Lead-radium dating of golden tilefish (*Lopholatilus chamaeleonticeps*)

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In satisfaction of:

Marine Fisheries Initiative Program In-House,

Requisition #NFFN7100-19358

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July 2009

Introduction

Much of the complex life history of golden tilefish (*Lopholatilus chamaeleonticeps*) has been described, including age and growth (Grimes and Turner 1999), but validation of age estimates remains unresolved. Application of marginal increment analyses to fin ray and otolith sections have provided support for age estimates and procedures (Turner et al. 1983, Harris and Grossman 1985), but use of this technique requires an extrapolation of trends to the oldest ages. An attempt to apply the bomb radiocarbon technique to core material of adult golden tilefish provided complicated results that may have been the result of larvae or juveniles remaining in deep water (Harris 2005). Thus, confidence in the ability to determine age and longevity is low for golden tilefish. A technique that can assist with age determination is lead-radium dating.

Lead-radium dating is a geochronological technique that has been used to date recent geological formations, such as accretionary carbonates (e.g. Condominesa and Rihs 2006). Use of this system as a chronometer relies on the decay of the relatively long-lived radioisotope radium-226 (^{226}Ra), a naturally occurring product of the uranium-238 (^{238}U) decay series (Figure 1), to the relatively short-lived granddaughter product lead-210 (^{210}Pb). Because the half-life of radium-226 is much greater (~1600 years) than lead-210 (22.26 years) the disequilibrium of the lead-radium system can function as a natural chronometer as lead-210 builds into equilibrium with radium-226. Once radium-226 is incorporated and isolated by some kind of structure (e.g. crystalline lattice), it is the ingrowth of lead-210 activity relative to radium-226 activity that provides a measure of time. In an ideal system there would be no exogenous source of lead-210 and the lead-radium ratio would increase purely from ingrowth. This ingrowth would exponentially approach a ratio of one, at which time the rate of lead-210 decay would be equal to the rate of lead-210 ingrowth from radium-226 (Figure 2). In this line of research, it is the radioactivity (often expressed simply as "activity") of each isotope that is measured in decays per minute (dpm) per unit mass (g), expressed as $dpm \cdot g^{-1}$. This dynamic equilibrium is called secular equilibrium and is achieved to within 1% in a period of 156 years or seven lead-210 half-lives.

For fish, lead-radium dating depends on the incorporation of radium-226 from the environment, where it is locked into the otolith matrix and subsequently decays to lead-210. The otolith lead-radium system can be used to provide an independent estimate of age, as well as a form of age validation for age estimation methodologies (Smith et al. 1991, Panfili et al. 2002).

The feasibility of lead-radium dating otolith material depends heavily on the levels of radium-226 uptake. For a successful application to work on small quantities of otolith material, radium-226 levels need to be relatively high. Measured levels of radium-226 from otoliths of marine fishes can vary by approximately two orders of magnitude (~0.01 to 1.0 $dpm \cdot g^{-1}$). This was demonstrated in two recent age and growth papers on bocaccio rockfish (*Sebastes paucispinis*; Andrews et al. 2005) and Atlantic tarpon (*Megalops atlanticus*; Andrews et al. 2001). The bocaccio rockfish study exemplified the limits of detection and applicability of the technique by providing only rough estimates of age; the levels for radium-226 (consequently lead-210) were too low to provide a low margin of error associated with the calculated radiometric age. Conversely, the Atlantic tarpon study exemplified use of low sample size for meaningful lead-radium dating because radium-226 levels were some of the highest reported from otoliths; as a result of this and other factors, individual fish could be aged using lead-radium dating.

Lead-radium dating has a well recognized record of success in the literature as a tool for the age validation of numerous long-lived fish species (Bennett et al. 1982, Campana et al. 1990, Fenton et al. 1990, Fenton et al. 1991, Fenton and Short 1992, Kastelle et al. 1994, Fenton and Short 1995, Milton et al. 1995, Smith et al. 1995, Stewart et al. 1995, Kline 1996, Burton et al. 1999, Andrews et al. 1999a, Kastelle et al. 2000, Andrews et al. 2001, 2002, Stevens et al. 2004, Andrews et al. 2005, Stransky et al. 2005, Watters et al. 2006, Andrews et al. 2007, Andrews 2009, Andrews et al. 2009). This technique is well established at MLML (Moss Landing Marine Laboratories), where it has been modified and refined (Andrews et al. 1999b), and continues to be a pursuit in novel applications (e.g., ICPMS for radium-226 measurement; C. Lundstrom pers. comm., University of Illinois -

Urbana Champaign, Department of Geology, Urbana, Illinois 61801) focusing on improving the precision and accuracy of the technique. In a recent application to orange roughy otolith cores, issues that have been raised in other studies were addressed in detail and firm support was provided for lead-radium dating as a valid tool in fish age determination (Andrews et al. 2009).

In this study, groups of golden tilefish otoliths were analyzed using lead-radium dating to provide age determinations for age-groups. The hypothesis was that age could be estimated from growth zones counted in otolith sections and that lead-radium dating would confirm the age estimations. These data were used to provide an age validated basis for further developing an age estimation criteria for golden tilefish from the coastal waters of Florida, which will be used in future stock assessments (scheduled SEDAR Gulf of Mexico and South Atlantic in 2010).

Materials and Methods

Methods and structures used for age estimation vary among fishes. The most promising structures for golden tilefish have been otolith and fin ray sections (Turner et al. 1983, Harris and Grossman 1985). In this study, otoliths were chosen based on the applicability of lead-radium dating and the possibility of using such validated age determinations as a basis for assisting with the development of age estimation criteria. Otolith pairs from golden tilefish collections were selected for age estimation from growth-zone counting by taking a transverse section (dorso-ventral plane) through the focus using a petrographic-type saw (completed at NOAA Fisheries Service, Panama City, FL). Sectioned otoliths were aged by two readers (MLML - Age and Longevity Research and NMFS - Panama City) using transmitted light on a dissecting microscope. Each reader made initial estimates of age by examining the otolith sections with a magnification that was wide-ranging to fully investigate the quantifiable growth patterns. Initial estimates of age were then compared between readers and growth pattern recognition was discussed to develop age estimation criteria. Once age estimation procedures were agreed upon between readers, all otoliths were read multiple times and reader precision estimates (average percent error and percent agreement ± 1 and ± 2 bands) were determined between readers (Campana 2001). Finalized age estimates for the otolith series were used to determine what otoliths would be considered for lead-radium dating.

The application of lead-radium dating has limitations that must be considered prior to forming otolith age groups. Estimating the limitations of lead-radium dating for this study were based on several factors: 1) core size and potential age from measurements of juvenile otoliths; 2) individual and collective sample mass availability for juvenile and cored adult otoliths; 3) potential ^{226}Ra activity; and 4) total sample age (estimated age plus time since capture). This approach was similar to most other studies performed by this laboratory in that initial sample masses were chosen to provide a good indication of lead-210 and radium-226 activity, given a best guess at the lowest case scenario. Typical radium-226 activity in otolith material is 0.03 to 0.05 $dpm \cdot g^{-1}$. Based on this estimate, a minimum of 0.5 grams of core material was targeted for each group to collect sufficient counts at the alpha-spectrometer (α-spectrometer), with a more optimal target of more than 1.0 g for each age group.

Because of its rarity in collections, only one juvenile otolith was available as a reference for adult otolith coring (Figure 3). Age was estimated at 2 years and based on the dimensions and whole otolith weight of this otolith, the target of core extractions was approximately 8 mm L x 4 mm W x 1 mm T and a weight of 0.05 g. Hence, the number of otoliths required for an adequate sample size of 0.5 grams was ~10, with more than 10 providing more optimal conditions for measuring lead-radium activities.

The basic experimental design for the age-group series was to cover as much of the estimated age ranges as possible, allow for separation of sexes and possibly replicate samples within each age group. The youngest age groups, where enough otoliths were available, were 5-7 years, which were partitoned into 2 male and 2 female groups (Appendix I-II). Middle aged groups were 10 - 13 years with 2 male and 2 female groups as well (Appendix III-IV). Each of these groups was randomly allocated to replicate age group for each sex. Older groups were limited by sample availability. A set of 15-19 year age groups was considered, but fewer otoliths were available and sex was not available for most of the specimens. Therefore, 2 age groups were formed that covered low otolith weight and high otolith weight scenarios within the older age groups (Appendix V). The options were similar for the oldest age group, but the potential age range needed to be expanded for enough otoliths to form groups. A low otolith weight group of 20-27 years formed one group and the other was a high otolith weight group of 22-28 years (Appendix V). All otoliths used in this study were collected in 2007 from intercepts of commercial long-line vessels fishing off the east coast of Florida.

Once the otoliths were selected for the age groups, each otolith was cored to the first 2 years of growth by: 1) grinding on a lapidary wheel; and 2) comparing the extracted core microscopically, as well as macroscopically, to the reference juvenile otolith mentioned earlier. Growth zones visible in the otolith at hand were used to verify the concentric structure of each core to the first few years of growth. Careful consideration was given to the shape of the juvenile otolith as the extraction took place. It was noted that the orientation of the otolith slowly rotated upward on the anterior end within the first few years of growth. In addition, the shape of the juvenile otolith was slightly concaved to the distal side. Both of these morphological characteristics were approximated in the core extractions, where a combination microscopic examination and measurements provided the best indication of when the core extraction was finished. The final determination was made with the otolith core weight once the core was dry (room temperature). In most cases, the cores needed fine-tuning with minor grinding and more microscopic and measurement observations. Finalized otolith cores were pooled into the respective age groups and prepared for lead-radium dating analysis.

A detailed protocol describing sample preparation, chromatographic separation of radium-226 from barium and calcium, and analysis of radium-226 using mass spectrometry was described elsewhere (Andrews et al. 1999b). These procedures have not changed for this study, except for two aspects of the analysis: 1) radium recovery was improved by shifting the collection interval on the final chromatography column to begin at 200 µL (as opposed to 250 µL); and 2) purified radium samples were analyzed using an improved ICP-MS

(Inductively Coupled Plasma Mass Spectrometry) technique. Other than these details, only an overview of the radium-226 procedures is given here with details on the determination of lead-210 activity. Because the levels of radium-226 and lead-210 typically found in otoliths were extremely low (femtograms (10^{-15} g) for radium-226 and attograms (10^{-18} g) for lead-210) and the great potential for contamination of various forms and sources, trace-metal clean procedures and equipment were used throughout sample preparation, separation, and analysis. All acids used were ultra-pure, double distilled (GFS Chemicals®) and dilutions were made using Millipore® filtered Milli-Q water (18 MΩ cm^{-1}).

Dried and weighed samples were dissolved in TFE beakers on hot plates at 90°C by adding 8N HNO_3 in 1-2 mL aliquots (Figure 4). Alternation between 8N HNO_3 and 6N HCl, with an aqua regia transition, several times resulted in complete sample dissolution. The dried sample, after dissolution, formed yellowish precipitate. To reduce remaining organics (otolin), and to put the residue into the chloride form required for the lead-210 activity determination procedure, the samples were redissolved in 1 mL 6N HCl and taken to dryness five times at 90-120°C. A whitish residue indicated that sufficient amounts of the organics have been removed. These samples were used to determine lead-210 activity prior to ICP-MS analysis.

To determine lead-210 activity in the otolith samples, the α-decay of polonium-210 was used as a daughter proxy for lead-210. To ensure that activity of polonium-210 was due solely to ingrowth from lead-210, the time elapsed from capture to polonium-210 determination was greater than 2 yr, with the exception of the adult age group; because the adult age group consisted of otolith cores, the 2 yr waiting period was not necessary. Samples prepared for polonium-210 analysis were spiked with polonium-208, a yield tracer. The amount of polonium-208 added was estimated based on observed radium-226 levels in other studies of deepwater fishes. This amount was adjusted to about 5 times the expected polonium-210 activity in the otolith sample to reduce error in the lead-210 activity determination. The spiked samples were redissolved in approximately 50 mL of 0.5N HCl on a hot plate at 90°C covered with a watch glass. The polonium-210 and polonium-208-tracer was autodeposited for 4 hours onto a silver planchet. The activities of these isotopes were determined using α-spectrometry on the plated samples (Figure 5). Additional procedural and system details are described elsewhere (Andrews et al. 1999a). The solution remaining after polonium plating was dried and saved for radium-226 analyses.

Radium-226 analyses were performed by isotope dilution techniques following the procedure of Andrews et al. (1999b), except that analyses in this study were performed using a Multicollector ICPMS in place of TIMS. The new mass spectrometer analysis took place on a Nu Plasma™ HR instrument located in the Department of Geology at University of Illinois-Urbana, Champagne. The analysis introduced the chemically purified radium as a 2% HNO_3 solution into a desolvating nebulizer. The sample was converted into dry aerosols which were swept into the argon plasma and into the mass spectrometer. Sensitivity during radium analysis corresponds to approximately 25 counts per second (cps) $\cdot ppq^{-1}$ radium at an uptake rate of 70 $\mu L \cdot min^{-1}$. Once in the spectrometer, isotope ratios were measured by switching the magnet back and forth between atomic mass units (amu) 226 and 228 after a 1 minute background taken at amu 225.5 or 227.5. An individual sample analysis consisted of 10 measured ratios representing 10 second integrations on each amu peak. After each analysis, the system was washed successively with 5% HNO_3 and 2% HNO_3 for 10 minutes until no residual radium signal could be observed. Count rates on samples in this study were usually >100 cps for each radium isotope, compared to the nominal background on clean acid, which was <1 cps.

Radiometric age was determined from the measured lead-210 and radium-226 activities. Because the activities were measured using the same sample, the calculation was independent of sample mass. Radiometric age was calculated using an equation derived from Smith et al. (1991) to compensate for the ingrowth gradient of lead-210:radium-226 in the otolith core,

$$t_{age} = \frac{\ln\left(\dfrac{1-\left(\dfrac{A^{210}Pb}{A^{226}Ra}\right)}{\left(1-R_0\right)\left(\dfrac{1-e^{-\lambda T}}{\lambda T}\right)}\right)}{-\lambda} + T,$$

where t_{age} was the radiometric age at the time of analysis, $A^{210}Pb$ was the measured lead-210 activity at time of analysis and reported as $dpm \cdot g^{-1}$ (disintegrations per minute per gram), $A^{226}Ra$ was the radium-226 activity measured using ICPMS (reported as $dpm \cdot g^{-1}$), R_0 was the activity ratio of lead-210 and radium-226 initially incorporated, λ was the decay constant for lead-210 ($\ln(2) \cdot 22.26 \cdot yr^{-1}$), and T was the estimated core age based on the first few growth zones. An initial uptake ratio of $R_0 = 0.0$ was used based on the close agreement of the measured juvenile age group lead-radium ratio with the expected ingrowth curve; however, other studies have accounted for what appeared to be exogenous lead-210 with minor adjustments necessary (e.g. Kastelle et al. 2000, Stransky et al. 2005). A radiometric age range, based on the analytical uncertainty, was calculated for each sample by using error propagation through to the final age determinations (2 SE, standard error). Calculated error included the standard sources of error (i.e. pipetting, spike and calibration uncertainties, etc.), alpha-counting statistics for lead-210, and the ICPMS analysis routine.

The 95% confidence interval (2 SE) from lead-radium dating was used to interpret the validity of growth zone counts, and to determine the strength and limits of age confirmations. To describe the trend between age estimation from growth zone counts and lead-radium dating a simple linear regression was applied. Age agreement or disagreement between the methods, in terms of potential ageing bias, was given considering the potential error (2 SE).

To address growth relative to radiometric age, a von Bertalanffy growth function was fitted to these data, but it was necessary to fix $t_0 = 0.0$ because early age data was unavailable.

Differences in average whole otolith weight relative to radiometric age were also explored out of interest.

Results

Golden tilefish thin-sectioned otoliths were difficult to interpret given several different shapes of otolith sections and diverse patterns of growth deposition. Otolith sections were interpreted between 10 – 20x with a stereo microscope aided by reflected light. Initial reader agreements resulted in 18% average percent error (APE), 8% reader agreement, and reader agreement ± 1 band 22% and ± 2 bands 26%. After multiple reads of otoliths, reader agreement increased to 28%, APE was reduced to a more acceptable value of 6%, with percent agreements ± 1 band and ± 2 bands increased to 78% and 95%, respectively. Final age estimates based on the agreed pattern of recognition were used for further analysis.

Twelve age groups were formed for the lead-radium analysis of golden tilefish otoliths (Table 1). Estimated age for the series of groups ranged from 5-7 years to 22-28 years with sexes separated for the first two age groups. Within the separate-sex age groups, each was randomly split into sample replicates, resulting in 2 male and 2 female groups for both 5-7 year and 10-13 year groups. Randomization led to age ranges that differed slightly in range (i.e. GTL 5-7 M1 = 6-7 years, and GTL 10-13 M1 = 10-12 years); however, the average estimated age was relatively consistent at 6.2 to 6.4 years for the 5-7 yr groups, and 10.6 to 11.4 years for the 10-13 yr groups. Sexes could not be separated for the older age groups because of a lack of information and low sample availability. Two 15-19 year groups were separated by otolith weight into a low (A) and high (B) weight classification. A similar situation was the result for the oldest age groups, where randomization led to slightly different age ranges, the low weight age group ranged from 20-27 years and the higher otolith weight group ranged from 22-28 years. Fish length was lowest on average for the 5-7 yr female groups and range up to more than 750 mm FL on average for the oldest age groups. In general, the length of fish increased with estimated age, but some age groups included some relatively large individuals (e.g. GTL 5-7 M1, maximum length = 860 mm

FL). Whole otolith weight was also lowest for the 5-7 yr female groups at below 0.4 g on average. Otoliths for adults were massive and exceeded 1.7 g on average for the 22-28 yr group. For the younger randomized age groups, average otolith weight was lower for females relative to males in all cases. Hence, relative to estimated age, females were typically smaller with lighter otoliths for the first two age groups (5-7 yr and 10-13 yr). For the two older age groups, the heaviest 15-19 yr group (GTL 15-19 B) was similar on average for both fish size and otolith weight to the 20-27 yr group. The oldest age group (GTL 22-28) exceeded almost all groups in terms of otolith weight both on average and in range; only GTL 15-19 B included otoliths that overlapped in weight.

Lead-radium determinations were made for all 12 age-group samples (Table 2). The number of otoliths that made up each age group ranged from 9 to 21 for total sample weights of just over 0.5 g to greater than 1.5 g. Average core weight was slightly greater than the target weight of 0.05 g on average and ranged from 0.06167 g to 0.08130 g. This was anticipated to an extent because the cleaning process usually removes ~5% of the external material, but in this study removed 1-3%. To make a better approximation on the representation of core age in radiometric modeling, 3 years was used *in lieu* of 2 years as the core age. Lead-210 activity increased as expected from the youngest to the oldest age groups by a factor of ~3 times. Samples ranged from 0.00419 ± 13.8% $dpm \cdot g^{-1}$ for GTL 5-7 F1 to 0.01359 ± 6.7% $dpm \cdot g^{-1}$ for GTL 22-28. Radium-226 activity was lower than expected for the region by a factor of about 2 to 5 times. The activity ranged from an average of 0.01413 ± 22.6% $dpm \cdot g^{-1}$ for the GTL 10-13 M1 groups to 0.02573 ± 16.1% $dpm \cdot g^{-1}$ for GTL 22-28. Radium-226 recovery was low for a few samples (the most massive samples may have overloaded the Sr column with barium causing radium recovery to suffer) and the runs were deemed unreliable (error greater than 30%). To recover the opportunity to age the samples, an average of all measured values with less than 25% error (13-23%) was used in place of the unreliable values (n = 9; 0.01989 ± 15.7% $dpm \cdot g^{-1}$); this replacement occurred for GTL 5-7 M1, M2, and GTL 10-13 F2. For the other randomly split age groups an average of the measured values for the pair was used as the radium-226 activity for the groups. For the older age groups that were not randomly split, sample specific radium-226 activities were used.

To compare radiometric age with age estimated from growth zone counting, either the total sample age (estimated age plus time since collection) or age corrected for time since collection must be determined (Table 3). All groups were collected just over 1 year prior to the radiometric analysis, making correction relatively simple. Agreement between radiometric age and estimated age from growth zone counts was good for some sample groups and markedly different from what was expected for other groups (Figure 6). Young female and the older mixed age groups were largely in agreement, but the oldest male age groups were not in agreement by approximately a decade (Figure 7). In general, age was underestimated for the male age groups by approximately 5 to 10 years and agreement was good for the oldest age groups. For the 15-19 yr groups age was underestimated by a few years on average. No apparent trend related to otolith weight was discernable based on the similarity of radiometric age determinations for the oldest groups (GTL 15-19 A and B, GTL 20-27, and GTL 22-28).

To explore the observed differences in radiometric age for the male groups (GTL 10-13 M1 and M2), radiometric age was plotted relative to otolith weight and fish length. Given the radiometric age determinations, otolith mass accretion rates may differ considerably between sexes where females of a similar length or age may have otoliths up to twice as massive as males (Figure 8); however, for most of the mixed age groups sex was not known. A fit of the von Bertalanffy growth function to the radiometric ages and average fish length led to an estimate of growth parameters with a t_0 fixed to zero because the smallest fish were not available for dating (Figure 9).

Discussion

These findings provided some support for the age estimation methodology, but also elucidated potential problems with the age estimation of males and sexual dimorphism in otolith growth. Male otoliths in the 10-13 year age groups were older according to lead-radium dating by approximately 10 or 15 years. While most of the other age groups were relatively accurate, some other groups were also under-aged by a few years. In general, the age estimates for the oldest age groups were in good agreement with the expected lead-radium ratios. The complication is a lack of information on sex composition for the oldest groups, but it is likely that most of the fish in these groups were females. Attempts to develop a discriminating function for sex using fish length and otolith weight were not successful for these groups (L. Lombardi, personal communication). These data may indicate that otolith growth zones in sectioned male otoliths need to be counted in a different manner relative to female otoliths. This notion was supported by the notable differences in otolith weight for fish with similar in length, which was also observed for separate sexes from the region (L. Lombardi, personal communication on a 2007 preliminary report). Use of radiometric age relative to fish length seems to normalize these differences with a similarity in fish age relative to fish length.

Radium-226 levels were lower than expected (0.3 to 0.5 $dpm \cdot g^{-1}$) and this is difficult to explain in the broader context of ^{226}Ra fluxes to the environment (Andrews 2009). The flux of radium-226 is typically greatest near continental margins and sea floors with low sedimentation rates (Broeker and Peng 1982), or from nearshore environments like the coastal waterways of Florida (Fanning et al. 1982). Because the collection locations were along eastern Florida it was expected that radium-226 values might be relatively elevated. However, little or no information exist for the early life stages of golden tilefish and all fisheries report commercial catches greater than 400 mm FL (Freeman and Turner 1977). The only exception on record was with the 210 mm FL juvenile that was recovered from the mouth of moray eel by an observer (L. Lombardi, personal communication). Small fish may be avoiding the gear because most long-liners use large circle hooks (15/0-13/0) and fishing occurs at depths (>200 m), a depth that may not be selected by fish of that size. Hence, it is uncertain where juveniles reside for the first few years of life and how the uptake of environmental radium-226 occurs.

Despite the low levels of radium-226, reasonable measures of radiometric age were made for each group of fish. Independent of growth zone counting, the measures of age provide an accurate determination of age for groups of fish (n = 9 to 21) within a margin of analytical uncertainty (2 SE). Male and female fish can attain ages of at least 20 years and there is confidence that fish in these groups were older. Otolith weight was used to separate two oldest age groupings (GTL 15-19, and GTL 20-27 and 22-28) to potentially elucidate unperceived differences in age, yet the corresponding radiometric ages provide an indication that otolith weight can vary considerably within a given age grouping.

An application of bomb radiocarbon dating could provide more detailed information on the age and growth of adult golden tilefish, but a recent application alludes to problems with the uptake of radiocarbon (Harris 2005). Harris (2005) stated that the anomalous birth date results (phase-lagged and attenuated signal) may be from: 1) a short exposure of larvae or juveniles to the near surface or mixed ocean layer, where the timing and strength of the bomb radiocarbon signal would be more in synch with regional records; or 2) regional oceanographic conditions provide a deep radiocarbon signature; or 3) both of these conditions worked together to create a otolith sample time series that was difficult to explain; or 4) age was underestimated by as much as 10 years. However, to fully evaluate the findings of Harris (2005), the fish and sample data for the radiocarbon sample series need to be made available. Of great importance would be the estimated age of each fish and its uncertainty, its collection year, and all associated fish data (i.e. otolith weight, fish length, etc.). In addition, the core extraction methods, resultant sample mass that was analyzed using accelerator mass spectrometry (AMS), tabulated radiocarbon values and their respective uncertainty would assist greatly with a proper evaluation of these data. To provide a comparative relationship for age determinations made in this study, otoliths could be reinvestigated to make a good assessment of whether environmental or age-reading was responsible for the anomalous results. The fact that one data point was aged properly and was well fitted to the regional reference curve is intriguing and begs further exploration of these otolith samples.

As a follow up to the work performed in this study it is recommended that several aspects of this and other studies be explored further. In concert with a reinvestigation of the Harris (2005) radiocarbon data series, it is recommended that further work be performed with age estimation procedures to answer questions about the underestimation of age for the all male age groups. In general, the aging methodology derived in this study was supported by the lead-radium dating, yet it is difficult to explain why male otolith growth would be so different. Lead-radium dating indicates the otoliths of some males may accrete at a rate close to half as much as some females. Work is currently being performed to gain a better understanding of the reproduction of golden tilefish and there is evidence that hermaphroditism is exhibited, but not by all members of the populations. One of the biggest problems with this study was a lack of sex determination for the oldest and largest fish. It is recommended that all future collections include sampling of gonadal tissues and standardized analysis of these tissues. Because lead-radium dating was successful with these age groups, it is also recommended that an additional series of otolith age-groups be analyzed from larger fish groups where sexes have been identified and can be separated for lead-radium dating.

Acknowledgements

I thank Heather Hawk at Moss Landing Marine Laboratories for assistance with sample processing and Craig Lundstrom at University of Illinois-Urbana Champaign for ICPMS processing of the purified radium samples. I express sincere thanks to Dr. Gregor Cailliet of Moss Landing Marine Laboratories for supporting this line of work and the research efforts of the Age and Longevity Research Laboratory.

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Table 1. Summary of estimated age with fish and otolith characteristics for golden tilefish age-groups processed in this study. Estimated age composition, fish length, and whole otolith weight are given. The sex composition for samples GTL 5-7 and 10-13 was signified by an M or F in the sample number. Sexes were mixed or unavailable for the older age groups. Specific sample details can be accessed in the appendices of this report.

Age group & sample number	Age range (yr)	Average age (yr)	Average fish length (mm FL)	Fish length range (2 SE)	Average whole otolith wt. (g)	Otolith weight range (2 SE)
GTL 5-7 M1	6-7	6.4	549	436-860 (39)	0.470	0.348-0.596 (0.034)
GTL 5-7 M2	5-7	6.3	520	465-620 (17)	0.453	0.330-0.663 (0.030)
GTL 5-7 F1	5-7	6.4	483	402-535 (28)	0.391	0.277-0.504 (0.046)
GTL 5-7 F2	5-7	6.2	465	412-508 (18)	0.366	0.270-0.488 (0.039)
GTL 10-13 M1	10-12	10.6	683	494-796 (37)	0.889	0.681-1.198 (0.079)
GTL 10-13 M2	10-13	10.8	729	570-810 (40)	0.964	0.630-1.261 (0.095)
GTL 10-13 F1	10-13	11.1	613	524-660 (22)	0.776	0.592-0.964 (0.071)
GTL 10-13 F2	10-13	11.4	620	570-725 (24)	0.757	0.589-1.063 (0.073)
GTL 15-19 A	15-19	16.8	699	620-780 (31)	1.024	0.899-1.124 (0.037)
GTL 15-19 B	15-19	16.4	750	643-842 (36)	1.345	1.139-1.628 (0.095)
GTL 20-27	20-27	22.5	731	680-824 (28)	1.287	1.073-1.521 (0.086)
GTL 22-28	22-28	25.2	763	700-900 (43)	1.710	1.541-2.002 (0.096)

Table 2. Coring and radiometric results for golden tilefish age groups. The total number of otoliths, age group weight and the average core weight are listed with the measured ^{210}Pb and ^{226}Ra activities for the samples (± 2 SE). The activity ratios and the corresponding margin of error were used to calculate sample age and uncertainty (Table 3).

Age group & sample number	Number of otoliths	Sample weight (g)[1]	Average core weight (g)[2]	^{210}Pb ($dpm \cdot g^{-1}$) ± % error[3]	^{226}Ra ($dpm \cdot g^{-1}$) ± % error[3]	^{210}Pb:^{226}Ra (2 SE)
GTL 5-7 M1	20	1.52521	0.07626	0.00491 ± 7.8%	0.01989 ± 15.7%[4]	0.2469 (0.0432)
GTL 5-7 M2	21	1.57928	0.07520	0.00589 ± 6.1%	0.01989 ± 15.7%[4]	0.2961 (0.0497)
GTL 5-7 F1	9	0.57104	0.06345	0.00419 ± 13.8%	0.02478 ± 18.2%[5]	0.1692 (0.0319)
GTL 5-7 F2	10	0.70606	0.07061	0.00564 ± 9.9%	0.02478 ± 18.2%[5]	0.2276 (0.0369)
GTL 10-13 M1	15	1.02671	0.06845	0.00783 ± 6.6%	0.01413 ± 22.6%[5]	0.5539 (0.0960)
GTL 10-13 M2	14	1.03334	0.07381	0.00737 ± 6.8%	0.01413 ± 22.6%[5]	0.5217 (0.0908)
GTL 10-13 F1	11	0.75149	0.06832	0.00593 ± 8.9%	0.02083 ± 13.1%[6]	0.2847 (0.0451)
GTL 10-13 F2	11	0.89425	0.08130	0.00766 ± 7.0%	0.01989 ± 15.7%[4]	0.3852 (0.0660)
GTL 15-19 A	12	0.79502	0.06625	0.00866 ± 7.1%	0.01758 ± 23.2%[6]	0.4924 (0.1192)
GTL 15-19 B	10	0.67835	0.06167	0.00862 ± 8.2%	0.01917 ± 14.1%[6]	0.4499 (0.0733)
GTL 20-27	10	0.67733	0.06773	0.00886 ± 7.8%	0.01788 ± 20.1%[6]	0.4955 (0.1067)
GTL 22-28	10	0.68193	0.06819	0.01359 ± 6.7%	0.02573 ± 16.1%[6]	0.5283 (0.0922)

[1] Cleaned and dried sample weight prior to processing.

[2] Extracted otolith cores after cleaning.

[3] Calculation based on propagation of 2 SE using the delta method (Knoll 1989) and the ICPMS analysis routine (± 2 SE).

[4] Poor radium recover from original sample led to use of an average for all sample specific measurements below 25% error.

[5] Average radium-226 for sample replicates.

[6] Sample specific radium-226.

Table 3. Comparison of estimated age and radiometric age for golden tilefish. Total sample age is given as the average age plus the time since capture for direct comparison with radiometric age. Radiometric age was calculated from the measured ^{210}Pb:^{226}Ra activity ratios and age range was based on the analytical uncertainty and error propagation (2 SE). Corrected age for time since capture date was calculated for direct comparison with the estimated average age of the age group.

Age group & sample number	Average age (yr)	Time since capture (yr)	Total sample age (yr)[1]	Radiometric age (range; yr)	Corrected age (range; yr)
GTL 5-7 M1	6.4	1.27	7.7	10.6 (8.8-12.5)	9.3 (7.6-11.2)
GTL 5-7 M2	6.3	1.33	7.6	12.8 (10.6-15.1)	11.5 (9.3-13.8)
GTL 5-7 F1	6.4	1.37	7.8	7.5 (6.3-8.7)	6.1 (4.9-7.4)
GTL 5-7 F2	6.2	1.24	7.4	9.8 (8.3-11.4)	8.6 (7.1-10.1)
GTL 10-13 M1	10.6	1.40	12.0	27.4 (21.2-35.2)	26.0 (19.8-33.8)
GTL 10-13 M2	10.8	1.43	12.2	25.2 (19.6-32.0)	23.8 (18.2-30.5)
GTL 10-13 F1	11.1	1.39	12.5	12.3 (10.3-14.4)	10.9 (8.9-13.0)
GTL 10-13 F2	11.4	1.42	12.8	17.1 (13.9-20.8)	15.7 (12.4-19.4)
GTL 15-19 A	16.8	1.49	18.3	23.3 (16.5-31.9)	21.8 (15.0-30.4)
GTL 15-19 B	16.4	1.47	17.9	20.7 (16.7-25.3)	19.2 (15.0-23.8)
GTL 20-27	22.5	1.46	24.0	23.5 (17.3-31.1)	22.0 (15.9-29.7)
GTL 22-28	25.2	1.42	26.6	25.6 (19.9-32.6)	24.2 (18.5-31.2)

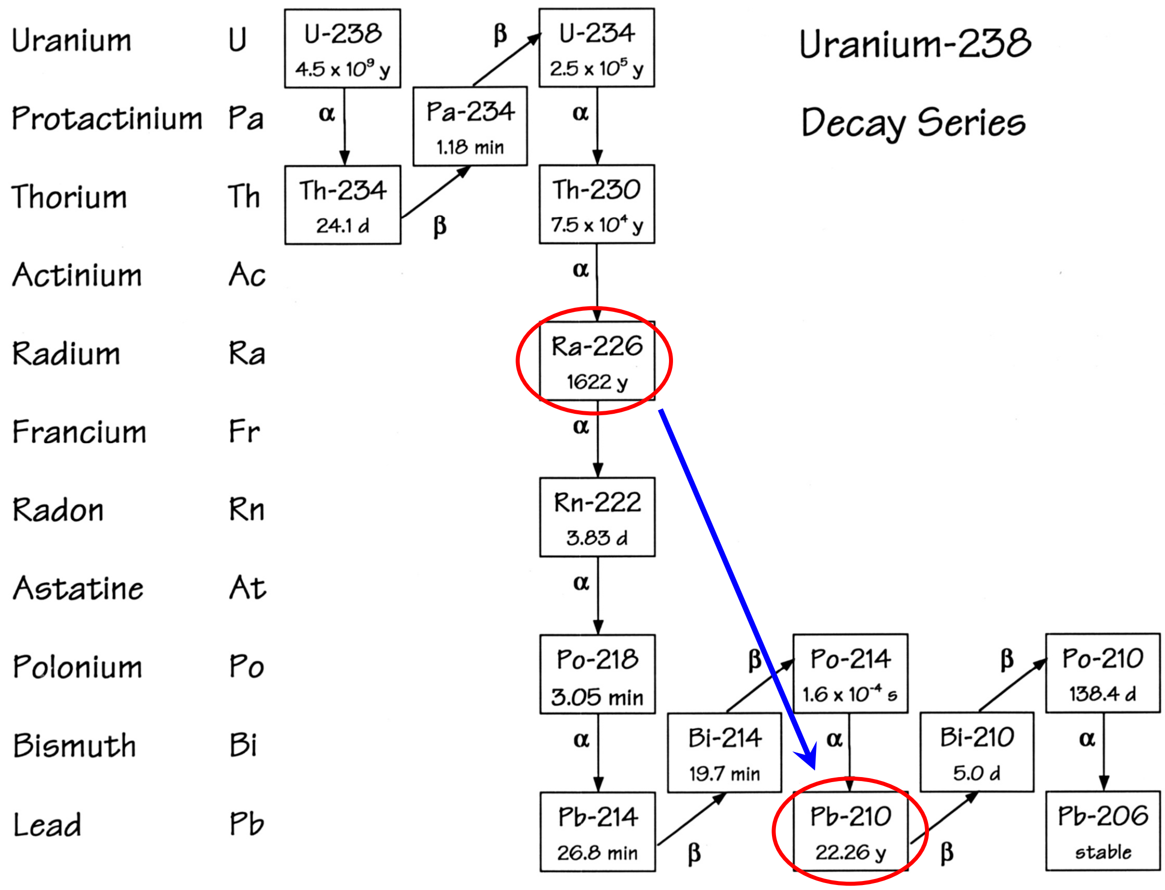

Figure 1. Diagram of the uranium-238 decay series with the half-life for individual isotopes given in each cell. Of interest to lead-radium dating is the isolation of radium-226 from the environment and its subsequent decay to lead-210. Note that the half-lives of the intermediate isotopes are far less than the half-life of lead-210, hence the decay of radium-226 over the period of interest for fishes (decades) can be simplified to a direct decay to lead-210 and a disequilibrium relative to time (see Figure 3).

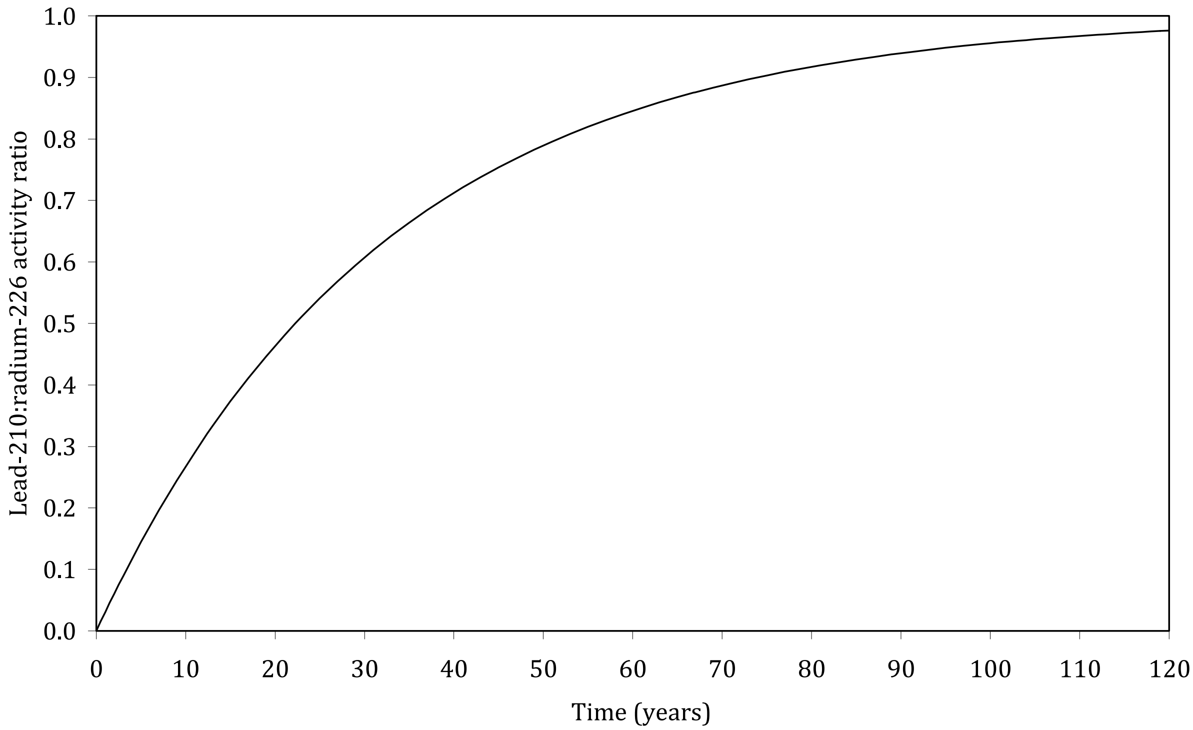

Figure 2. The relationship used for lead-radium dating begins with the ingrowth of lead-210 activity at time zero from radium-226. Over a period of up to approximately 120 years the activity ratio of lead-210 to radium-226 approaches secular equilibrium or a ratio of one. It is the measured disequilibria of lead-210 and radium-226 activities that provide a measure of time or age in the case of fishes.

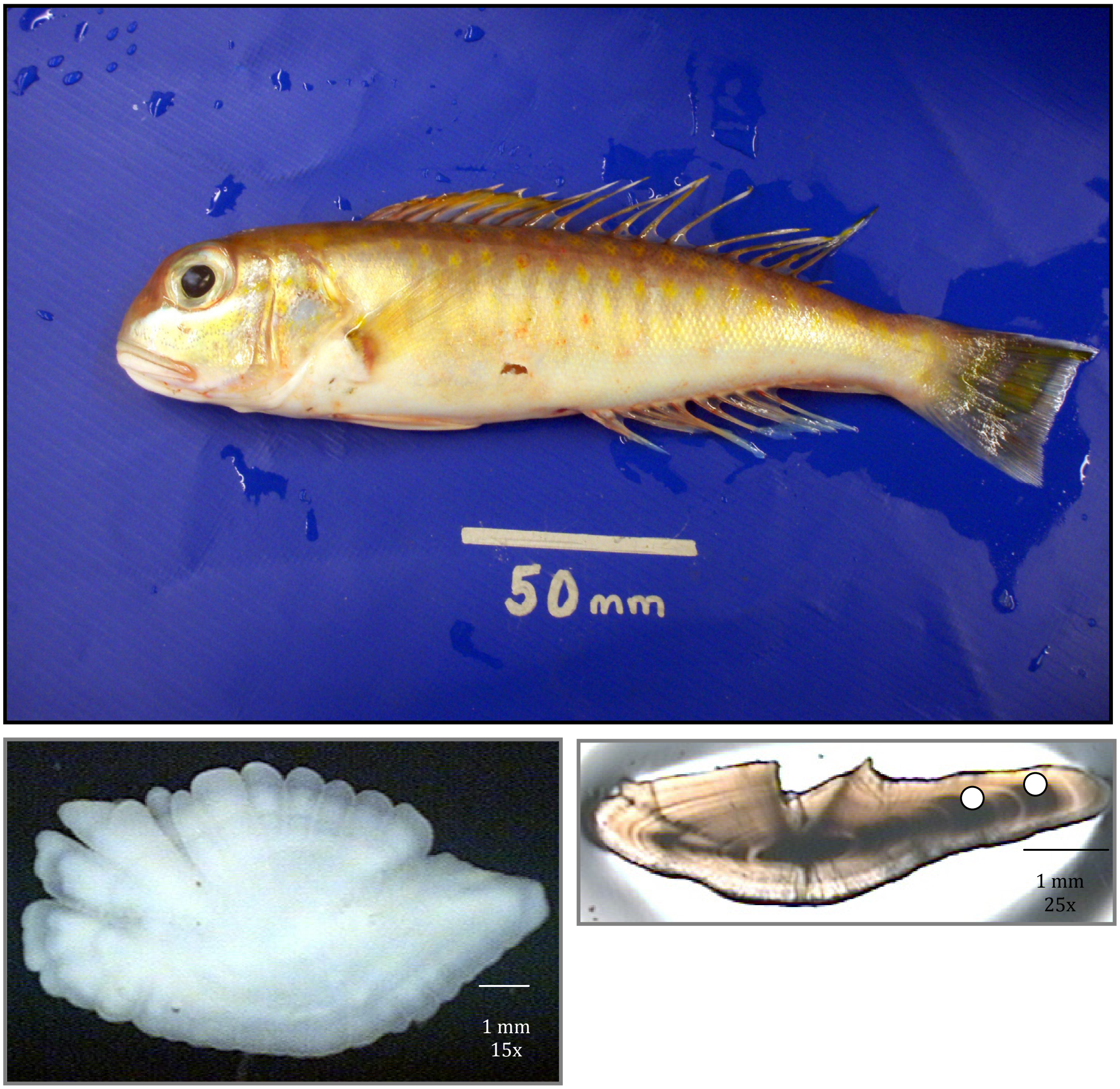

Figure 3. This juvenile golden tilefish was collected by a commercial fishing observer from the mouth of a moray eel caught with long-line gear on 25 January 2008 (L. Lombardi, personal communication). The rarity of life stages below 400 mm FL precludes understanding life history characteristics, but it was fortunate to have the otolith available from this 210 mm FL fish for development of age estimation criteria and in the determination of core extraction dimensions and weight in the lead-radium dating process. The two white dots represent estimated first and second year growth zones.

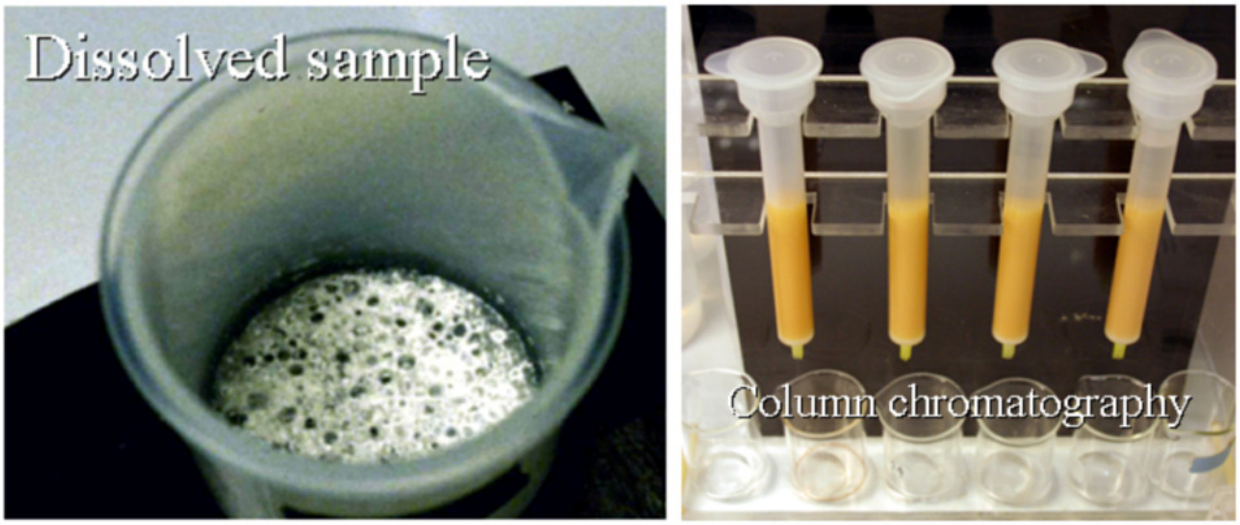

Figure 4. Dissolved otolith sample in a TFE beaker prior to plating polonium isotopes for α-spectrometry. After plating, the sample remnant was processed to isolate radium using column chromatography. On the right is a photograph of the first of three chromatographic columns used to isolate and purify the radium sample that is analyzed with ICP-MS.

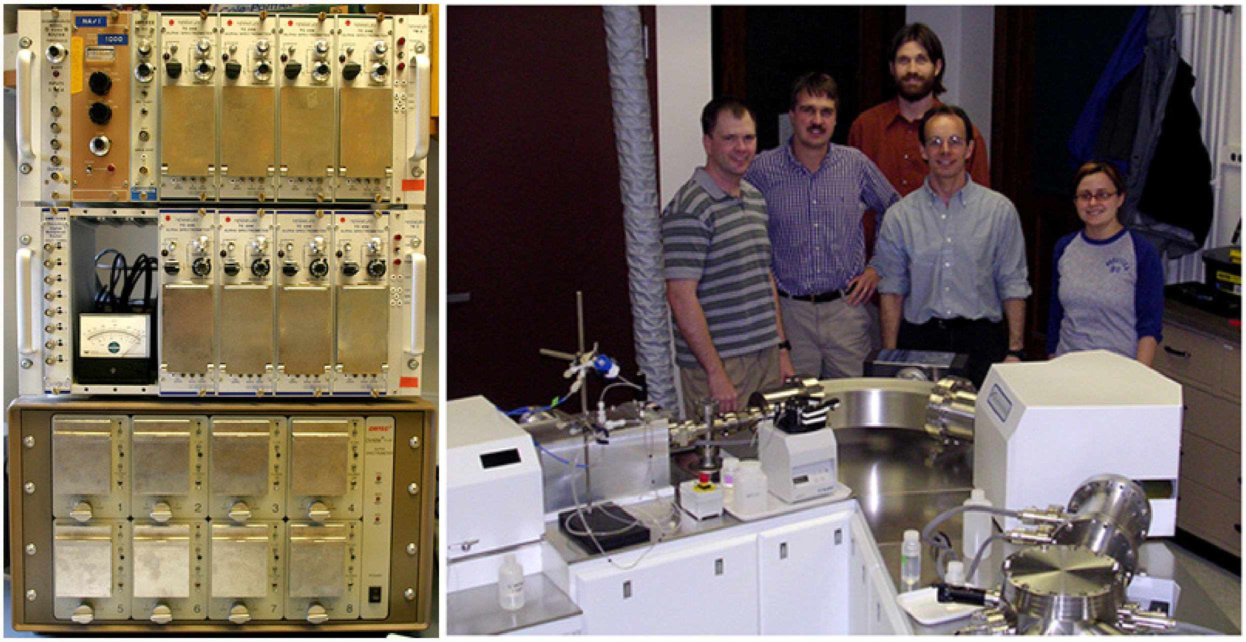

Figure 5. Photograph of the α-spectrometer (left) used in polonium-210 determinations (proxy for lead-210). The system consists of the classic Tennelec® TC-256 α-spectrometers and a newer Ortec® Octete Plus unit. On the right are members of the mass-spectrometry research group in the Department of Geology at University of Illinois, Urbana-Champaign with the Nu Plasma HR (MC-ICP-MS) used to determine radium-226 in the purified samples processed at the Age and Longevity Research Laboratory, Moss Landing Marine Laboratories.

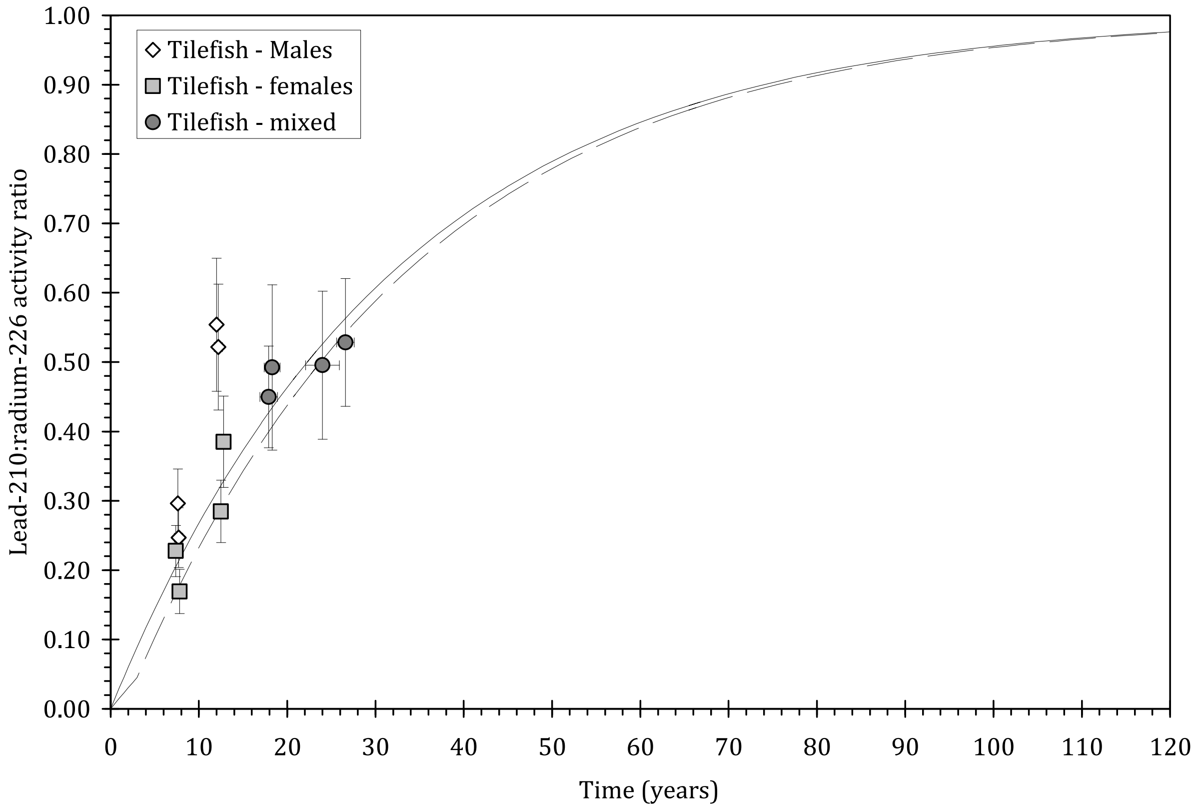

Figure 6. Total sample age for each age group (time since collection plus average estimated fish age) was plotted relative to measured lead-radium activity for each sample. Sexes were analyzed separately for the younger age groups and combined out of necessity for the older age groups. Measured ratios and estimated age were compared with the expected lead-radium ingrowth model using the proximity of these data with the error bars. Vertical error bars represent 2 SE from the measured lead-radium ratios. Horizontal error bars represent 2 SE of the estimated age for the given age group. The solid line represents straight ingrowth of lead-210 from radium-226 and the dashed line represents the core compensated (3 years) ingrowth curve.

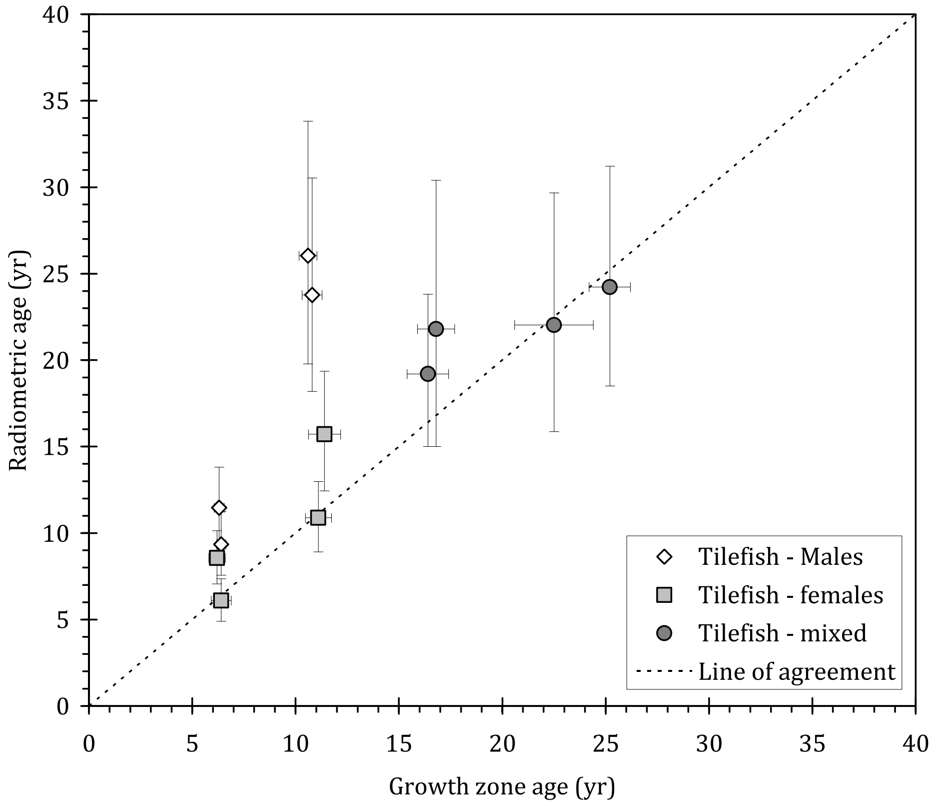

Figure 7. Age agreement plot provides a direct comparison between radiometric age and growth zone derived age for golden tilefish age groups. Vertical error bars represent 2 SE from the measured lead-radium ratios. Horizontal error bars represent 2 SE of the estimated age for the given age group. Age agreement was good for most age groups, but markedly different for the 10-13 yr male age groups. No regression or test for statistical differences was applied to these data because the group characteristics differed considerably through the various age groups.

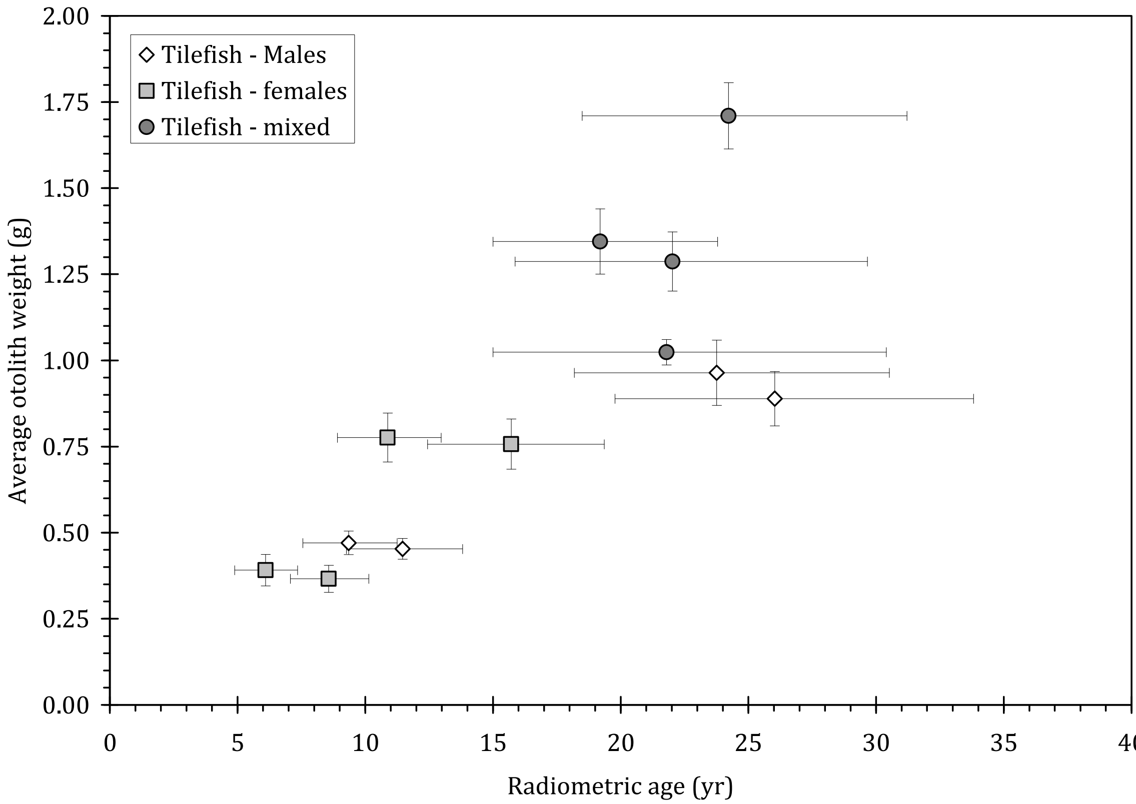

Figure 8. Plot of radiometric age relative to otolith weight revealed the otoliths of males were generally much less massive than otoliths from fish of similar size. Vertical error bars represent 2 SE from the measured average otolith weights (g). Horizontal error bars represent 2 SE of the estimated age for the given age group. It is likely that the largest fish analyzed in this study were mostly female, but these data were not collected and a discriminating function for sex from otolith weight and fish length did not work (L. Lombardi, personal communication).

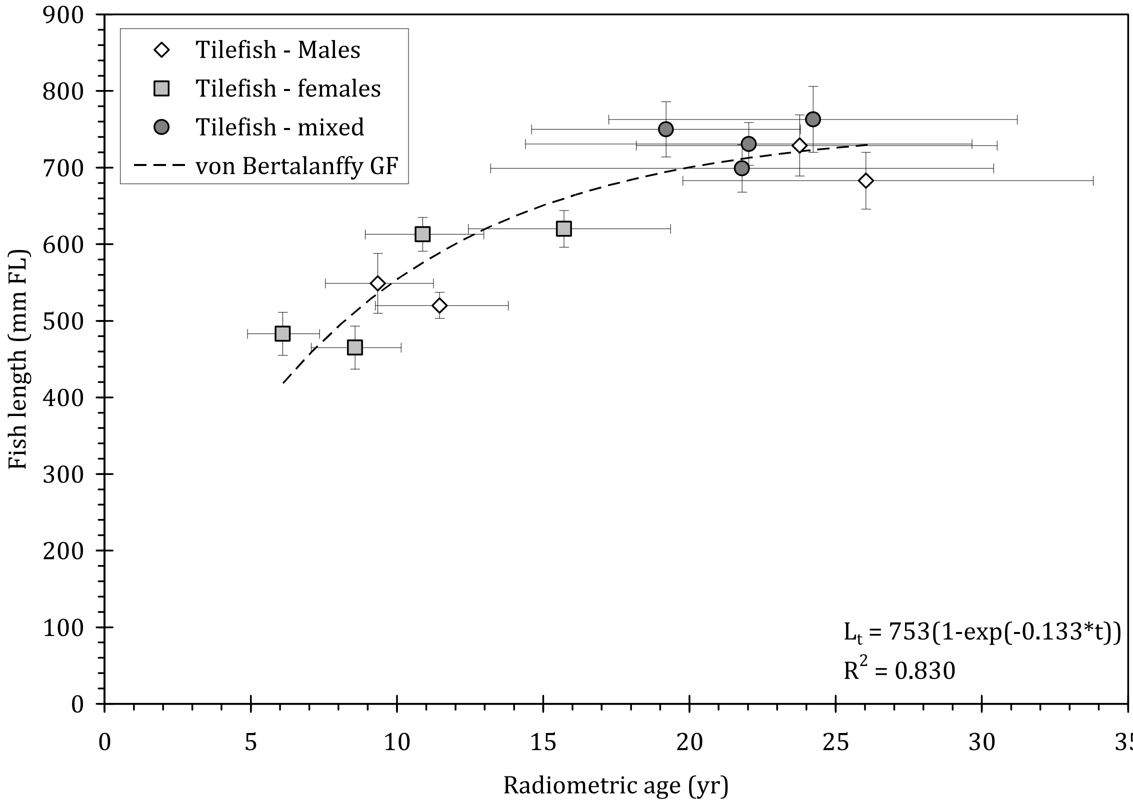

Figure 9. Von Bertalanffy growth function fitted to the radiometric age data and average fish length for each age group provided an age validated growth function; however, the growth parameters were from only 12 data points and it was necessary to fix t_0 to zero because there was a lack of the youngest age classes.

Appendices I-V: A comprehensive list of sample specific data that was associated with the golden tilefish used in the age groups is provided in the following appendices.

Appendix I
Golden tilefish age groups 5-7 M1 and 5-7 M2

Year & Species	PC Coll #	Fish #	Date	Source	Source #	State	Location	FL (mm)	Samples	Sex	R Otolith Wt (g)	L Otolith Wt (g)	Ave Oto Wt (g)	Final age (yr)	Group			
2007 GTL	83	1610	9/28/2007	TIP	18FL283939	E FL	Volusia	436	OG	M	0.3483	0.3539	0.3511	6	5-7 M-1	ave age 1	6.40	0.50 SD
2007 GTL	11	438	2/12/2007	TIP	18FL253956	E FL	Ft. Pierce	547	OG	M	0.4478	0.4576	0.4527	6	5-7 M-1			0.22 2SE
2007 GTL	83	1612	9/28/2007	TIP	18FL283939	E FL	Volusia	477	OG	M		0.4083	0.4083	6	5-7 M-1	ave length	549	87.5 SD
2007 GTL	10	327	1/26/2007	TIP	18FL253325	E FL	Ft. Pierce	561	OG	M	0.5129	0.5195	0.5162	6	5-7 M-1	low	436	39.1 2SE
2007 GTL	10	333	1/26/2007	TIP	18FL253325	E FL	Ft. Pierce	507	OG	M	0.425	0.4133	0.4192	6	5-7 M-1	high	860	
2007 GTL	11	424	2/12/2007	TIP	18FL253956	E FL	Ft. Pierce	491	OG	M	0.3649	0.3707	0.3678	6	5-7 M-1	ave oto wt	0.470	0.076 SD
2007 GTL	11	426	2/12/2007	TIP	18FL253956	E FL	Ft. Pierce	508	OG	M	0.4393		0.4393	6	5-7 M-1	low	0.348	0.034 2SE
2007 GTL	11	436	2/12/2007	TIP	18FL253956	E FL	Ft. Pierce	507	OG	M	0.4049	0.407	0.4060	6	5-7 M-1	high	0.596	
2007 GTL	83	1586	9/28/2007	TIP	18FL283939	E FL	Volusia	505	OG	M	0.4442	0.4514	0.4478	6	5-7 M-1			
2007 GTL	83	1591	9/28/2007	TIP	18FL283939	E FL	Volusia	566	OG	M	0.5453	0.5605	0.5529	6	5-7 M-1	ave1	4/21/2007	
2007 GTL	83	1599	9/28/2007	TIP	18FL283939	E FL	Volusia	500	OG	M	0.4541	0.4635	0.4588	6	5-7 M-1	N1	20	
2007 GTL	83	1607	9/28/2007	TIP	18FL283939	E FL	Volusia	477	OG	M	0.4308		0.4308	6	5-7 M-1			
2007 GTL	11	431	2/12/2007	TIP	18FL253956	E FL	Ft. Pierce	517	OG	M	0.4138	0.4181	0.4160	7	5-7 M-1			
2007 GTL	10	328	1/26/2007	TIP	18FL253325	E FL	Ft. Pierce	555	OG	M		0.589	0.5890	7	5-7 M-1			
2007 GTL	11	427	2/12/2007	TIP	18FL253956	E FL	Ft. Pierce	609	OG	M	0.5713		0.5713	7	5-7 M-1			
2007 GTL	33	592	3/8/2007	TIP	18FL255655	E FL	Brevard	574	OG	M	0.532	0.5276	0.5298	7	5-7 M-1			
2007 GTL	33	593	3/8/2007	TIP	18FL255655	E FL	Brevard	574	OG	M	0.3835	0.387	0.3853	7	5-7 M-1			
2007 GTL	18	107	1/31/2007	SBLOP	JLC-002-002	E FL	Port Orange	580	OG	M	0.5169		0.5169	7	5-7 M-1			
2007 GTL	33	590	3/8/2007	TIP	18FL255655	E FL	Brevard	622	OG	M		0.5958	0.5958	7	5-7 M-1			
2007 GTL	22	120	2/7/2007	SBLOP	JLC-003-003	E FL	Port Orange	860	OG	M	0.5581	0.5513	0.5547	7	5-7 M-1			
2007 GTL	10	310	1/26/2007	TIP	18FL253325	E FL	Ft. Pierce	465	OG	M	0.3854	0.3756	0.3805	5	5-7 M-2	ave age 2	6.29	0.56 SD
2007 GTL	11	419	2/12/2007	TIP	18FL253956	E FL	Ft. Pierce	500	OG	M	0.4182	0.4313	0.4248	6	5-7 M-2			0.24 2SE
2007 GTL	11	429	2/12/2007	TIP	18FL253956	E FL	Ft. Pierce	530	OG	M	0.4937		0.4937	6	5-7 M-2	ave length	520	38.0 SD
2007 GTL	11	430	2/12/2007	TIP	18FL253956	E FL	Ft. Pierce	524	OG	M	0.4102	0.4112	0.4107	6	5-7 M-2	low	465	16.6 2SE
2007 GTL	22	102	2/7/2007	SBLOP	JLC-003-003	E FL	Port Orange	530	og	M	0.4465	0.4465	0.4465	6	5-7 M-2	high	620	
2007 GTL	83	1589	9/28/2007	TIP	18FL283939	E FL	Volusia	473	OG	M	0.3816	0.3684	0.3750	6	5-7 M-2	ave oto wt	0.453	0.069 SD
2007 GTL	1	201	1/11/2007	TIP	18FL251969	E FL	Indian River	530	og	M	0.4508		0.4508	6	5-7 M-2	low	0.330	0.030 2SE
2007 GTL	11	428	2/12/2007	TIP	18FL253956	E FL	Ft. Pierce	529	OG	M		0.3912	0.3912	6	5-7 M-2	high	0.663	
2007 GTL	19	122	1/31/2007	SBLOP	JLC-002-001	E FL	Port Orange	480	OG	M	0.3894	0.387	0.3882	6	5-7 M-2			
2007 GTL	20	101	2/6/2007	SBLOP	JLC-003-001	E FL	Port Orange	560	og	M	0.4785	0.4839	0.4812	6	5-7 M-2	ave2	3/30/2007	
2007 GTL	83	1590	9/28/2007	TIP	18FL283939	E FL	Volusia	510	OG	M		0.4783	0.4783	6	5-7 M-2	N2	21	
2007 GTL	83	1598	9/28/2007	TIP	18FL283939	E FL	Volusia	499	OG	M	0.441		0.4410	6	5-7 M-2			
2007 GTL	83	1611	9/28/2007	TIP	18FL283939	E FL	Volusia	532	OG	M	0.5036	0.5032	0.5034	6	5-7 M-2			
2007 GTL	83	1602	9/28/2007	TIP	18FL283939	E FL	Volusia	499	OG	M	0.4694	0.4474	0.4584	6	5-7 M-2			
2007 GTL	19	108	1/31/2007	SBLOP	JLC-002-001	E FL	Port Orange	470	OG	M	0.3327	0.3296	0.3312	7	5-7 M-2			
2007 GTL	21	165	2/6/2007	SBLOP	JLC-003-002	E FL	Port Orange	550	OG	M	0.4533	0.4106	0.4320	7	5-7 M-2			
2007 GTL	11	423	2/12/2007	TIP	18FL253956	E FL	Ft. Pierce	560	OG	M	0.526	0.5204	0.5232	7	5-7 M-2			
2007 GTL	24	169	2/7/2007	SBLOP	JLC-003-005	E FL	Port Orange	620	OG	M	0.663	0.6482	0.6556	7	5-7 M-2			
2007 GTL	1	177	1/11/2007	TIP	18FL251969	E FL	Indian River	504	OG	M		0.4729	0.4729	7	5-7 M-2			
2007 GTL	1	197	1/11/2007	TIP	18FL251969	E FL	Indian River	570	OG	M	0.5492	0.5067	0.5280	7	5-7 M-2			
2007 GTL	11	434	2/12/2007	TIP	18FL253956	E FL	Ft. Pierce	492	OG	M	0.4515	0.4378	0.4447	7	5-7 M-2			

Appendix II
Golden tilefish age groups 5-7 F1 and 5-7 F2

Year & Species	PC Coll #	Fish #	Date	Source	Source #	State	Location	FL (mm)	Samples	Sex	R Otolith Wt (g)	L Otolith Wt (g)	Ave Oto Wt (g)	Final age (yr)	Group					
2007 GTL	10	308	1/26/2007	TIP	18FL253325	E FL	Ft. Pierce	402	OG	F	0.2787	0.2771	0.2779	5	5-7 F-1	ave age 1	6.4	yr	0.73	SD
2007 GTL	83	1600	9/28/2007	TIP	18FL283939	E FL	Indian River	466	OG	F	0.3272	0.3283	0.3278	6	5-7 F-1				0.484	2SE
2007 GTL	1	196	1/11/2007	TIP	18FL251969	E FL	Indian River	535	OG	F		0.4502	0.4502	6	5-7 F-1	ave length	483		41.7	SD
2007 GTL	1	198	1/11/2007	TIP	18FL251969	E FL	Volusia	523	OG	F	0.4586	0.4508	0.4547	6	5-7 F-1	low	402		27.83	2SE
2007 GTL	1	199	1/11/2007	TIP	18FL251969	E FL	Ft. Pierce	474	OG	F		0.3698	0.3698	7	5-7 F-1	high	535			
2007 GTL	2	304	1/18/2007	TIP	18FL252598	E FL	Volusia	462	OG	F	0.3871	0.3844	0.3858	7	5-7 F-1	ave oto wt	0.391		0.07	SD
2007 GTL	18	144	1/31/2007	SBLOP	JLC-002-002	E FL	Ft. Pierce	462	OG	F	0.3598	0.3517	0.3558	7	5-7 F-1	low	0.277		0.046	2SE
2007 GTL	18	196	1/31/2007	SBLOP	JLC-002-002	E FL	Ft. Pierce	495	OG	F	0.3931	0.3894	0.3913	7	5-7 F-1	high	0.504			
2007 GTL	83	1584	9/28/2007	TIP	18FL283939	E FL	Ft. Pierce	524	OG	F	0.5038	0.5032	0.5035	7	5-7 F-1	N1	9			
																ave1	3/16/2007			
2007 GTL	83	1596	9/28/2007	TIP	18FL283939	E FL	Volusia	412	OG	F	0.2695	0.2739	0.2717	5	5-7 F-2	Ave age 2	6.2	yr	0.6	SD
2007 GTL	83	1597	9/28/2007	TIP	18FL283939	E FL	Indian River	471	OG	F	0.3934	0.3775	0.3855	6	5-7 F-2				0.4	2SE
2007 GTL	2	298	1/18/2007	TIP	18FL252598	E FL	Ft. Pierce	465	OG	F	0.3890		0.3890	6	5-7 F-2	ave length	465		27.6	SD
2007 GTL	83	1606	9/28/2007	TIP	18FL283939	E FL	Port Orange	430	OG	F	0.3029	0.3029	0.3029	6	5-7 F-2	low	412		17.47	2SE
2007 GTL	83	1609	9/28/2007	TIP	18FL283939	E FL	Port Orange	480	OG	F	0.3900	0.3909	0.3905	6	5-7 F-2	high	508			
2007 GTL	2	278	1/18/2007	TIP	18FL252598	E FL	Volusia	491	og	F				6	5-7 F-2	ave oto wt	0.366		0.061	SD
2007 GTL	2	292	1/18/2007	TIP	18FL252598	E FL	Volusia	464	OG	F	0.3824	0.3827	0.3826	6	5-7 F-2	low	0.270		0.039	2SE
2007 GTL	2	301	1/18/2007	TIP	18FL252598	E FL	Volusia	470	OG	F	0.3575	0.3390	0.3483	7	5-7 F-2	high	0.488			
2007 GTL	11	437	2/12/2007	TIP	18FL253956	E FL	Ft. Pierce	508	OG	F	0.4820	0.4880	0.4850	7	5-7 F-2	N2	10			
2007 GTL	21	162	2/6/2007	SBLOP	JLC-003-002	E FL	Port Orange	460	OG	F	0.3261	0.3469	0.3365	7	5-7 F-2	ave2	5/3/2007			

Appendix III

Golden tilefish age groups10-13 M1 and 10-13 M2

Year & Species	PC Coll #	Fish #	Date	Source	Source #	State	Location	FL (mm)	Samples	Sex	R Otolith Wt (g)	L Otolith Wt (g)	Ave Oto Wt (g)	Final age (yr)	Group				
2007 GTL	1	185	1/11/2007	TIP	18FL251969	E FL	Indian River	796	OG	M				10	10-13 M-1	ave age 1	10.60	0.83	SD
2007 GTL	2	277	1/18/2007	TIP	18FL252598	E FL	Ft. Pierce	731	OG	M	0.9675		0.9675	10	10-13 M-1			0.43	2SE
2007 GTL	33	594	3/8/2007	TIP	18FL255655	E FL	Brevard	744	OG	M	1.0531		1.0531	10	10-13 M-1	ave length	683	72.4	SD
2007 GTL	83	1613	9/28/2007	TIP	18FL283939	E FL	Volusia	640	OG	M		0.7287	0.7287	10	10-13 M-1	low	494	37.4	2SE
2007 GTL	2	280	1/18/2007	TIP	18FL252598	E FL	Ft. Pierce	636	OG	M	0.6808		0.6808	10	10-13 M-1	high	796		
2007 GTL	18	146	1/31/2007	SBLOP	JLC-002-002	E FL	Port Orange	700	OG	M	0.9384	0.9372	0.9378	10	10-13 M-1	ave oto wt	0.889	0.154	SD
2007 GTL	21	112	2/6/2007	SBLOP	JLC-003-002	E FL	Port Orange	650	OG	M	0.7801	0.7435	0.7618	10	10-13 M-1	low	0.681	0.079	2SE
2007 GTL	33	595	3/8/2007	TIP	18FL255655	E FL	Brevard	762	OG	M	0.9927		0.9927	10	10-13 M-1	high	1.198		
2007 GTL	2	282	1/18/2007	TIP	18FL252598	E FL	Ft. Pierce	681	OG	M	0.8456		0.8456	10	10-13 M-1				
2007 GTL	21	161	2/6/2007	SBLOP	JLC-003-002	E FL	Port Orange	720	OG	M	0.834	0.8726	0.8533	11	10-13 M-1	ave1	3/6/2007		
2007 GTL	23	175	2/7/2007	SBLOP	JLC-003-004	E FL	Port Orange	620	OG	M	0.7544	0.7423	0.7484	11	10-13 M-1	N1	15		
2007 GTL	22	103	2/7/2007	SBLOP	JLC-003-003	E FL	Port Orange	670	OG	M	0.7064	0.7204	0.7134	11	10-13 M-1				
2007 GTL	22	121	2/7/2007	SBLOP	JLC-003-003	E FL	Port Orange	680	OG	M	1.1448	1.1978	1.1713	12	10-13 M-1				
2007 GTL	83	1604	9/28/2007	TIP	18FL283939	E FL	Volusia	494	OG	M	1.1014	1.0898	1.0956	12	10-13 M-1				
2007 GTL	2	279	1/18/2007	TIP	18FL252598	E FL	Ft. Pierce	724	OG	M		0.9029	0.9029	12	10-13 M-1				
2007 GTL	21	172	2/6/2007	SBLOP	JLC-003-002	E FL	Port Orange	680	OG	F	0.8456	0.7991	0.8224	10	10-13 M-2	ave age 2	10.79	0.89	SD
2007 GTL	10	321	1/26/2007	TIP	18FL253325	E FL	Ft. Pierce	729	OG	M	0.8496		0.8496	10	10-13 M-2			0.48	2SE
2007 GTL	22	119	2/7/2007	SBLOP	JLC-003-003	E FL	Port Orange	570	OG	M	0.7747	0.7726	0.7737	10	10-13 M-2	ave length	729	75.1	SD
2007 GTL	23	104	2/7/2007	SBLOP	JLC-003-004	E FL	Port Orange	630	OG	M	0.6378	0.6299	0.6339	10	10-13 M-2	low	570	40.1	2SE
2007 GTL	83	1593	9/28/2007	TIP	18FL283939	E FL	Volusia	758	OG	M				10	10-13 M-2	high	810		
2007 GTL	21	115	2/6/2007	SBLOP	JLC-003-002	E FL	Port Orange	790	OG	M	1.1464	1.1286	1.1375	10	10-13 M-2	ave oto wt	0.964	0.178	SD
2007 GTL	24	105	2/7/2007	SBLOP	JLC-003-005	E FL	Port Orange	780	OG	M	1.0445	1.0189	1.0317	11	10-13 M-2	low	0.630	0.095	2SE
2007 GTL	33	596	3/8/2007	TIP	18FL255655	E FL	Brevard	770	OG	M	1.0388		1.0388	11	10-13 M-2	high	1.261		
2007 GTL	24	170	2/7/2007	SBLOP	JLC-003-005	E FL	Port Orange	630	OG	M	0.8439	0.8369	0.8404	11	10-13 M-2				
2007 GTL	1	194	1/11/2007	TIP	18FL251969	E FL	Indian River	775	OG	M		1.0781	1.0781	11	10-13 M-2	ave2	2/22/2007		
2007 GTL	20	111	2/6/2007	SBLOP	JLC-003-001	E FL	Port Orange	800	OG	M	1.2449	1.2608	1.2529	11	10-13 M-2	N2	14		
2007 GTL	20	115	2/6/2007	SBLOP	JLC-003-001	E FL	Port Orange	810	OG	M	1.1146		1.1146	11	10-13 M-2				
2007 GTL	22	109	2/7/2007	SBLOP	JLC-003-003	E FL	Port Orange	780	OG	M	1.0992	1.0932	1.0962	12	10-13 M-2				
2007 GTL	23	101	2/7/2007	SBLOP	JLC-003-004	E FL	Port Orange	700	og	M	0.8651	0.8544	0.8598	13	10-13 M-2				

Histology on 21-172 determined this specimen was a Female. This otolith was inadvertently included in the

Appendix IV
Golden tilefish age groups10-13 F1 and 10-13 F2

Year & Species	PC Coll #	Fish #	Date	Source	Source #	State	Location	FL (mm)	Samples	Sex	R Otolith Wt (g)	L Otolith Wt (g)	Ave Oto Wt (g)	Final age (yr)	Group				
2007 GTL	18	129	1/31/2007	SBLOP	JLC-002-002	E FL	Port Orange	620	OG	F	0.6281	0.6405	0.6343	10	10-13 F-1	ave age 1	11.09	1.04	SD
2007 GTL	1	188	1/11/2007	TIP	18FL251969	E FL	Indian River	604	OG	F	0.7597		0.7597	10	10-13 F-1			0.63	2SE
2007 GTL	62	697	5/14/2007	TIP	18FL277058	E FL	Martin	524	OG	F	0.6108	0.5920	0.6014	10	10-13 F-1	ave length	613	36.8	SD
2007 GTL	78	709	6/22/2007	TIP	18FL279490	E FL	Palm Beach	619	OG	F	0.7313		0.7313	10	10-13 F-1	low	524	22.22	2SE
2007 GTL	32	497	3/1/2007	TIP	18FL254420	E FL	Brevard	591	OG	F	0.8325	0.8353	0.8339	11	10-13 F-1	high	660		
2007 GTL	32	501	3/1/2007	TIP	18FL254420	E FL	Brevard	594	OG	F	0.6412		0.6412	11	10-13 F-1	ave oto wt	0.776	0.117	SD
2007 GTL	19	119	1/31/2007	SBLOP	JLC-002-001	E FL	Port Orange	660	OG	F	0.8344	0.8231	0.8288	11	10-13 F-1	low	0.592	0.071	2SE
2007 GTL	62	698	5/14/2007	TIP	18FL277058	E FL	Martin	631	OG	F	0.9220	0.9471	0.9346	12	10-13 F-1	high	0.964		
2007 GTL	20	103	2/6/2007	SBLOP	JLC-003-001	E FL	Port Orange	610	OG	F	0.8086	0.8035	0.8061	12	10-13 F-1				
2007 GTL	21	101	2/6/2007	SBLOP	JLC-003-002	E FL	Port Orange	640	og	F	0.8061	0.8122	0.8092	12	10-13 F-1	ave 1	3/8/2007		
2007 GTL	24	168	2/7/2007	SBLOP	JLC-003-005	E FL	Port Orange	650	OG	F	0.9556	0.9637	0.9597	13	10-13 F-1	n	11		

2007 GTL	21	159	2/6/2007	SBLOP	JLC-003-002	E FL	Port Orange	580	OG	F	0.6255	0.5885	0.6070	10	10-13 F-2	ave age 2	11.36	1.29	SD
2007 GTL	22	107	2/7/2007	SBLOP	JLC-003-003	E FL	Port Orange	570	OG	F	0.6578	0.6518	0.6548	10	10-13 F-2			0.776	2SE
2007 GTL	23	173	2/7/2007	SBLOP	JLC-003-004	E FL	Port Orange	630	OG	F	0.8108	0.8005	0.8057	10	10-13 F-2	ave length	620	40.4	SD
2007 GTL	18	172	1/31/2007	SBLOP	JLC-002-002	E FL	Port Orange	610	OG	F	0.6738	0.6622	0.6680	10	10-13 F-2	low	570	24.35	2SE
2007 GTL	2	293	1/18/2007	TIP	18FL252598	E FL	Ft. Pierce	596	OG	F	0.7561		0.7561	11	10-13 F-2	high	725		
2007 GTL	21	152	2/6/2007	SBLOP	JLC-003-002	E FL	Port Orange	620	OG	F	0.6753	0.6650	0.6702	11	10-13 F-2	ave oto wt	0.757	0.121	SD
2007 GTL	20	102	2/6/2007	SBLOP	JLC-003-001	E FL	Port Orange	620	OG	F	0.8230	0.7986	0.8108	12	10-13 F-2	low	0.589	0.073	2SE
2007 GTL	2	305	1/18/2007	TIP	18FL252598	E FL	Ft. Pierce	612	OG	F	0.7455		0.7455	12	10-13 F-2	high	1.063		
2007 GTL	32	502	3/1/2007	TIP	18FL254420	E FL	Brevard	624	OG	F	0.7899		0.7899	13	10-13 F-2				
2007 GTL	62	699	5/14/2007	TIP	18FL277058	E FL	Martin	638	OG	F	0.7569		0.7569	13	10-13 F-2	ave 2	2/25/2007		
2007 GTL	78	708	6/22/2007	TIP	18FL279490	E FL	Palm Beach	725	OG	F	1.0528	1.0631	1.0580	13	10-13 F-2	n	11		

Appendix V

Golden tilefish oldest age groups

Age group	Year Species	PC Coll #	Fish #	Date	Source	Source #	State	Location	FL (mm)	Samples	Sex	R Otolith Wt (g)	L Otolith Wt (g)	Ave oto wt (g)	Final age (yr)	Age	Oto wt	Length	
15-19 yr	2007 GTL	19	110	1/31/2007	SBLOP	JLC-002-001	E FL	Port Orange	640	OG	F	0.9464	0.8988	0.9226	15	16.8	1.024	699	Average
low weight	2007 GTL	20	161	2/6/2007	SBLOP	JLC-003-001	E FL	Port Orange	660	OG	F	0.9248	0.9235	0.9242	17	1.5	0.064	54	SD
ave collection	2007 GTL	20	114	2/6/2007	SBLOP	JLC-003-001	E FL	Port Orange	660	OG	F	0.9941	0.9382	0.9662	19	0.9	0.037	31	2SE
2/22/2007	2007 GTL	73	1071	04/23/07	TIP	18FL276890	E FL	Volusia	755	O			1.0158	1.0158	15	15	0.899	620	Min
	2007 GTL	78	711	6/22/2007	TIP	18FL279490	E FL	Palm Beach	720	OG	F	1.0706	0.9933	1.0320	16	19	1.124	780	Max
	2007 GTL	21	183	2/6/2007	SBLOP	JLC-003-002	E FL	Port Orange	620	OG	M	1.0405	1.0271	1.0338	18	n	12		
	2007 GTL	23	174	2/7/2007	SBLOP	JLC-003-004	E FL	Port Orange	780	OG	M	1.0474	1.0285	1.0380	15				
	2007 GTL	68	794	03/30/07	TIP	18FL276647	E FL	Volusia	735	O			1.0445	1.0445	19				
	2007 GTL	37	78	01/06/07	TIP	18fl251824	E FL	Volusia	773	O		1.0445	1.0765	1.0605	15				
	2007 GTL	20	120	2/6/2007	SBLOP	JLC-003-001	E FL	Port Orange	650	OG	F	1.0640	1.0613	1.0627	18				
	2007 GTL	18	123	1/31/2007	SBLOP	JLC-002-002	E FL	Port Orange	690	og	F	1.0993	1.0519	1.0756	17				
	2007 GTL	14	132	01/08/07	TIP	18FL251966	E FL	Volusia	708	O		1.1242	1.1128	1.1185	17				

Age group	Year Species	PC Coll #	Fish #	Date	Source	Source #	State	Location	FL (mm)	Samples	Sex	R Otolith Wt (g)	L Otolith Wt (g)	Ave oto wt (g)	Final age (yr)				
15-19 yr	2007 GTL	32	503	3/1/2007	TIP	18FL254420	E FL	Brevard	643	OG	F	1.1392		1.1392	19	Age	Oto wt	Length	
high weight	2007 GTL	39	616	03/12/07	TIP	18FL255656	E FL	Volusia	762	O			1.1686	1.1686	18	16.4	1.345	750	Average
ave collection	2007 GTL	76	775	03/30/07	TIP	18FL276646	E FL	Volusia	809	O		1.1912	1.2362	1.2137	16	1.5	0.150	57	SD
3/4/2007	2007 GTL	67	709	03/29/07	TIP	18FL276625	E FL	Volusia	799	O		1.2824		1.2824	15	1.0	0.095	36	2SE
	2007 GTL	38	701	03/13/07	TIP	18FL255663	E FL	Volusia	704	O		1.2940	1.3275	1.3108	15	15	1.139	643	Min
	2007 GTL	15	242	01/17/07	TIP	18FL252546	E FL	Volusia	742	O		1.3124		1.3124	16	19	1.628	842	Max
	2007 GTL	76	759	03/30/07	TIP	18FL276646	E FL	Volusia	718	O		1.3317	1.2960	1.3139	17	n	10		
	2007 GTL	73	1052	04/23/07	TIP	18FL276890	E FL	Volusia	743	O		1.3848		1.3848	18				
	2007 GTL	15	240	01/17/07	TIP	18FL252546	E FL	Volusia	733	O		1.5792	1.4429	1.5111	15				
	2007 GTL	13	232	01/17/07	TIP	18FL252545	E FL	Volusia	842	O		1.5687	1.6276	1.5982	15				
	2007 GTL	44	487	02/26/07	TIP	18FL254385	E FL	Volusia	935	O		2.2659	2.1087	2.1873	18				

Anomalously heavy otolith not used

Age group	Year Species	PC Coll #	Fish #	Date	Source	Source #	State	Location	FL (mm)	Samples	Sex	R Otolith Wt (g)	L Otolith Wt (g)	Ave oto wt (g)	Final age (yr)				
20-27 yr	2007 GTL	25	113	02/08/07	SBLOP	JLC-003-006	E FL	Port Orange	700	O		1.0727	1.0919	1.0823	20	Age	Oto wt	Length	
low weight	2007 GTL	24	101	2/7/2007	SBLOP	JLC-003-005	E FL	Port Orange	710	og	F	1.1195	1.1710	1.1453	20	22.5	1.287	731	Average
ave collection	2007 GTL	37	98	01/06/07	TIP	18FL251824	E FL	Volusia	705	O		1.2557	1.2133	1.2345	20	3.1	0.136	44	SD
3/8/2007	2007 GTL	78	707	6/22/2007	TIP	18FL279490	E FL	Palm Beach	734	OG	F	1.2615	1.2258	1.2437	26	1.9	0.086	28	2SE
	2007 GTL	25	110	02/08/07	SBLOP	JLC-003-006	E FL	Port Orange	710	O		1.2685	1.3065	1.2875	27	20	1.073	680	Min
	2007 GTL	13	231	01/17/07	TIP	18FL252545	E FL	Volusia	702	O		1.2905		1.2905	20	27	1.521	824	Max
	2007 GTL	2	287	1/18/2007	TIP	18FL252598	E FL	Ft. Pierce	680	OG	F	1.3149		1.3149	23	n	10		
	2007 GTL	62	693	5/14/2007	TIP	18FL277058	E FL	Martin	770	og	F	1.4154	1.4004	1.4079	20				
	2007 GTL	25	123	02/08/07	SBLOP	JLC-003-006	E FL	Port Orange	770	O		1.4274		1.4274	27				
	2007 GTL	78	710	6/22/2007	TIP	18FL279490	E FL	Palm Beach	824	OG	F	1.5209	1.5161	1.5185	22				

Age group	Year Species	PC Coll #	Fish #	Date	Source	Source #	State	Location	FL (mm)	Samples	Sex	R Otolith Wt (g)	L Otolith Wt (g)	Ave oto wt (g)	Final age (yr)				
22-28 yr	2007 GTL	25	115	02/08/07	SBLOP	JLC-003-006	E FL	Port Orange	700	O		1.5588	1.5619	1.5604	25	Age	Oto wt	Length	
high weight	2007 GTL	25	133	02/08/07	SBLOP	JLC-003-006	E FL	Port Orange	710	O		1.5414	1.5914	1.5664	25	25.2	1.710	763	Average
ave collection	2007 GTL	38	691	03/13/07	TIP	18FL255663	E FL	Volusia	719	O		1.5872	1.5615	1.5744	26	1.5	0.152	67	SD
3/23/2007	2007 GTL	76	756	03/30/07	TIP	18FL276646	E FL	Volusia	703	O		1.5505	1.6106	1.5806	26	1.0	0.096	43	2SE
	2007 GTL	66	1110	04/25/07	TIP	18FL276938	E FL	Volusia	774	O			1.5965	1.5965	22	22	1.541	700	Min
	2007 GTL	62	695	5/14/2007	TIP	18FL277058	E FL	Martin	811	OG	F	1.6746	1.7642	1.7194	25	28	2.002	900	Max
	2007 GTL	74	729	03/29/07	TIP	18FL276645	E FL	Volusia	705	O		1.7488	1.7272	1.7380	26	n	10		
	2007 GTL	78	712	6/22/2007	TIP	18FL279490	E FL	Palm Beach	824	OG	F	1.8455	1.8487	1.8471	24				
	2007 GTL	25	132	02/08/07	SBLOP	JLC-003-006	E FL	Port Orange	780	O		1.8633	1.9004	1.8819	28				
	2007 GTL	25	112	02/08/07	SBLOP	JLC-003-006	E FL	Port Orange	900	O		1.9467	2.0020	1.9744	25				