts^{2xx}Po_{ta}$ was the decay corrected $^{210}Po$ or $^{208}Po$ counts to the time of autodeposition, $Cts^{2xx}Po_{m}$ was the measured $^{210}Po$ or $^{208}Po$ counts, and $\lambda^{2xx}Po$ was the decay constant for $^{210}Po$ or $^{208}Po$. Because the $^{210}Po/^{208}Po$ activity ratio was equal to the measured $^{210}Po/^{208}Po$ count ratio and the $^{208}Po$ yield-tracer activity was known, the $^{210}Po$ activity was determined using,

$$A^{210}Po_{unk} = A^{208}Po_{known} * \left( \frac{Cts^{210}Po}{Cts^{208}Po} \right),$$

where $A^{210}Po_{unk}$ was the unknown $^{210}Po$ activity of the sample, $A^{208}Po_{known}$ was the activity of the $^{208}Po$ yield tracer, and $Cts^{210}Po/Cts^{208}Po$ was the ratio of the corrected counts for $^{210}Po$ and $^{208}Po$.

Since the activity of $^{210}Po$ is in secular equilibrium with $^{210}Pb$, the two activities were considered equal and subsequently corrected for $^{210}Pb$ ingrowth from the time of capture to autodeposition by applying,

$$A^{210}Pb_{tc} = A^{210}Pb_{ta} - A^{226}Ra_{TIMS} * \left(1 - e^{(-\lambda dt)}\right),$$

where $A^{210}Pb_{tc}$ was the $^{210}Pb$ activity at the time of capture, $A^{210}Pb_{ta}$ was the $^{210}Pb$ activity corrected to the time of autodeposition, $A^{226}Ra_{TIMS}$ was the $^{226}Ra$ activity measured using TIMS, $\lambda$ was the decay constant for $^{210}Pb$ (ln(2)/22.26 yr), and *dt* was the time between capture and autodeposition.

# APPENDIX B: $^{210}$Pb and $^{226}$Ra Error Calculations

Uncertainty involved in calculation of $^{210}$Pb and $^{226}$Ra activities were based on the total counts after correction for background and reagents and are as follows:

$$\sigma A^{210}Pb = A^{210}Pb * \sqrt{\left(\frac{\sqrt{N^{208}Po}}{N^{208}Po}\right)^2 + \left(\frac{\sqrt{N^{210}Po}}{N^{210}Po}\right)^2} \quad ,$$

where $\sigma A^{210}$Pb is the standard deviation of the $^{210}$Pb activity, $A^{210}$Pb is the corrected $^{210}$Pb activity, N is the number of counts corrected for background and reagents for $^{208}$Po or $^{210}$Po (Wang et al. 1975). Uncertainty for $^{226}$Ra activity was calculated during sample analysis (Andrews et al. 1999b). This uncertainty was used to calculate the radiometric age range (high and low):

$$low\ activity = \frac{A^{210}Pb - error}{A^{226}Ra + error}$$

$$high\ activity = \frac{A^{210}Pb + error}{A^{226}Ra - error}$$

$$t_{age} = \frac{\ln\left(1 - \frac{A^{210}Pb_P}{A^{226}Ra_{TIMS}}\right)}{-\lambda} - \Delta t,$$

Once high and low activities are calculated, they are inserted into the age determination equation shown in Methods section.

Appendix C: Measured values of $^{226}Ra$ activity for 14 pooled otolith groups

| Sample number | 226Ra activity ± % error |
|---|---|
| BG1 | N.D. |
| BG2 | N.D. |
| BG3 | N.D. |
| BG4 | 0.06796 ± 1.34 |
| BG5 | 0.06633 ± 2.09 |
| BG6 | 0.06276 ± 3.4 |
| BG7 | -0.01218 ± 15.3 |
| BG8 | 0.05871 ± 6.8 |
| BG9 | 0.06813 ± 2.3 |
| BG10 | 0.06469 ± 3.27 |
| BG11 | 0.06130 ± 3.09 |
| BG12 | 0.0846 ± 19.11 |
| BG13 | 0.05262 ± 13.68 |
| BG14 | 0.01196[a] ± 7.49 |

N.D. Not detected

[a] An improperly calibrated $^{228}Ra$ yield-tracer led a miscalculation in the volume of the spike to be added, resulting in extremely low value of $^{226}Ra$ for this sample.