

SUMMARY REPORT FOR PROCEEDINGS OF THE OTOLITH WORKSHOP, OREGON HATCHERY RESEARCH CENTER, OCTOBER 25-26, 2012

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BACKGROUND & CONTEXT

We organized an Otolith Workshop, which took place 25 – 26 October 2012 at the Oregon Hatchery Research Center. This report is a summary of the proceedings and conclusions of this workshop. A brief bibliography of otoliths is provided at the end of this report, followed by partial lists of informative websites and some laboratories focusing on otolith research.

The Objectives of the otolith workshop were: 1) to acquire knowledge from experts specializing in studies of otolith microstructure (ageing and back-calculation estimates of size-at-age and growth), otolith microchemistry, and stable isotopes of tissues other than otoliths, as related to fisheries research; 2) to learn details of the diversity of otolith techniques and applications; 3) to learn about the relative advantages and disadvantages of different techniques; and 4) to implement and balance this information with the needs of ODFW (and other agency) activities as projected over the future.

The information in this report, the bibliography and list of laboratories, procedures and techniques will be used to inform the direction of otolith research into which the Fish Life History Analysis Project (FLHAP) will expand. This information will also inform the First Draft of Operating Procedures for the FLHAP. The proceedings were video-taped for posterity and will likely be used as part of a distance education course on otoliths to be developed by Mark Terwilliger of OSU. The workshop was not designed to be tied in any way to the series of International Symposia on Fish Otolith Research and Application (see Secor et al. 1995; Fossum et al. 2000; Begg et al. 2005; Miller et al. 2010).

The FLHAP is part of the Western Oregon Research and Monitoring Program within the Northwest Region. The FLHAP provides technical support within this program and to other programs, research projects and management districts within ODFW. Until 2012, the FLHAP was known as the “Fish Scale Project” or the “Scale Analysis Project”. This old name gives an idea of that project’s focus: scale analyses (age, estimated growth, discernment of “hatchery” vs. “wild” fish, species identification; life history categorization [sub-yearling vs. yearling Chinook], etc.). These types of analyses are done primarily for salmonids, though the project does some work on warmwater fishes. The FLHAP processes scale samples of up to 22,000 fish per year. The bulk of the scale analyses comes from 2 sources, coastal Chinook surveys and Willamette Chinook research. The remainder of the scale analyses fulfills the different needs of various projects and districts. Samples come from spawning ground and creel surveys; mark-recapture, broodstock, juvenile fish outmigration, and adult trapping for return migrants. These data provide the foundation of estimates used to generate run size forecasts, status assessment, identification of hatchery strays, and growth analyses. Whenever possible, the project seeks to obtain reference samples from fish implanted with coded wire tags to inform and validate age estimations. However these types of analyses are limited to fish implanted with Coded Wire Tags (CWTs) — namely hatchery fish.

During 2012, fish biologists from ODFW were polled to ascertain the depth and breadth of their interest in various life history indices for the fishes of Oregon. We received 16 responses from several different programs within ODFW. The responses indicated a continued interest in life history data for salmonids. Interest was expressed on some non-salmonid species from the Native Fish Investigations Project as well. Several respondents mentioned an interest in life history data across life stages, from fry to adults. The poll identified 3 ODFW programs make use of laboratories from other organizations (including 2 out of state programs) to conduct analyses on Oregon fishes, and another program is actively seeking a laboratory to conduct analyses. This poll identified 4 areas of research interest for ODFW:

1. Otolith microstructure (annular banding patterns) for identification of origin (hatchery vs. wild) for unclipped salmonids via examination for thermal marks from the hatchery;
2. Otolith microchemistry and gross morphology (size and shape) for stock/life history identification
 - Estuarine entrance and residence timing
 - Freshwater basin of origin
 - Early life history validation for run timing and early life history variants of freshwater rearing (reservoir vs. stream rearing);
3. Otoliths age estimations (daily, annual) and verifications in comparison with scale reads;
4. Estimating growth rates (daily, annual)
 - Environmental effects on larval survival and daily growth

- Growth rate back-calculations
- Validations.

Finally, any information gleaned from otoliths can be used to supplement and support information gleaned from scales. Data unique to otoliths, but that may be correlated with circuli patterns in scales, would provide strong rationale for increasing sample sizes for monitoring. This is because scales can be sampled from fishes non-lethally and processed and analyzed easily.

OTOLITHS

Otoliths — bony structures inside the semicircular canals of fishes aiding in detections of balance, sound and pressure (Popper and Lu 2000) — have been a focal structure of fisheries research aimed at age and growth estimates and as “recorders” of past environs inhabited by fishes. This is because otoliths grow continuously and lay down repeated rings of daily and other frequencies and constantly incorporate the chemical milieu inhabited by the fish. A multitude of papers over the past 30-40 years have focused on otoliths for various aspects of fisheries research, demonstrating that the information contained in these structures, if properly analyzed in the right context, can be used to help answer particular questions relevant to fish biology and fisheries management (Miller et al. 2010).

Otolith research can be categorized into three general areas, from macro- to micro-structure and microchemistry. Macro- to micro-structure refer to gross otolith morphologies (shape, size), and microscopic morphologies (e.g., “increment analyses” of the radii of successive growth increments; age and size-at-age estimates). Microchemistry of otoliths has different approaches. For example, microchemistry of otoliths can be used to determine maternal origin and maternal run time (e.g., anadromy vs. residency), natal basin of origin; migratory variation (diversity in estuarine entrance timing and residency), and wild vs. hatchery origin. These 3 approaches, macrostructure, microstructure, and microchemistry, have variously been used to discriminate among fish taxa and stocks; to inform stock assessment models and improve understanding of population dynamics, including migration behaviors, rearing environments, and overall habitat use at particular ages. Moreover, information from otoliths requires collecting a fish once whereas PIT and CWTs require capture and handling of the fish at least twice. From these general examples it is apparent that otolith analyses can be a particularly relevant and useful tool to informing fisheries management. Scales are often used to estimate the age of fishes, and have been used as such since at least the 1800s (Jackson 2007). However, otoliths are believed by many agencies to yield more accurate and more precise age estimates. The increased value of otolith studies are borne out by the numerous reports in the literature (Maceina et al. 2007; Miller et al. 2010).

ATTENDEES & SPEAKERS

There were 50 attendees to the otolith workshop, 22 whom were from ODFW. The remaining 28 attendees were from 3 universities, 3 tribes, and 3 federal agencies. A list of attendees is provided at the end of this report. We invited 6 speakers to provide 45 – 60 min oral presentations on their respective areas of expertise. The speakers and the titles of their presentations are listed below, followed by brief synopses of these presentations.

1. *David H. Secor*, Center for Environmental Science, Chesapeake Biological Laboratory, University of Maryland, Solomons, MD USA: ***Are otoliths truly Pannella's Rosetta Stone?***
2. *Mark Terwilliger & Doug Markle*, Department of Fisheries & Wildlife, Oregon State University, Corvallis, OR USA: ***Methods and applications of age and growth data for endangered species research***
3. *Jessica Miller*, Department of Fisheries & Wildlife, Oregon State University, Corvallis, OR USA: ***Exploring life history variation, natal origin, and maternal origin in Pacific salmon (Oncorhynchus spp.)***
4. *Yongwen Gao*, Makah Fisheries Management, Neah Bay, WA USA & College of Fisheries, Huazhong Agricultural University, Wuhan, Hubei China: ***Use and abuse of stable isotopic composition of fish otoliths***
5. *M. Robbins Church*, U.S. EPA, National Health and Environmental Effects Research Laboratory, Western Ecology Division, Corvallis, OR USA: ***Uses of stable isotopes in fish ecology.***

BRIEF SYNOPSES OF PRESENTATIONS

*David H. Secor: **Are otoliths truly Pannella's Rosetta Stone?***

Dave is fisheries ecologist working within the intersecting domains of population dynamics, migration behavior and habitat use. He is interested in partial migration for a model, estuarine-dependent species; specifically, the propensity to migrate versus residency, and the resulting growth rates, recruitment and populations dynamics. His work is done via cohort-based analyses of microchemical otolith signatures and size-at-age back calculations to estimate estuary-entrance timing and growth rates. These techniques are used to elucidate population diversity, dynamics, and persistence over time, based on the prevailing climate and population structure. Tying these elements together, Dr. Secor featured an “otolith-informed spatially explicit population model”.

Mark Terwilliger & Doug Markle: *Methods and applications of age and growth data for endangered species research*

Mark and Doug are interested in the age, growth, early life history, and general ecology of suckers (Family Catostomidae) in Upper Klamath Lake. They use otoliths from young-of-the-year (YOY) and adult fish for age and back-calculated growth estimates (increment width measures in the otoliths for YOY as proxies for somatic growth) of two Klamath Lake suckers in conjunction with environmental variables (temperature, dissolved oxygen, wind frequency, emergent aquatic plants) to estimate growth rates, historic and contemporary population dynamics, and environmental (and anthropogenic) associations/causes for the aforementioned. In adults, there was an uncoupling of otolith growth (continuous) with somatic growth (determinate). (The suckers are long-lived, the oldest estimated age being 57 years). This means that as the fish got older, and their growth slowed considerably, growth increments in the lapilli (their otolith of choice) became more densely packed. Growth trajectories were significantly different among sexes and among the historic and contemporary samples. Moreover, age class distribution differed between these two collections. Using this information they were able to conclude that there is currently a lack of recent year-class diversity and that the suite of environmental factors measured were identified with an apparent selection for hatch rate success occurring from mid-May through mid-June. They also demonstrated that parasites that use fish as an intermediate host had a negative impact on juvenile sucker growth and accounted for an increase in the daily mortality rate.

Jessica Miller: *Exploring life history variation, natal origin, and maternal origin in Pacific salmon (Oncorhynchus spp.)*

Jessica is a marine ecologist interested in the ecology, evolution, and maintenance of life history diversity in fishes. Jessica has used anadromous Chinook salmon (*Oncorhynchus tshawytscha*) in the Pacific Northwest as a focal species of her research with the goals of determining habitat requirements, identifying stocks, and the degree of intermixing of stocks through their various migration behaviors. Jessica noted that the types of otolith analyses she has done are most relevant to stock-specific (i.e., informed by genetic analyses and CWT data) ecological questions. She has conducted field studies to determine maternal and natal origin, and life history diversity by measuring microchemical signatures and growth rates via size-at-age back calculations to address questions about timing of entry into marine waters, marine residence, and habitat-specific growth rates. She has found that otolith and somatic sizes are directly related, but that uncoupling between these two indices can occur. Therefore the back-calculation model used to estimate size-at-age and habitat-specific growth rates matters. She also conducted empirical studies on the degree of assimilation of elements into the otolith in relation to environmental factors (salinity, barium concentrations, and temperature) as a means to validate her other research. Water chemistry and temperature, food composition and maternal contributions can all affect assimilation of elements and isotopes into fish otoliths, and these are all contingent upon species and environmental variation. Further, there are limitations to accurate

interpretation of microchemical composition in relation to sampling logistics, mixing curves (sampling equations describing assimilation of particular elements into the otoliths in relation to environmental factors) and lag effects (delayed effects between environmental exposure and assimilation of environmental elements into the otoliths).

Elements: Strontium : calcium ratios (Sr : Ca) in the otolith are usually much higher during the saltwater phase of the life history, whereas the inverse is generally true for barium : calcium ratios (Ba : Ca). Similarly, there is a maternal signal from the saltwater environment in the core region of the otoliths (within the exogenous feeding check) wherein the Sr : Ca and Ba : Ca ratios show a small positive and negative peak, respectively. The magnitude of the maternal effect will vary with adult run timing and maternal migration distance. The freshwater environment needs to be significantly different from the saltwater environment with respect to these ratios in order for measurements to be meaningful.

Two pieces of equipment are used for elemental analyses: 1) the “*Single-collector*” Inductively Coupled Plasma Mass Spectrometer, and 2) the electron microprobe.

Isotopes: Freshwater strontium isotopic ratios ($^{87}\text{Sr} : ^{86}\text{Sr}$) vary with regional geology and are a useful proxy for delineating maternal and natal origins and migration histories. This is due to the fact that marine $^{87}\text{Sr} : ^{86}\text{Sr}$ is relatively stable at values of 0.70918. Freshwater $^{87}\text{Sr} : ^{86}\text{Sr}$ are often significantly different than the marine value, with river values lower (basaltic watersheds) or higher (granitic watersheds) than marine values. Maternal effects can be evident in otoliths of Chinook salmon, from the mother’s saltwater influences, and appears as a shift towards marine values of $^{87}\text{Sr} : ^{86}\text{Sr}$ ratios in the core region. To be meaningful, measures of these ratios should be compared with a baseline — either all of the otoliths themselves, the water, or both.

Other isotopic ratios have been successfully assayed to determine hatchery vs. wild origin of fishes ($^{34}\text{S} : ^{32}\text{S}$) or thermal history of the fish in question ($^{18}\text{O} : ^{16}\text{O}$).

Four instruments can be used for isotopic analyses:

- 1) the “*Multi-collector*” Inductively Coupled Plasma Mass Spectrometer for $^{87}\text{Sr} : ^{86}\text{Sr}$ ratios
- 2) the Thermal Ionization Mass Spectrometer for $^{34}\text{S} : ^{32}\text{S}$, $^{18}\text{O} : ^{16}\text{O}$
- 3) the Micro Mill and the Isotopic Ratio Mass Spectrometer for $^{18}\text{O} : ^{16}\text{O}$, $^{13}\text{C} : ^{12}\text{C}$

The costs for using specific equipment to measure elemental and isotopic ratios in fish otoliths are below. The number of otoliths that can be processed per unit time varies with the size of the otoliths, the number of sample locations on each otolith, and the number of analytes (elements or isotopes) being measured, but usually ranges from 30 – 100 otoliths per day.

Costs:

\$600 – 800 per day for instrument time + costs for training and assisted user rates.
\$10 – 15/sample stable isotopes.

Yongwen Gao: *Use and abuse of stable isotopic composition of fish otoliths*

Yongwen is a trained biogeochemist specializing in chemical analyses of hard parts of fishes (e.g., otoliths and bones) as a proxy for marine environmental studies. His research focus is on stable isotope analyses of otoliths of fishes to address questions about early life history, stock structure, migration and climate regime shifts.

Of the three pairs of otoliths (sagittae, asterisci, and lapilli), sagittae are the largest in marine fishes, and therefore most commonly used in stable isotope analyses. However, the relative size and shape of these otolith pairs vary among freshwater fish species.

The carbon dioxide and water reaction equilibrium can result in carbonic acid, bicarbonate, and carbonate. These equilibria will affect the composition of the fish otolith, which is comprised of calcium carbonate. Yongwen noted that otoliths are formed in, or close to, oxygen isotopic equilibrium with the ambient seawater. This is the cornerstone of using stable isotopic composition in otoliths and is consistent with the experiments on isotopic temperature scales from biogenic calcite and aragonite.

Some general considerations of isotopes are as follows:

- There are latitude effects (through the Global Meteoric Water Line $\delta^2\text{H} = 8\delta^{18}\text{O} + 10$) and depth variations (correlated to salinity profile) in the ocean on oxygen isotopic composition;
- The carbon isotopic composition of a particular animal is dependent on its diet, offset by a few units.
- The combination of $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ thus reflects both the food (metabolism; dietary switches; trophic position) and the water (temperature; salinity; chemical composition) conditions that a fish encountered.
- Microsampling techniques are a new development in stable isotopic analyses of otoliths :
 - Microsampler (20-40 μm zones)
 - DM-2800 (seasonal otolith zones)
 - Dremel (annual zones)

$\delta^{18}\text{O}$ versus $\delta^{13}\text{C}$ in fish otoliths

The ratio of these two isotopes can be used:

- As a habitat index
- For identifying natal source
- For identifying stock structure
- For identifying life history and migration
- For aiding understanding of climate regime shifts.

Yongwen provided two research examples, the Pacific herring (*Clupea pallasii*) in Puget Sound and the Pacific halibut (*Hippoglossus stenolepis*) along the west coast, to demonstrate the use of $\delta^{18}\text{O}$ vs. $\delta^{13}\text{C}$ of otoliths in fisheries management.

$\delta^{15}\text{N}$ in fish otoliths

This is different from otolith $\delta^{18}\text{O}$ & $\delta^{13}\text{C}$ in terms of sampling, isotopic fractionation, differences in theory and applications.

$\delta^{34}\text{S}$ in fish otoliths

Variation in nature is the result of deduction of ions by anaerobic bacteria in aquatic sediments. There are different sources, and for application one must know the isotopic composition of those sources, including natural (precipitation; volcanic; organic compounds from plants) and anthropogenic (coal, fuel oil; auto exhaust).

$\delta^{87}\text{Sr}$ in fish otoliths

- $^{87}\text{Sr} : ^{86}\text{Sr}$ is variable because of the formation of ^{87}Sr by the decay of ^{87}Rb
- $^{87}\text{Sr} : ^{86}\text{Sr}$ of water depends on the age and mineral composition of the bed rocks.

Trace elements in fish otoliths

- It is challenging to interpret these analytical data.
- There are substantial differences in theory and analyses of stable isotopes vs. trace elements.
- Stable isotope ratios are MORE sensitive and hence powerful than trace elemental analyses.

*M. Robbins Church: **Uses of stable isotopes in fish ecology***

Robbins is an aquatic ecologist and watershed biogeochemist who for the past several years has worked on stable isotope ecology of fish. The goal of this research is to use the science of stable isotope ecology to learn about fish ecology.

For a particular element, the stable isotope with the greater number of neutrons is heavier and therefore has a greater attractant force and lower “escape” or “release” velocity in chemical reactions, including those involving living tissue. This is called “fractionation,” which reflects the results of the myriad reactions occurring along physiological pathways.

- The light stable isotopes used in ecological studies are those of H, C, N, O, and S.
- The standard measure of isotopic composition for a sample is the “delta” value.
Delta of a sample = ((Heavy Isotope : Light Isotope in sample) / (Heavy Isotope : Light Isotope in a standard sample) -1) X 1000

- + delta = enriched (relative to the standard for that element); - delta = depleted (relative to the standard for that element).
- Delta values of organism tissues are enriched (in different amounts for different elements) relative to their diet – this termed trophic shift.
- Single pool (source) or multiple pool (source) models can be used to evaluate the relative contributions of sources (e.g., diet vs. tissue catabolism) to resultant tissue isotopic composition.
- Robbins has used these types of calculations with stable isotopes of nitrogen (which has the greatest stable isotope trophic shift of the light elements) to investigate diet switches by coho (*Oncorhynchus kisutch*) juveniles in streams.
- Carbon isotopes are useful to investigate habitat use by fish with regards to a variety of influences including diet, temperature, and current velocity.
- Sulfur isotopes can similarly be used to help identify habitat use, particularly fine sediments with anaerobic environments vs. coarse substrates with oxidizing environments.
- Oxygen isotopes reflect the hydrologic history of water in which the fish live and can show regional patterns with regards to rainfall characteristics as well as fine-scale effects with regards to tributary vs. mainstem habitats (as a result of local evaporative histories).
- Hydrogen isotopes also can be used to discern habitat type based upon nutrient sources and hydrologic histories.
- The stable isotopes of carbon and nitrogen are, by far, those most frequently used in isotopic studies of fish ecology.

Different fish tissues have different isotopic turnover rates, based upon metabolic turnover of the tissue. Muscle and fin tissues are slowest, whereas epidermal mucus can be quite fast (Church et al., 2009). Comparative studies involving the use of a variety of stable isotopes as well as a variety of tissues holds promise further investigations of fish ecology.

GENERAL GUIDANCE FOR THE FLHAP OF ODFW

- Recommended to specialize in otolith preparation, archiving, analyses for age and growth estimates, and crystalline structure status (aragonitic vs. vateritic). The preparation would be for age and growth estimates to be done by the FLHAP of ODFW, and preparation for microchemistry, to be done by laboratories collaborating with ODFW. Although not explicitly suggested, there seemed to be

a general recommendation to adapt to identify thermal marks in the otoliths of hatchery fish. It was learned that thermal marking in hatcheries is not ubiquitous and not standardized outside of the Willamette Basin. Costs of creating thermal marks on otoliths, as well as costs of interpreting otoliths need to be considered for ongoing monitoring and specific research projects.

METHODOLOGICAL GUIDANCE

- There are three pairs of otoliths within the semi-circular canals of fishes: the sagittae, asterisci, and lapilli. The largest, most useful otolith to extract from the fish carcass and to analyze depends on the species and the study objectives.
- Sagittae are the largest otolith in salmonids, and therefore the otolith of choice for these fishes.
- Store otoliths dry (no preservative or liquid of any kind) in vials. It is not recommended to store otoliths in envelopes, as they can easily be broken and crushed.
- For most teleost species, the sagittal otolith pair is isomorphic—that is, each otolith should be a near-duplicate copy of its paired counterpart.
- Within fishes, the crystalline structure (aragonitic vs. vateritic) of the otoliths depends, to some degree, on phylogeny and origin (hatchery vs. wild). There is some recent experimental literature on this subject (see Maisey 1987 and Coffin et al. 2012).
- It is quite common for salmonids, particularly hatchery fish to exhibit vateritic otoliths, which are opaque, and therefore difficult to age. Although vateritic otoliths have been observed to commonly occur in hatchery salmonids, at best this feature could only work on a very crude scale for discerning fish origin. Also, although vateritic otoliths are relatively common in salmonids, it is believed that enough salmonids exhibit aragonitic otoliths to justify using otoliths for age and growth estimates.
- Compound light microscopes are sometimes needed to adequately view and age otoliths. In certain species that have relatively flat, thin sagittae, these particular otoliths can often be read by placing them in glycerine or water, and reading them under a dissecting microscope.
- Digital images are difficult to age. It is easier to age actual structures in real time by focusing in and out on the otolith.

OBSERVATIONS ON GENERAL TERMINOLOGY

- As with any scientific field, it is very important to use consistent terminology whenever possible and to define the terminology being used.
- Consistent and defined terminology needs to be used for anatomical structures, life history “types”, stages and ages with regards to time and space.

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BIBLIOGRAPHY (*Not comprehensive*)

This bibliography is *not* intended to be comprehensive in nature. Very little of this literature covers marine fishes. The citations are included in 14 different categories:

1. GENERAL
2. SALMONID-FOCUS
3. OTOLITH REMOVAL & PREPARATION
4. OTOLITHS & THERMAL MARKS FOR HATCHERY IDENTIFICATION
5. OTOLITHS & AGE VALIDATION
6. OTOLITHS, MARGINAL INCREMENT ANALYSIS, ANNULI FORMATION
7. OTOLITHS & GROWTH BACK-CALCULATIONS
8. OTOLITH MORPHOLOGY, MICROSTRUCTURE & IMAGING
9. MICROCHEMISTRY: GENERAL
10. MICROCHEMISTRY: HANDLING & STORAGE
11. MICROCHEMISTRY TO ELUCIDATE MIGRATIONS & ECOLOGY
12. MICROCHEMISTRY VALIDATIONS
13. STOCK IDENTIFICATION
14. REFERENCES FROM SPEAKERS

Some of the citations naturally fit into more than one category and so were included as such. We likely have missed instances in which particular citations should have been included in more than one category. References from speakers include pertinent literature that they referred to in their presentations, plus in some cases, ancillary publications by the speaker.

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1. GENERAL

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Windsor Aguirre, otolith biology and morphology:

http://life.bio.sunysb.edu/ee/seatrout/fish_otoliths.html#growth

Online otolith laboratory (University of Alaska Southeast):

<http://elearning.uaf.edu/cc/otolith/collection.htm>

OTO – Otolith Training Online: <http://www.marine.ie/oto/otoliths+on+the+web/index.htm>

Arthur Popper: Bioacoustics and Fishes: <http://www.popperlab.umd.edu/index.htm>

Glossary for otolith studies: http://horizon.documentation.ird.fr/exl-doc/pleins_textes/pleins_textes_6/b_fdi_35-36/42209.pdf

Introduction to ageing fish with otoliths: <http://myfwc.com/research/saltwater/fish/age-growth-lab/aging-fish-otoliths/>

Pedro Ré's larval otolith microstructure studies:

http://www.astrosurf.com/re/otolith_research_portugal.pdf

Burke Museum, University of Washington—information about newly acquired otolith collection: <http://burkemuseum.blogspot.com/2012/10/two-million-fish-ear-bones-give.html>

NOAA Southeast Fisheries Science Center:

<http://www.sefsc.noaa.gov/labs/panama/fb/otolith.htm>

Alaska Fisheries Science Center interactive ageing demo:

<http://www.afsc.noaa.gov/refm/age/interactive.htm>

Sclerochronology laboratory, Department of Fisheries and Oceans, Canada:

<http://www.dfo-mpo.gc.ca/science/publications/article/2012/04-27-12-eng.html>

OTOLITH LABORATORIES (Not comprehensive)

Alaska Department of Fish and Game's Mark, Tag and Age Laboratory

<http://tagotoweb.adfg.state.ak.us/>

Barnett-Johnson's Fisheries and Otolith Laboratory, Institute of Marine Sciences,
University of California <http://www.barnett-johnson.com/research.html>

Keck Laboratory for plasma spectrometry at Oregon State University
<http://wmkeck-icpms.coas.oregonstate.edu/>

Steven Campana's Otolith Laboratory, Bedford Institute of Oceanography, Nova Scotia
<http://www.marinebiodiversity.ca/otolith/english/home.htm>

David Secor's Migration and Habitat Ecology Fisheries Laboratory
<http://fishconnectivity.cbl.umces.edu/>

Stable Isotope Laboratory, College of Oceanic and Atmospheric Sciences, Oregon
State University
<http://stable-isotope.coas.oregonstate.edu/research/otolith/otolith.html>

Stable Isotope Core Laboratory, College of Sciences, Washington State University
<http://www.isotopes.wsu.edu/>