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Identification of riverine, estuarine, and coastal contingents of Hudson River striped bass based upon otolith elemental fingerprints

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ABSTRACT: Elemental fingerprints of otoliths from Hudson River striped bass *Morone saxatilis* were used to define resident, estuarine, and ocean migratory contingents, which had previously been determined by otolith microprobe analysis of Sr:Ca. Using solution-based inductively coupled plasma mass-spectrometry, 7 metals were quantified in whole otoliths. Discriminant analysis of elements showed a high degree of separation among the 3 migratory contingents. Barium was significantly higher in otoliths from the freshwater resident group, while Sr and Na were significantly lower in comparison to mesohaline and ocean contingents. Identification of contingents by the bulk chemistry method indicated that divergent migratory patterns persist over lifetimes for Hudson River striped bass.

KEY WORDS: Hudson River · Striped bass · Anadromy · Migration · Otolith microchemistry · Strontium · Elemental fingerprint

INTRODUCTION

Patterns of migrations in coastal and estuarine fishes are known to be variable at individual and sub-population levels (Leggett 1984, Wroblewski et al. 1994). Migrations within populations are affected by changes in population abundance, climate, flow regimes, and degradation of migration corridors (Leggett 1977). Variable migrations result in differential vulnerability to exploitation and habitat degradation (Kohlenstein 1981, Limburg & Schmidt 1990, Rose & Leggett 1991 Frank 1992, Fogarty 1998, Zlokovitz & Secor 1999). Measuring migration variability within populations is complex because methodologies (e.g. tag-recapture, telemetry, hydroacoustics, biochemical markers) are usually applied at the population level and are rarely applied at the temporal and spatial scales necessary to evaluate variability in seasonal and lifetime migrations (Secor & Rooker 2000).

The striped bass *Morone saxatilis* is a relatively long-lived teleost (ca 30 yr: Secor et al. 1995b), with populations historically ranging between the St. Lawrence River and Gulf of Mexico in North America. The Hudson River population of striped bass is 1 of 2 principal populations contributing to coastal fisheries in the US (Wirgin et al. 1993). The population is facultatively anadromous, showing high variability in the degree to which individuals will undertake coastal migrations. Based upon early tagging studies, Clark (1968) proposed the existence of migratory 'contingents' of sub-population aggregates that share common migratory

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histories. This explanation for seasonal and spatial variations in tag-recaptures was criticized because tagged striped bass could not be confidently differentiated from Chesapeake Bay striped bass, the other major contributor to coastal stocks (Waldman et al. 1990). Also, biases in sampling intensity occurred over spatial and temporal scales, compromising interpretations. More recent population-level explanations of Hudson River striped bass migratory patterns specify size- and sex-specific rates of coastal emigration applied to the entire population (McLaren et al. 1981, Waldman et al. 1990, Dorazio et al. 1994, Secor & Piccoli 1996).

Clark's contingent hypothesis was revisited by Zlokovitz & Secor (1999), who used microprobe analysis of otolith Sr to explore ontogenetic patterns of migration and habitat use. Otolith Sr serves as a tracer of salinity encountered by striped bass (Secor et al. 1995a), and thus microprobe of Sr across annuli within the microstructure of otoliths can be used to reconstruct lifetime history of habitat use along a salinity gradient (Secor & Piccoli 1996). Otolith Sr:Ca analysis revealed 3 migratory groups for Hudson River striped bass (Fig. 1): (1) a resident group, inhabiting freshwater and oligohaline regions of the Hudson River; (2) a lower estuary 'mesohaline' group, inhabiting mesohaline and polyhaline regions (New York City Harbor region and Long Island Sound); (3) an ocean migratory group, which periodically inhabited marine regions.

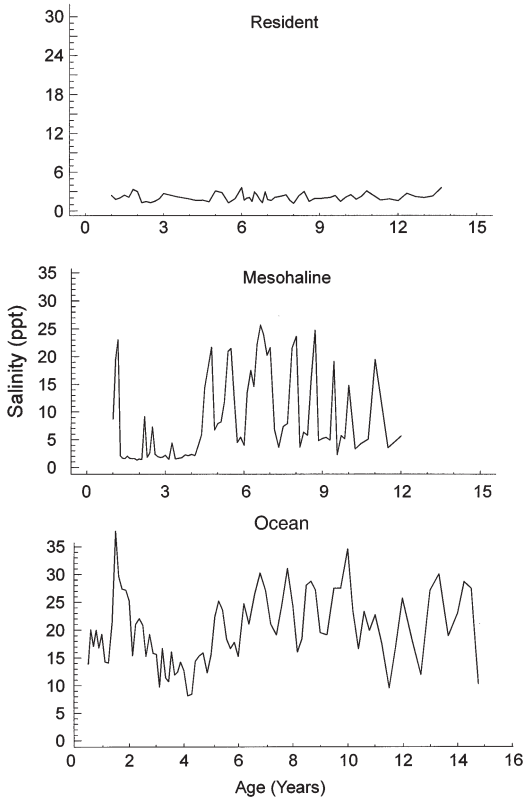

Fig. 1. *Morone saxatilis.* Representative lifetime salinity chronologies for Hudson River striped bass. Chronologies were constructed from WDS (X-ray wave length dispersive spectrometry) otolith microanalysis of Sr:Ca (Secor et el. 1995a). Migratory classifications (resident, mesohaline or ocean) are indicated

While otolith Sr is an important scalar of variable migrations by Hudson River striped bass (Secor & Piccoli 1996), otoliths contain other elements, which might record more subtle environmental gradients (Thorrold et al. 1997), and thereby more precisely define migratory contingents. Elemental fingerprints have been used as a means to identify natal source and evaluate migration patterns for several coastal species (Edmonds et al. 1989, 1991, 1992, Campana et al. 1994, 1995, Thresher et al. 1994, Secor & Zdanowicz 1998). The purpose of this paper is to use otolith elemental fingerprints to examine migratory groups of Hudson River striped bass. Corroboration between approaches is first addressed by comparing otolith Sr measured by microprobe (X-ray wave-length dispersive spectrometry [WDS]) and bulk chemistry (solution-based inductively coupled plasma mass spectrometry [ICPMS] and atomic absorption spectrophotometry (AAs). Then, otolith composition is contrasted among contingents to evaluate which elements, other than Sr, are useful indicators of freshwater, estuarine and marine habitation.

METHODS

Collections. Striped bass *Morone saxatilis* were collected during August to December 1994 using a beach-haul seine (100 m long × 3 m deep); some fish from coastal sites were also provided by recreational anglers. Adult females (n = 7) and males (n = 14) were sampled from the Troy Dam region (246 km from the river's mouth [river km 246]), Catskill (river km 162), Poughkeepsie (river km 125), Haverstraw Bay (river km 60), Tappan Zee (river km 40), New York Harbor, and Long Island Sound (Table 1, Fig. 2). According to laboratory protocols for ageing fish, sagittal otoliths were removed, cleaned with 10% bleach solution, dried and stored (Secor et al. 1995b). Right otoliths were later prepared for WDS analysis (see Secor & Piccoli 1996 for methods), left otoliths were retained for ICPMS analysis.

WDS classification of contingents. Otolith microprobe analysis of Sr and Ca was performed by X-ray WDS using a JEOL JXA-840A microprobe (Center for Microanalysis, University of Maryland, College Park, Maryland). Measurement of Sr and Ca was calibrated using Strontianite ($SrCO_3$) and calcite ($CaCO_3$) standards (Secor 1992). The detection limit was 300 ppm

Table 1. *Morone saxatilis*. Hudson River sample used for ICPMS (solution-based inductively coupled plasma mass spectrometry) analysis. Classification of contingents was based upon inspection of individual salinity chronologies and life-salinity statistics. Sr:Ca ratio and lifetime salinity (±SE) determined as mean of all Sr:Ca or salinity (estimated from Eq. 1) records for an individual. Means are presented for each classification. For Sr:Ca ratio and lifetime salinity, standard errors are reported for group means. TL = total length (mm); F = female; M = male

Classification TL (mm)	Sex	Age (yr)	Capture month (1994)	Capture site	Sr:Ca ratio (10^3)	Lifetime salinity (ppt)
Ocean						
686	F	10	Oct	New York Harbor	3.17	27.8 ± 9.2
696	F	8	Oct	New York Harbor	3.00	25.3 ± 5.8
840	F	13	Oct	New York Harbor	3.00	25.6 ± 4.6
945	F	14	Oct	Long Island	3.03	25.9 ± 8.2
Mean	792				3.05	26.1 ± 7.0
Mesohaline						
559	F	4	Oct	New York Harbor	2.63	19.9 ± 5.0
1007	F	15	Oct	New York Harbor	2.64	20.1 ± 5.9
521	M	5	Apr	Haverstraw Bay	2.32	15.4 ± 4.1
574	M	4	Apr	Poughkeepsie	2.47	17.5 ± 5.6
611	M	5	Dec	Haverstraw Bay	2.22	13.9 ± 7.1
690	M	6	Apr	Tappan Zee	2.65	20.1 ± 6.6
718	M	7	Oct	New York Harbor	2.39	16.3 ± 7.4
772	M	14	Nov	Haverstraw Bay	2.19	13.4 ± 7.7
Mean	681				2.44	17.1 ± 6.2
Resident						
950	F	14	Aug	Troy	0.99	3.0 ± 1.9
502	M	6	Oct	Troy	0.6	1.7 ± 1.1
528	M	8	Aug	Troy	0.49	1.5 ± 1.3
534	M	10	Nov	Haverstraw Bay	0.82	2.4 ± 3.8
538	M	8	Jun	Troy	0.45	1.4 ± 0.6
541	M	8	Oct	Troy	0.66	1.9 ± 1.6
570	M	6	Aug	Troy	0.59	1.7 ± 0.9
600	M	16	May	Catskill	0.88	2.6 ± 2.7
685	M	13	Oct	Troy	0.71	2.0 ± 0.7
Mean	605				0.69	2.0 ± 1.6

for Sr. A series of point measurements of Sr and Ca were taken across similar transects of the otolith microstructure. Each point was approximately 5 µm in diameter and approximately 1 µm deep. Intervals between points ranged between 13 and 25 µm. To minimize effects of instrumental variability between runs, Sr was expressed as a ratio (Sr:Ca). Point measurements were related to the annulus or interannular material they sampled. Chronologies based upon Sr:Ca were compiled for each specimen using a logistic relationship between salinity and otolith Sr:Ca based upon laboratory and field experiments (Secor et al. 1995a):

$$\text{Salinity habitation (ppt)} = 40.3\,(1 + 56.3e^{-1523(\text{Sr:Ca})})^{-1} \quad (1)$$

This model was used to convert Sr:Ca ratios to salinity habitation. Salinity chronologies were then constructed for each individual (Fig. 1). Contingents of striped bass were initially classified on the basis of visual inspection of salinity chronologies (Zlokovitz & Secor 1999). Mean lifetime salinity (the mean of all salinity records from transect points for an individual) corroborated these classifications (Table 1).

Lifetime Sr means computed from WDS measures were compared with Sr levels obtained from whole-otolith analysis of Sr by ICPMS. Because lifetime Sr means integrate over entire life histories, it was assumed they represent a similar temporal scale to that represented by the bulk composition of the whole otolith obtained by ICPMS analysis.

ICPMS analysis of whole otoliths. In the laboratory, left otoliths were carefully decontaminated. All reagents used were ultrapure grade and all implements and containers were cleaned with dilute nitric acid (HNO_3) and rinsed with 18 mega-ohm doubly deionized water ($DDIH_2O$). Before analysis, otoliths were carefully decontaminated. First, they were soaked in $DDIH_2O$ to hydrate biological residue adhering to the surface of the sample; this residue was removed using fine-tipped forceps. Next, the otoliths were soaked in 3% hydrogen peroxide for 5 min to dissolve any re-

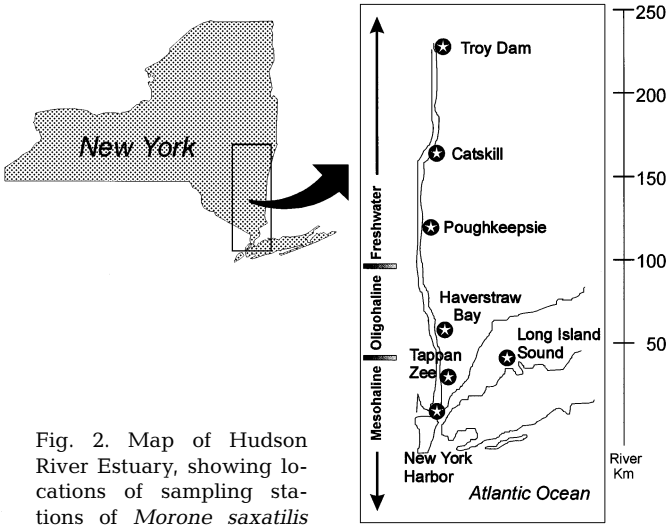

Fig. 2. Map of Hudson River Estuary, showing locations of sampling stations of *Morone saxatilis*

maining biological residue. They were then immersed for 5 min in 1% nitric acid to remove surface contamination, and then flooded with $DDIH_2O$ for 5 min to remove the acid. Finally, they were dried under a Class 100 laminar flow hood and stored in plastic vials. Otolith mass was consistently reduced by approximately 4% as a result of the decontamination procedure. In preparation for instrumental analysis, each otolith was weighed to the nearest 0.01 mg and placed in a plastic centrifuge tube. They were digested in concentrated nitric acid. Quantities of acid used and volumes of the digests were proportional to sample weights to insure that all resulting solutions were of similar composition in order to minimize possible matrix effects that might complicate instrumental analysis. The digests were diluted with $DDIH_2O$ to a final acid concentration of 1% HNO_3. Internal standards were added to all solutions to compensate for possible instrument drift.

Elemental concentrations (except Na and K) were determined using a Perkin-Elmer ELAN 5000 quadrupole inductively coupled plasma mass spectrometer (QICPMS). Levels of Mg, Mn and Ba were quantified using the method of standard additions; levels of Ca and Sr were determined using external calibration standards. Concentrations of Na and K were measured by atomic absorption spectrophotometry (AAS) using a Perkin-Elmer Model 3300 AA spectrophotometer. Samples were analyzed in random order to avoid possible sequence effects. Procedural blanks and a standard reference material (SRM) were concurrently digested and analyzed following the same procedures. The SRM was NIST 915a (calcium carbonate clinical standard), obtained through the National Institute of Standards and Technology (Gaithersburg, Maryland, USA), and was used to estimate the recovery, precision and accuracy of the method. This SRM is not certified for trace-metal content, so only non-certified values are available for a few elements. Relevant values are (µg g^{-1} dry weight; Ca in %): Mg, 1.0; Ca, 40.0; and Mn, 0.6. Our results (means ± SD, n = 3) were: Mg, 1.04 ± 0.05; Ca, 39.6 ± 0.6; and Mn, 0.62 ± 0.06. Samples of an otolith certified reference material (CRM) (Yoshinaga et al. 2000) produced at the National Institute of Environmental Studies (NIES) of Japan have been analyzed on several occasions, although not concurrently with these samples, using this method. Certified values for the CRM are (µg g^{-1} dry weight; Ca in %): Na, 2230 ± 100; Mg, 21 ± 1; K, 282 ± 8; Ca, 38.8 ± 0.5; Sr, 2360 ± 50; and Ba, 2.89 ± 0.09. Our results were (Avg ± SD, n = 18): Na, 2380 ± 103; Mg, 21.1 ± 2.5; K, 334 ± 21; Ca, 37.6 ± 1.8; Sr, 2240 ± 124; and Ba, 2.84 ± 0.53.

We used a much more rigorous approach to decontaminate otoliths than in previous studies, because we believed that there was a high likelihood of contamination from otolith removal, handling, and storage procedures (Milton & Chenery 1998, Proctor & Thresher 1998, Thresher 1999). Acid immersion resulted in a mass loss of 4 to 5%, lost independent of otolith mass or fish size. Due to the loss of mass, compositional changes might also occur. However, comparison of 2 sets of paired otoliths, one acid-rinsed and the other untreated, showed <5% difference in concentrations of Ca, Sr and Ba; 5 to 10% differences were observed for Mg and Mn; Na showed a 12% apparent loss in concentration associated with the acid treatment (Fig. 3). Low variances for each element indicated that effect of the acid treatment was consistent among ele-

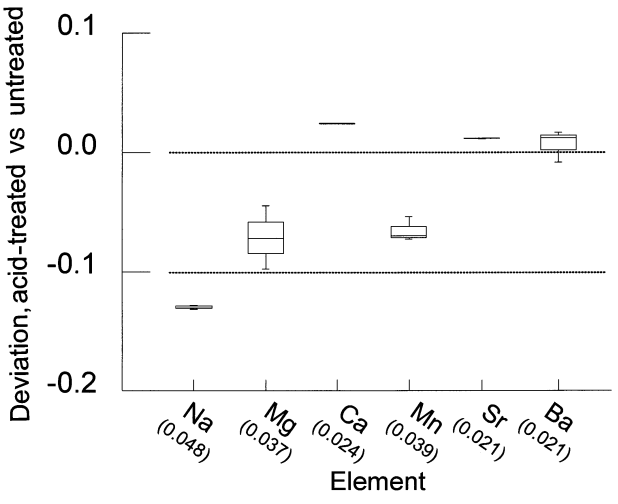

Fig. 3. *Morone saxatilis.* Deviation (absolute difference/mean of elemental concentrations of paired otoliths) between acid-treated and untreated otolith pairs (n = 3) for elements Na, Mg, Ca, Mn, Sr, and Ba. Below each element (in parentheses) are control deviations between right and left paired otoliths for a separate set of fish that were both left untreated

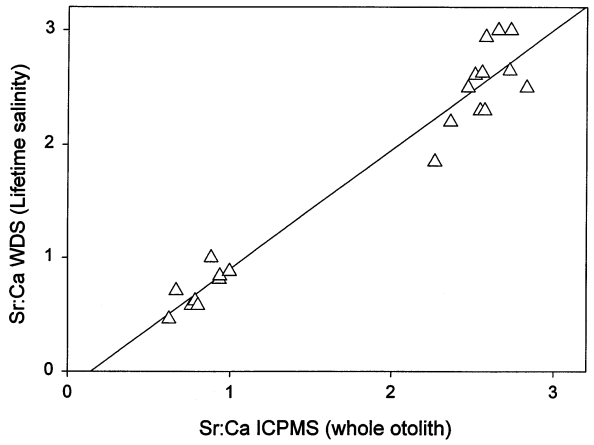

Fig. 4. *Morone saxatilis.* Linear relationship between WDS Sr:Ca (10^{-3}) ratio (life history transect) and ICPMS Sr:Ca (10^{-3}) ratio (bulk composition of whole otolith) of individual striped bass. Left and right sagittal otoliths from individual striped bass were used for ICPMS and WDS analyses, respectively

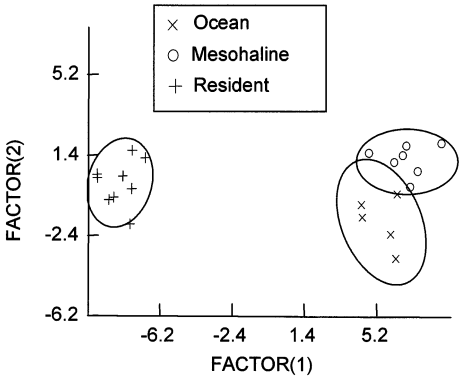

Fig. 5. *Morone saxatilis.* Canonical variable plot of migratory contingents from discriminant analysis. 95% confidence ellipses of each group are given

ments. Campana et al. (2000) found no significant differences between acid rinsed and un-rinsed cod *Gadus morhua* otolith pairs for tested elements Li, Mg, Mn, Sr, and Ba. A more comprehensive study on handling and cleaning effects on Atlantic tunas *Thunnus* spp. (Rooker et al. unpubl.) showed that the decontamination procedure was effective in removing Mg, Mn, and Ba in deliberately contaminated otoliths (only these 3 elements were tested), without affecting the original composition of the otolith.

Element concentrations were used in a discriminant analysis employing the WDS-designated groupings as a factor. Because otolith mass did not vary significantly among migratory groups ($p = 0.23$), no corrections were made for mass effects on elemental concentrations. Discriminant analysis tested for multivariate differences among the 3 migratory classifications. The relative importance of individual elements in discriminating among groups was assessed by using *F*-statistics estimated by the discriminant-analysis procedure. Cross-correlation of individual elements was evaluated using tolerance (Wilkinson 1996), which is inversely related to the correlation of the individual element to others in the multivariate analysis. Thus, a high tolerance indicates independence in the contribution of that element to the model. Principal component analysis was used to evaluate affinity among elements. Individual element concentrations were contrasted among migratory groups using analysis of variance (ANOVA). To meet assumptions of normality, natural logarithms of elemental concentrations were used in univariate contrasts.

RESULTS

The measures of lifetime Sr for *Morone saxatilis* were positively and strongly correlated between the ICPMS and WDS methods: WDS Sr:Ca = −0.150 + 1.051 ICPMS Sr:Ca ($r^2 = 0.95$; $n = 21$) (Fig. 4). The slope of WDS on ICPMS Sr (1.05) was not significantly different than the expected slope of unity ($p > 0.05$).

Discriminant analysis using Na, Mg, K, Ca, Mn, Sr and Ba showed clear separation of resident, mesohaline, and ocean contingents (Fig. 5). Strontium was the single largest contributing element to the multivariate analysis, but Ca, Mn and Ba were also influential (*F*-statistic, Table 2). Tolerance statistics indicated that Sr, Mg, and Ba showed the highest degree of independence in their individual contributions to the multivariate analysis. Group membership was correctly assigned (100%) by a classification matrix. A jack-knifed classification matrix (group assignment excluded case being classified) performed similarly for the resident group, but poorly distinguished between mesohaline

Table 2. *Morone saxatilis*. Summary of discriminant analysis of otolith elemental concentrations among the 3 contingents from the Hudson River Estuary. *F*-statistic indicates the relative importance of the element in model; tolerance measures the correlation of elements in the model (range: 0.0 = high correlation, 1.0 = low correlation)

Element	*F*-statistic	Tolerance
Na	7.01	0.11
Mg	0.26	0.50
K	1.40	0.31
Ca	7.23	0.15
Mn	2.69	0.19
Sr	227.84	0.50
Ba	2.04	0.45

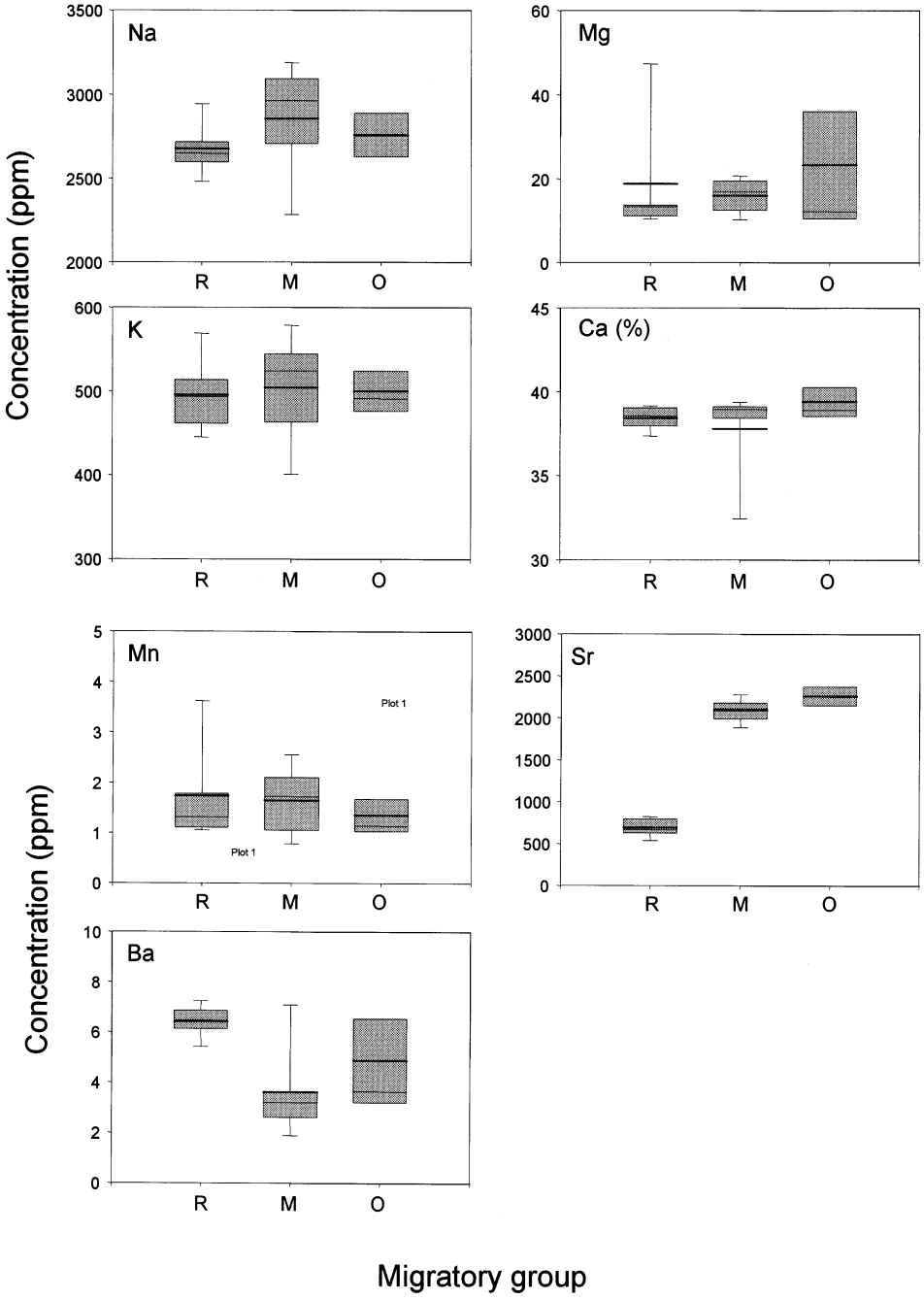

Fig. 6. *Morone saxatilis.* Element concentrations (µg g^{-1} dry otolith mass) for striped bass from the 3 contingents, R = resident, M = mesohaline, and O = ocean. Interquartile range (25th and 75th percentile) is shown by extent of boxes, with normal and boldface horizontal lines within boxes representing median (50th percentile) and mean, respectively. Error bars denote range of 10th and 90th percentiles

and ocean designations: 100, 57, and 40% of the resident, mesohaline, and ocean groups were classified correctly.

Univariate analyses showed that significant differences occurred among migratory groups for Sr and Ba. Barium was significantly higher, and Sr significantly lower (Tukey multiple-comparison test; $p < 0.05$), in resident fish (Fig. 6). In addition, the ocean contingent tended to have slightly higher Ca levels than the other 2 contingents.

DISCUSSION

Elemental fingerprints determined by bulk chemical analysis correctly identified contingents of striped bass *Morone saxatilis* previously classified through otolith microprobe analysis of Sr:Ca by WDS. Discriminant function analysis showed no misclassifications among contingents. A more robust approach, the jack-knifed classification procedure, resulted in a higher degree of misclassification of mesohaline and ocean classes. Therefore, definitive discriminant functions for the 3 contingents should be based upon a larger sample containing more individuals classified by WDS as mesohaline and ocean.

Corroboration between the WDS and ICPMS methods demonstrated that groups of Hudson River striped bass have unique lifetime patterns of habitat use. Each method has attendant strengths and limitations. WDS analysis has superb spatial resolution with which to estimate temporal patterns of habitat use. However, the number of elements that can be measured is limited to those which occur at concentrations greater than ca 100 ppm (Campana et al. 1997). Alternatively, solution-based ICPMS analysis of otoliths has much greater sensitivity (<1 ppm) but cannot resolve seasonal or ontogenetic patterns of habitat use and migration.

Consistency between WDS and ICPMS measurements was directly compared for Sr. A higher level of agreement (95%) occurred for paired measures of Sr than reported in the inter-laboratory comparison exercise conducted by Campana et al. (1997). In that study, concentrations of Sr in Atlantic croaker *Micropogonias undulatus* otoliths showed much lower correlation (8 to 28%) between WDS and ICPMS methods. In a separate test, a measurement of enhanced concentrations of Sr in artificial beads composed of homogenized Atlantic croaker otoliths showed good agreement between Sr determinations by WDS and ICPMS otolith microprobe methods. Because WDS is sensitive to spatial heterogeneity of Sr in the specimen while ICPMS bulk analysis is not, comparisons between the methods is expected to show reduced correspondence due to nonhomogeneous distribution of Sr in the otolith's microstructure.

The rationale and empirical evidence for the use of Sr as a salinity tracer is well documented (see Secor & Rooker 2000). Associations between other elements in otoliths and ambient exposure remain poorly investigated. Fowler et al. (1995) found that Atlantic croaker reared at 26 psu salinity contained slightly lower levels of Ca and Sr than croaker reared at 35 psu. Based upon laser-ablation ICPMS analyses of juvenile Atlantic croaker otoliths, Thorrold et al. (1997) speculated that patterns in Mg, Ca, and Ba were related to ingress. They concluded that Mg and Ca were positively and Ba negatively related to salinity.

In our study, Ba concentrations were higher and Sr concentrations lower in otoliths of resident fish. One might expect to find positive correlations between salinity and Na, Mg, K, Ca, Sr and Ba, since concentrations of those elements are much higher in seawater than freshwater. While trends in Na, Ca and Sr were consistent with this expectation, differences in Ba between resident and other contingents were opposed to expected effects of salinity, and no trend was observed for Mg or K. Similar to these results, simple correlations were not observed between habitat metal concentrations and otolith metal concentrations in a recent study of the elemental composition of otoliths of Atlantic croaker collected along an estuarine pollution gradient (Hanson & Zdanowicz 1999). It is well known that metals are metabolically regulated by fishes, and that exposure to elevated levels of contaminants does not insure elevated levels of metals in finfish tissues (Hanson 1997). Thus, the relationship between otolith composition and environmental conditions is complex and appears to be governed by numerous biological and geochemical factors (Campana 1999). Much experimental work is needed to elucidate the pathways of incorporation of elements into otoliths and the effects of habitat conditions on those pathways.

Identification of contingents by the ICPMS bulk chemistry method indicated that lifetime migratory patterns exist for Hudson River striped bass. Although the sample size was low and individual migratory behaviors within groups were divergent, we were still capable of resolving discrete migratory modes. Resident behaviors shown by otolith microprobe analysis were most often attributed to males (Table 1; and Secor & Piccoli 1996). Sex-specific patterns of resident behavior are common to salmonids, where resident males typically show patterns of more rapid development and maturation than migratory males (Jonnson & Jonnson 1993). Striped bass male residents do not show the dwarf phenotype common to salmonids (Secor 1999). In addition, several resident females have been observed. Divergent patterns of resident and migratory behaviors are documented for other anadromous and coastal fishes (Jonnson & Jonnson 1993). For Atlantic cod *Gadus morhua*, Wrobleswki et al. (1994) observed a resident 'contingent' which overwintered in Trinity Bay (Newfoundland), while most other cod of the associated northern stock migrated offshore. Moreover, Beamish & McFarlane (1988) observed resident versus migratory behaviors for groups of adult sablefish *Anoplopoma fimbria* off the west coast of Canada.

Results for striped bass and documentation of migratory modes for other anadromous and coastal fishes (Beamish & McFarlane 1988, Jonnson & Jonnson 1993,

Wroblewski et al. 1994) lead us to speculate that alternate migratory behaviors may be accomplished by contingents with proclivities towards discrete migratory modes. The idea that populations are structured as spatial contingents is compatible with recent considerations on metapopulation stock structures (Pulliam 1988, Frank & Leggett 1994). However, rather than specifying that multiple reproductively isolated populations or sub-populations contribute to the dynamics of an overall metapopulation, we believe that at the population level, resiliency to exploitation and environmental change may be conferred by the maintenance of divergent life-cycle pathways (Kaitala et al. 1993, Secor 1999).

Future studies employing otolith elemental analyses will provide a unique opportunity to examine population structure according to variations in habitat use and migration behaviors. Previous studies on resident and migrant salmonids have relied on phenotypic differences between these forms (Jonnson & Jonnson 1993). For other families, phenotypic (or genotypic) differences between resident and more migratory contingents may be subtle or absent. Otolith elemental fingerprinting should permit identification of resident and migratory contingents of striped bass and other fishes so that alternate life-cycle pathways within populations can be more rigorously investigated.

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