Preliminary use of oxygen stable isotopes and the 1983 El Niño to assess the accuracy of aging black rockfish (*Sebastes melanops*)

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Black rockfish (*Sebastes melanops*) range from California to Alaska and are found in both nearshore and shallow continental shelf waters (Love et al., 2002). Juveniles and subadults inhabit shallow water, moving deeper as they grow. Generally, adults are found at depths shallower than 55 meters and reportedly live up to 50 years. The species is currently managed by using information from an age-structured stock assessment model (Ralston and Dick, 2003).

In many studies, ages are assumed to be accurate and there is no effort to validate the accuracy of the ages (Beamish and McFarlane, 1983). Recent methods of age validation rely upon environmental events that serve as time markers (Campana, 2001). Bomb radiocarbon released during nuclear bomb testing has been used to validate fish ages (Kalish et al., 1996; Campana, 1997; Kalish et al., 1997). Unfortunately, bomb radiocarbon can be used only for fish that lived during the informative period (~1960–70); thus the technique has been used primarily on older ages. For many stock assessments, the validation of younger ages is more critical because of their importance in estimating vital rates, such as growth and maturity schedules.

In this note we apply the well-studied relationship between water temperature and the ratio of oxygen stable isotopes in otoliths to assess the accuracy of young black rockfish ages. Oxygen isotope ratios serve as a record of past water temperatures because the isotope ratio is incorporated into the otolith in near equilibrium with the ratio found in the environment (Patterson et al., 1993; Thorrold et al., 1997) and ambient water temperatures are inversely correlated with $^{18}O/^{16}O$ ratios (Gao et al., 2001). Calcified structures have a strong history of being used in environmental reconstructions based on incorporated trace elements and isotopes (Chivas et al., 1985; Holmden et al., 1997). Otolith microchemistry has been used to successfully reconstruct the environmental history of fish and to answer questions about natal homing (Thorrold et al., 2001) and population mixing (Campana et al., 1999). Variation in oxygen isotopes has been used to confirm visually observed growth increments (Campana, 2001). Recently, stable oxygen isotopes from Pacific halibut (*Hippoglossus stenolepis*) otoliths were used to examine regime shifts in the Northeast Pacific for the identification of changes in bottom water temperatures (Gao and Beamish, 2003). In addition, otolith chemistry may be used to identify environmental events that serve as natural tags for such studies (Campana and Thorrold, 2001). We used a strong regional environmental event, the 1983 El Niño, as a time marker to judge the accuracy of age assignment for black rockfish <15 years of age. The 1983 El Niño produced anomalously warm oceanic conditions along the coastlines in the eastern Pacific; therefore the stable oxygen isotope ratio from 1983 should reflect this change in oceanic conditions.

Materials and methods

We obtained nine pre-aged black rockfish otoliths collected during 1987–91 from recreationally caught fish off Cape Lookout, Oregon (~45.25°N, 145°W), from approximately 15–30 m water depth. One otolith was aged by Oregon Department of Fish and Wildlife scientists by using the traditional break-and-burn method; the matching otolith was used in the stable isotope analysis. Fish from a range of years and ages (Table 1) were selected to include the 1983 El Niño year. A time series of annual summer bottom water temperatures from the same region and depth where the black rockfish otolith samples were obtained, were provided by the Pacific Hindcast from the Columbia University International Research Institute for Climate Prediction, Palisades, New York.

To estimate the year containing the warmest oceanic conditions, we examined otolith material from all opaque growth zones within each otolith for oxygen isotopes ($^{18}O/^{16}O$) and

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Table 1

Age-specific $\delta^{18}O$ values for each black rockfish (*Sebastes melanops*), along with annulus age and collection year. Values replaced by "N/A" indicates samples that were not reported by the stable isotope laboratory.

	Sample number								
Age	1987–33	1987–86	1987–98	1988–7	1988–100	1991–27	1991–86	1991–168	1991–178
0+	−0.96	N/A	−0.633	−0.357	1.209	N/A	−0.128	−2.06	0.756
1+	−1.17	0.914	−0.981	−0.513	0.725	−0.53	−0.114	−1.77	0.948
2+	−0.42	0.654	−0.644	−0.504	−0.544	−0.42	−0.358	−1.09	0.869
3+	−0.04	0.461	−0.518	−0.579	1.037	−0.39	−0.409	−0.64	0.741
4+	0.42	1.006	−0.202	−0.320	N/A	−0.09	−0.082	−0.85	0.338
5+	0.28	0.946	−0.037	−0.257	N/A	−0.22	−0.218	−0.73	N/A
6+		0.957	0.630	0.137	N/A	−0.05	0.1067	0.35	0.785
7+				0.962		1.0	0.512	1.08	1.054
8+						N/A	0.805	1.07	1.113
9+						N/A	1.053	N/A	1.404
10+						N/A	1.164	N/A	1.510
11+						N/A	1.881		
Annulus age (yr)	6	7	7	8	7	12	12	11	11
Collection year	1987	1987	1987	1988	1988	1991	1991	1991	1991

assigned to a year of formation based on estimated age and capture year. Chemical assay and otolith processing were completed at the Stable Isotope Laboratory of the University of Michigan. Each otolith was embedded in epoxy resin and cut transversally with a low-speed diamond-bladed saw. Three or four thin sections ~150 μm thick were removed from the center of each otolith. The thin sections were then glued with cyanoacrilate glue to petrographic glass slides. Samples from multiple thin sections were combined for a single assay. Each opaque growth zone was sampled by using a Merchantek Micromilling system and assays were completed with a Finnigan 251 MAT mass spectrometer. All measurements were reported in standard Vienna Pee Dee Belemnite (VPDB) and notation as δ‰ (per mil), where

$$\delta^{18}O = \left(\left(({}^{18}O/{}^{16}O)_{\text{sample}} / ({}^{18}O/{}^{16}O)_{\text{standard}}\right) - 1 \times 1000\right).$$

A time series of $\delta^{18}O$ was constructed for each fish by using the assay from each year-specific sample of the otolith material. Assay results from the collection year were not included because of differences in the season of capture. Years with missing results were due to micromilling or assay errors that resulted in no results reported by the stable isotope laboratory.

To gauge the accuracy of age assignments, we fitted a linear model to each time series and analyzed the residuals from the linear model fit. The $\delta^{18}O$ value corresponding to the negative residual of greatest magnitude from that linear model would be associated with the anomalously warmest oceanic conditions (El Niño). If the age assignments were correct, that portion of the otolith corresponding to 1983 would have the negative residual of greatest magnitude because the observed $\delta^{18}O$ value was much lower than the linear model predicted. Temporal shifts of the most anomalous negative residual with respect to 1983 were interpreted as either an under- or over-estimation of age.

A randomization procedure (20,000 iterations) was used to determine if the magnitude of the average residual in any year was more negative than expected, thus identifying the signal associated with the 1983 El Niño. The residuals from the linear models within each of the fish were randomized with respect to year. Randomized residuals from all iterations were averaged across all fish to produce a distribution of averages. The original year-specific residual averages were compared to the randomization distribution to estimate statistical significance. We rejected the hypothesis of any year with an average residual ≥0 if less than 5% of the randomizations produced a negative average residual of equal or greater magnitude than the observed year-specific average residual, thus identifying anomalously warm years.

An iterative sensitivity analysis was performed by retrospectively removing sequential blocks of years of data and by estimating the statistical significance of the originally determined anomalous years with the reduced data sets. All data taken from years more recent that the cutoff year were removed, and the linear model fitting and randomization procedures were recalculated. The cutoff year was sequentially changed beginning with 1989 to 1986.

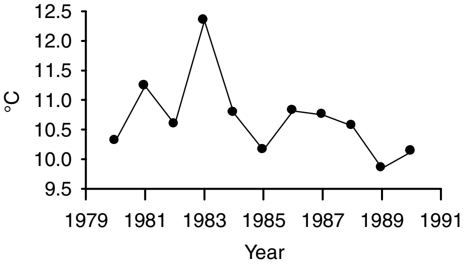

Figure 1

Average summer water temperatures (May–Sep) from Cape Lookout, Oregon.

Table 2

Results of the retrospective analysis that estimated the statistical significance of the magnitude of the average negative residual from the years 1983 and 1985. Assay results from otolith material formed after the cutoff year were removed from the randomization analysis.

Cutoff year	1983	1985
1989	*0.03	*0.05
1988	*0.03	*0.05
1987	*0.04	*0.06
1986	*0.05	*0.26

Results

The period 1980–90 was characterized by an isolated and historically strong 1983 El Niño event (Fig. 1), that resulted in a 1–2°C increase in water temperatures along the Oregon coast. Average summer water temperatures declined slightly over this period. The δ^{18}O values measured in each fish resulting from this period (Table 1) showed strong patterns that indicated temperature differences both within fish (between years) and between fish (same year). In addition, many fish contained trends in δ^{18}O across time (Fig. 2). Precision of the reported δ^{18}O measurements ranged from 0.01 to 0.07‰ (SD).

The residual patterns (Fig. 3A) showed that anomalously warm conditions existed in otolith material corresponding to those of 1983 (n=9, P=0.0338) and 1985 (n=7, P=0.0409). Both old (ages 11–12) and young (ages 6–8) fish appeared to have similar temporal patterns of residuals; however in older fish this pattern shifted by 1–2 years toward more recent years (Fig. 3B). The year-specific averaged residuals of the age 6–8 fish depicted a single anomalously warm year corresponding to 1983. The anomalously warm year in the age 11–12 fish was 1984–85, thus explaining the significance result in 1985. The results of the randomization test were not sensitive to the exclusion of data from the four most recent years (Table 2).

Discussion

The location of the anomalously warm signal in 1983, in the youngest and likely the more accurately aged fish, supports the hypothesis that the 1983 El Niño can be detected by using oxygen stable isotopes. From this analysis, we concluded that the break-and-burn aging method is accurate on average but has a potential tendency toward underaging fish >10 years.

Confirmation of the annual banding pattern in the ololiths of other *Sebastes* species has been accomplished by using a variety of methods. Woodbury (1999) confirmed the accuracy of age assignment in widow (*Sebastes entomelas*) and yellowtail (*S. flavidus*) rockfish, using the change in growth increment width associated with El Niño. Piner et al. (in press) has used bomb radiocarbon to confirm the annual pattern of otolith banding in canary rockfish (*S. pinniger*) and has reported a possible underaging bias for older fish. Andrews et al. (1999) used radiometric age determination to confirm the longevity of long-lived species. However, a larger study on black rockfish with stable isotopes is necessary to conclusively determine age estimates accurately and potential underaging bias.

The 1983 El Niño was chosen for the present study because it was one of the strongest recorded in the century (Sharp and McClain, 1993). Warm water conditions associated with the 1983 El Niño were sufficient to slow growth (MacLellan and Saunders, 1995; Woodbury, 1999) and alter reproductive patterns (VenTresca et al., 1995) in species occupying similar geographic ranges. In contrast, this study attempted to indirectly measure the environment experienced by black rockfish without the need to infer changes to biological processes. Nevertheless, our results appear to support the conclusions of MacLellan and Saunders (1995) and Woodbury (1999) that the anomalous oceanic conditions in 1983 are identifiable.

The analysis of model residuals rather than raw isotope ratios is more appropriate because of the obvious δ^{18}O temporal trend in some samples. Otolith processing difficulties also may have contributed to the trend. The opaque region of the otolith decreases in size with increasing age. The narrowing of the otolith region associated with older ages made precise sampling more difficult and may have resulted in accidental sampling from otolith material outside the opaque region. The sampling of otolith material from outside the opaque region may have contributed otolith material formed in cooler waters in contrast to the sampling of areas of the otolith associated with younger ages. The increasing trend in δ^{18}O was not explained solely by the decreasing temporal trend of summer water temperatures. However, an additional component of that trend may be the result of age-dependent fish movement to cooler waters that are deeper or more

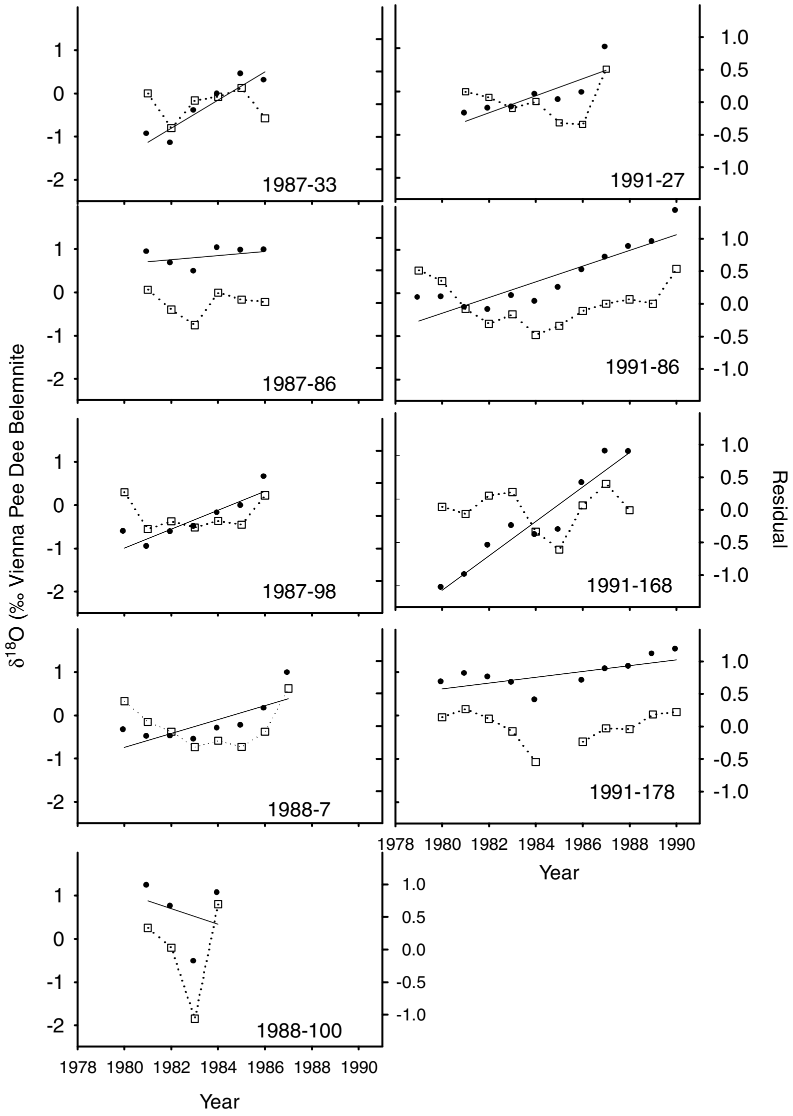

Figure 2

The time series of $\delta^{18}O$ (●, and left axis) and the linear model residuals (□, and right axis) taken from each black rockfish (*Sebastes melanops*) otolith used in the present study. The solid line is the linear model fit to the $\delta^{18}O$ data. A residual value of zero indicates perfect agreement between observed and predicted year-specific average residuals. Sample numbers corresponding to Table 1 are given inside each graph.

northerly. Furthermore, the isotope variability between fish may be due to fish inhabiting different areas in the early periods of life or to temporal differences in growth. Finally, changes in calibration of the spectrometer between assays may be a source of uncertainty.

A critical assumption behind the present study was that the lowest $\delta^{18}O$ corresponds to the warmest water temperature, and consequently the 1983 El Niño that serves as the time marker. The $\delta^{18}O$ values may be impacted by salinity in addition to water temperature (Dorval, 2004), and we assumed that salinity was constant and that the changes in $\delta^{18}O$ values were largely influenced by changes in temperature. A further confounding element to this kind of study is the ability of fish to move and potentially select microhabitats with different temperatures than that of the average local environment. Natural date-specific markers also must be monitored over a number of years to ensure that they remain identifiable within the otolith (Campana, 2001). We addressed this concern by selecting fish of

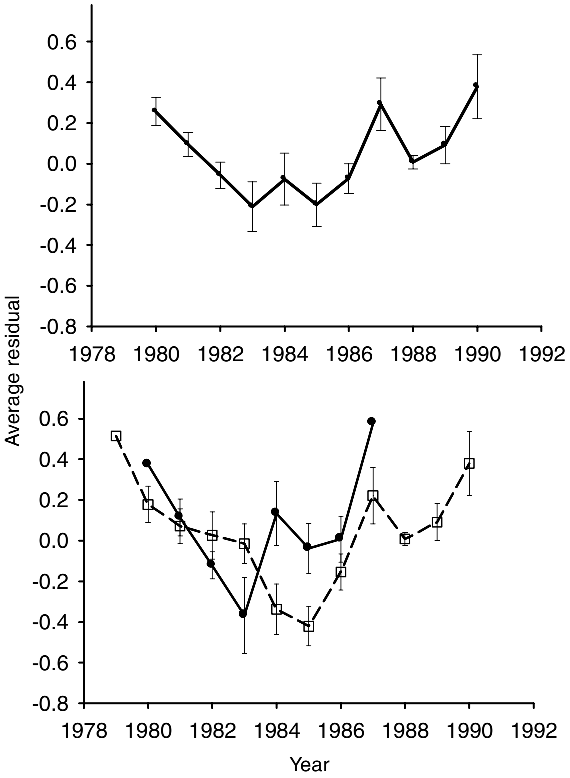

Figure 3

The year-specific average model residual from (**A**) all nine black rockfish (*Sebastes melanops*) and (**B**) ages 6–8 (●, solid line) and ages 11–12 (□, dashed line) fish. Error bars are ±1 SE.

various ages and from various collection dates and by performing the same analysis on each fish. Lastly, this method of age validation can be difficult to implement for fish with small otoliths or for long-lived fish because of the difficulties in obtaining sufficient otolith material from small growth increments.

The detection of El Niño events using $\delta^{18}O$ may allow the use of this reoccurring climatic event as a natural tag for age validation. Because previous studies that used El Niño events as time markers were forced to measure biological reactions to environmental changes, the use of $\delta^{18}O$ may be an improvement because it avoids assuming the intermediate step, namely that environment affects a biological process. The results from this study, however, were based on a small sample size and are, therefore, only preliminary. Further work in this area is warranted.

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