



lake systems and 786 mainstem and tributary rivers from all continents except Antarctica. Data from closed-basin salt or alkaline lakes were not included in our analyses or figures because the extreme chemistry in these environments often precludes fish occupation and the outlier Sr:Ca values presented scaling problems in our figure. Marine water chemistry data consisted of 171 individual records from published accounts of voyages into most of the major oceans and seas of the world, low and high latitudes, from surface waters to depths of more than 5000 m, and from coral reefs in coastal areas to mid-ocean regions. Data from mid-ocean vents and black smokers were not included. In all, almost 6000 individual measurements of water Sr and Ca concentrations were compiled. Sr:Ca level and variability within and among freshwater and marine habitats were illustrated with a histogram.

The variability of Sr:Ca within individual river systems was examined and graphically compared with the marine system using box plots. Sr:Ca data from 20 rivers were examined. Ten large river drainages from several continents for which Sr:Ca data were available from many mainstem and tributary sites were selected to illustrate the Sr:Ca variability within a drainage. Ten large North American rivers for which Sr:Ca data were available for multiple years and seasons from lower-drainage, mainstem sampling sites were selected to illustrate the Sr:Ca variability within a limited reach of a drainage over a long period of time. All 171 marine Sr:Ca observations were included.

Three rivers with median Sr:Ca levels less than marine water and one river with a median Sr:Ca level greater than marine water were selected to illustrate the relationship between Sr:Ca and salinity in estuary waters. The selected rivers included the Indigirka (Sr:Ca = 2.32) and the Indus (Sr:Ca = 3.58), which had relatively low levels of dissolved solutes, and the Mississippi (Sr:Ca = 2.01) and St. Johns (Sr:Ca = 13.83), which had relatively high levels of dissolved solutes. Concentrations of Sr and Ca were modeled across an estuarine salinity gradient from 0 to 35 practical salinity units (psu) with a progressive series of complementary mixing fractions of fresh and salt water using the following equation:

$$c_a = f c_f + (1-f) c_m$$

where c_a is the concentration (mg:kg) of element in ambient estuarine water, c_f is the concentration of element in freshwater, c_m is the concentration of element in marine water, f represents dissolved Sr or Ca, and ambient salinity is < 35 , where f ranges from 0 to 1. Freshwater Sr and Ca concentrations used in this model were median values for the selected rivers. Average marine water Sr and Ca concentrations from our literature sources were 7.64 (standard deviation (SD) = 0.53) and 405.87 (SD = 27.49) mg kg⁻¹, respectively, and the mean Sr:Ca level was 8.61 mmol:mol. The variable “ f ” ranged from 0 to 1 and reflected ambient salinity as a proportion of marine salinity, which was modeled at 35 psu. End-member concentrations of Sr and Ca were used to model Sr:Ca (mmol:mol) values and were plotted against salinity.

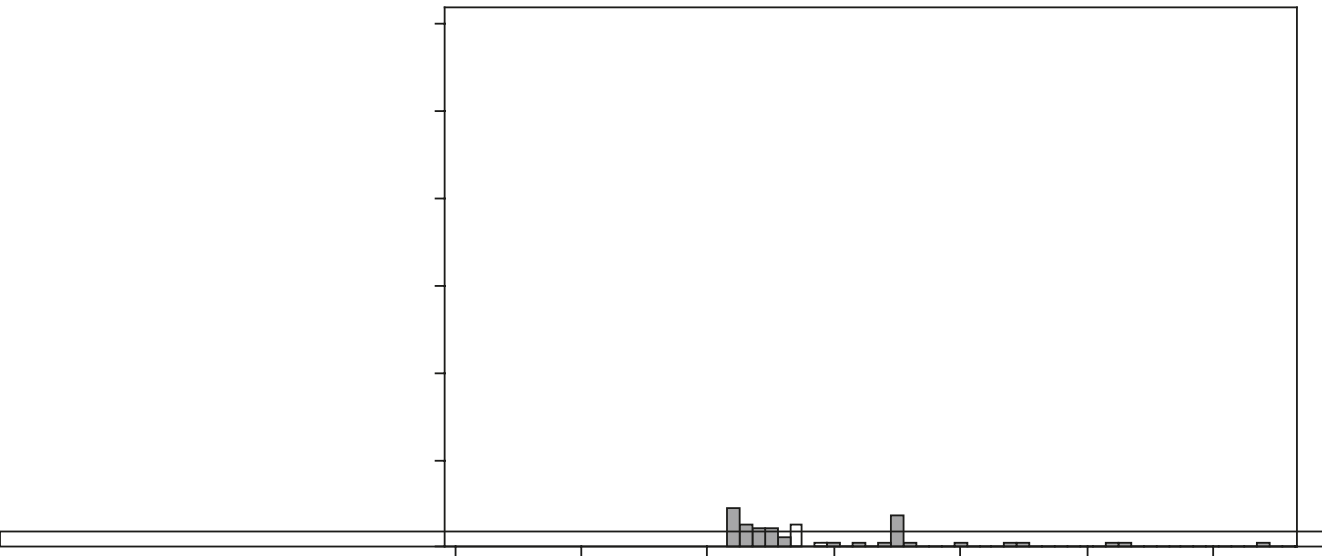
Fish otolith selection, preparation, and analysis

Otoliths from 28 freshwater, 21 diadromous, and 32 ma-

rine fish species were examined in this study (Appendix B). Taxonomy and nomenclature in this paper are consistent with Fishbase (2008). Mature-sized, wild-caught fish were used in all cases. They were collected from locations and in

tium concentration varied widely, ranging from just over our detection limit of approximately 330 mg kg^{-1} to more than 17000 mg kg^{-1} . The SEs of the Sr concentration estimates were proportionally greater near detection limits than at higher concentrations, resulting in approximately 150 mg kg^{-1} near detection limits and 300 mg kg^{-1} at the greatest concentrations (Fig. 1).

Three measures of otolith Sr and Sr:Ca variability were analyzed: () an index of the coefficient of variation (CV) of Sr X-ray count data, which is a function of each data point in a profile relative to the mean value; (



tween freshwater and marine environments (e.g., Tzeng 1996; Howland et al. 2001; Brenkman et al. 2007). General trends in otolith Sr:Ca common to each category were illustrated with a representative selection of species. Several species were represented in both freshwater and diadromous categories, and the Sr:Ca profiles of some of these pairs are presented to illustrate category-specific patterns. Several families were represented by multiple species, and Sr:Ca profiles of some of these family groups are presented to illustrate common patterns. Several additional unique or unusual otolith Sr:Ca profiles are presented and discussed.

Because the total number of sample points varied widely among otolith core-to-margin transects, profiles were created with Sr:Ca values plotted against the proportion of the core-to-margin transect for each point.

The partition coefficient for Sr was calculated as

$$D_{\text{Sr}} = \frac{\left(\frac{\text{Sr}}{\text{Ca}}\right)_{\text{otolith}}}{\left(\frac{\text{Sr}}{\text{Ca}}\right)_{\text{water}}}$$

When used in otolith chemistry studies, it is an indicator of the osmoregulatory resistance that an element encounters

when moving from the water, through the blood, into the endolymph, and eventually to a precipitation site on the otolith. Values near one indicate little resistance relative to Ca, and values approaching zero indicate high resistance (Campana 1999). Water Sr:Ca levels experienced by freshwater and diadromous species in this study were not known with

enough confidence to calculate D_{Sr} values. Marine fish, however, were considered to have experienced a relatively constant Sr:Ca environment of approximately 8.61 mmol:mol

strated with box plots and discussed. Maximum otolith Sr:Ca levels of marine species were thought to reflect their minimum osmoregulatory resistance to Sr while experiencing marine Sr:Ca levels. Distributions of maximum D_{Sr} values for marine species and for the sablefish group were illustrated with a box plot.

Results

Water chemistry

River and lake environments varied across a wider range of Sr:Ca than did marine environments (Fig. 2). Median river (2.39) and lake (1.92) Sr:Ca levels were much lower than the marine level (8.61). Sr:Ca levels ranged from 0.27 to 19.18 in rivers, 0.20 to 5.02 in lakes, and 8.17 to 8.87 in marine water. Less than 3% of the 786 rivers reviewed here,

and none of the lakes, had median Sr:Ca levels that exceeded minimum marine levels. Sr:Ca variability within entire drainages was clearly greater than in limited reaches of drainages (Fig. 3), and marine waters were comparatively invariable.

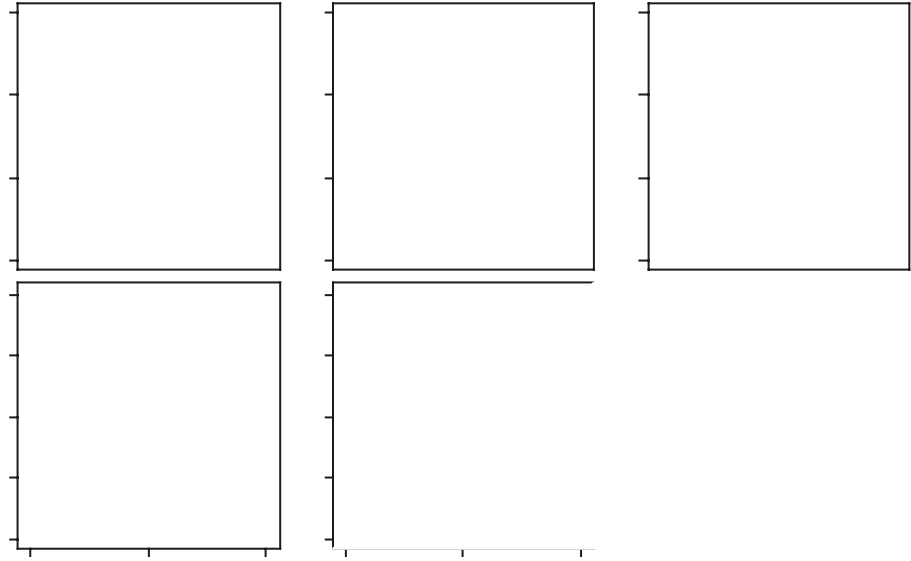
Mixing curves modeled across the estuarine salinity gradients from the four selected rivers revealed a high rate of Sr:Ca change at low salinity levels that declined exponentially as salinity increased (Fig. 4). Surge and Lohmann (2002) derived this same pattern empirically across three estuaries in Florida, and Zimmerman (2005) measured it in his experimental Sr:Ca habitats as well. Rivers with lower

Johns River, one of the rare rivers with Sr:Ca levels greater than marine levels, declined to the marine Sr:Ca level, whereas the other rivers rose to the marine level. These data indicate that diadromous fish moving through an estuary would experience greater Sr:Ca change between salinities 0 and 10, when they are hypertonic to the environment, than between salinities 10 and 35, as they become hypotonic to the environment.

Sr:Ca profiles

Sr:Ca profiles of pairs of freshwater and anadromous conspecifics revealed a visually distinctive pattern of Sr:Ca var-

Fig. 10a) and European eel (*A. anguilla*; Fig. 10b), revealed high levels of Sr:Ca in the core regions of their otoliths, consistent with their marine origins, followed by precipitous declines in Sr:Ca to low levels, consistent with their migrations into freshwater environments. Atlantic tarpon are not obligated to migrate into freshwater environ-



D_{Sr}

Substantial variability of D_{Sr} values was evident within individual otoliths of marine species, as well as among species (Fig. 11). Maximum D_{Sr} for marine species ranged from 0.20 for the fourspot herring (*e t c t . a d a c a t*) to 1.62 for the stout eelblenny. Maximum D_{Sr} for the sablefish species group ranged from 0.44 to 0.98, well within the range for the marine species group. The average level of the statistic was 0.54 for the marine species group and 0.66 for the sablefish group. Otolith Sr:Ca levels greater than 8.61 in marine species produce D_{Sr} greater than 1, indicating that Sr concentration is being enhanced in the endolymph relative to marine Sr:Ca levels or that Ca movement

not identified because we almost always interpret otolith Sr:Ca variation in diadromous species as an indication of migration between freshwater, estuarine, and marine environments (Howland et al. 2001; Arai et al. 2003; Yang et al. 2006). Despite this possibility, most scientists are comfortable interpreting the migration histories of freshwater and diadromous species based on their Sr:Ca profiles. The distinct patterns observed in the Sr:Ca profiles of marine

- Otolith chemistry reflects migratory characteristics of Pacific salmonids: using otolith core chemistry to distinguish maternal associations with sea and freshwaters. *Fish. Res.* **46**(1–3): 251–266. doi:10.1016/S0165-7836(00)00150-8.
- Yang, J., Arai, T., Liu, H., Miyazaki, N., and Tsukamoto, K. 2006. Reconstructing habitat use of *C. a. t.* and *C. a. e. e.* of the Yangtze River estuary, and of *C. a. e. e.* of Taihu Lake, based on otolith strontium and calcium. *J. Fish Biol.* **69**(4): 1120–1135. doi:10.1111/j.1095-8649.2006.01186.x.
- Zimmerman, C.E. 2005. Relationship of otolith strontium-to-calcium ratios to salinity: experimental validation for juvenile salmonids. *Can. J. Fish. Aquat. Sci.* **62**(1): 88–97. doi:10.1139/f04-182.
- Zimmerman, C.E., and Reeves, G.H. 2000. Population structure of sympatric anadromous and nonanadromous *O. c. c.*: evidence from spawning surveys and otolith microchemistry. *Can. J. Fish. Aquat. Sci.* **57**(10): 2152–2162. doi:10.1139/cjfas-57-10-2152.

Appendix A

Table A1. Literature sources of water chemistry data, habitat types, and geographic regions examined.

| Citation | Habitat | Geographic region |
|-----------------------------|-------------------------|-----------------------------------|
| Alexander et al. 2001 | River | Australia |
| Andersson et al. 1994 | River | Europe |
| Blum et al. 1994 | River | North America |
| Cameron et al. 1995 | River | North America |
| Culkin and Cox 1966 | Marine | Oceans worldwide |
| Dalai et al. 2003 | River | Asia |
| Dessert et al. 2001 | River | Asia |
| de Villiers 1999 | Marine | Atlantic and Pacific oceans |
| de Villiers et al. 1994 | Marine | Atlantic and Pacific oceans |
| Edmond et al. 1995 | River | South America |
| Edmond et al. 1996 | River | South America |
| Fabricand et al. 1967 | Marine | Atlantic Ocean |
| Faure et al. 1967 | Marine, river, and lake | North America and Atlantic Ocean |
| Gaillardet et al. 1997 | River | South America |
| Gislason et al. 1996 | River | Iceland |
| Goldstein and Jacobsen 1987 | River and lake | Worldwide |
| Han and Liu 2004 | River | Asia |
| Huh and Edmond 1999 | River | Asia |
| Huh et al. 1998a | River | Asia |
| Huh et al. 1998b | River | Asia |
| Karim and Veizer 2000 | River | Asia |
| Katz et al. 1977 | River | Middle East |
| Krishnaswami et al. 1992 | River | Asia |
| Livingston 1963 | River and lake | North America and Europe |
| Martin and Meybeck 1979 | River | Worldwide |
| Millot et al. 2003 | River | North America |
| Moon et al. 2007 | River | Asia |
| Negrel et al. 1993 | River | Africa |
| Odum 1957 | River and lake | North America and Pacific Islands |
| Pande et al. 1994 | River and lake | Asia |
| Petelet et al. 1998 | River | Europe |
| Qin et al. 2006 | River | Asia |
| Reeder et al. 1972 | River and lake | North America |
| Trivedi et al. 1995 | River | Asia |
| USGS 2007 | River | North America |
| Viers et al. 2000 | River | Africa |
| Wadleigh et al. 1985 | River | North America |
| Wu et al. 2005 | River and lake | Asia |
| Xu and Liu 2007 | River | Asia |
| Yang et al. 1996 | River and lake | North America |

References

- Alexander, J., Fielding, C.R., Wakefield, S.J., George, M.T., and Cottnam, C.F. 2001. Fluvial geochemistry through a short-duration, tropical-cyclone induced discharge event in the Burdekin River and Hann Creek, North Queensland, Australia. *Aquat. Geochem.* **7**(4): 275–293. doi:10.1023/A:1015203127320.
- Andersson, P.S., Wasserburg, G.J., Ingri, J., and Stordal, M.C. 1994. Strontium, dissolved and particulate loads in fresh and brackish waters: the Baltic Sea and Mississippi Delta. *Earth Pla-*

- net. *Sci. Lett.* **124**(1–4): 195–210. doi:10.1016/0012-821X(94)00062-X.
- Blum, J.D., Erel, Y., and Brown, K. 1994. $^{87}\text{Sr}/^{86}\text{Sr}$ ratios of Sierra Nevada stream waters: implications for relative mineral weathering rates. *Geochim. Cosmochim. Acta*, **58**: 5019–5025.
- Cameron, E.M., Hall, G.E.M., Veizer, J., and Krouse, H.R. 1995. Isotopic and elemental hydrogeochemistry of a major river system: Fraser River, British Columbia, Canada. *Chem. Geol.* **122**(1–4): 149–169. doi:10.1016/0009-2541(95)00007-9.
- Culkin, F., and Cox, R.A. 1966. Sodium, potassium, magnesium, calcium and strontium in sea water. *Deep-Sea Res.* **13**: 789–804.
- Dalai, T.K., Krishnaswami, S., and Kumar, A. 2003. Sr and $^{87}\text{Sr}/^{86}\text{Sr}$ in the Yamuna River system in the Himalaya: sources, fluxes, and controls on Sr isotope composition. *Geochim. Cosmochim. Acta*, **67**(16): 2931–2948. doi:10.1016/S0016-7037(03)00203-5.
- Dessert, C., Dupre, B., Francois, L.M., Schott, J., Gaillardet, J., Chakrapani, G., and Bajpai, S. 2001. Erosion of Deccan Traps determined by river geochemistry: impact on the global climate and the $^{87}\text{Sr}/^{86}\text{Sr}$ ratio of seawater. *Earth Planet. Sci. Lett.* **188**(3–4): 459–474. doi:10.1016/S0012-821X(01)00317-X.
- de Villiers, S. 1999. Seawater strontium and Sr/Ca variability in the Atlantic and Pacific oceans. *Earth Planet. Sci. Lett.* **171**(4): 623–634. doi:10.1016/S0012-821X(99)00174-0.
- de Villiers, S., Shen, G.T., and Nelson, B.K. 1994. The Sr/Ca–temperature relationship in coralline aragonite: influence of variability in $(\text{Sr}/\text{Ca})_{\text{seawater}}$ and skeletal growth parameters. *Geochim. Cosmochim. Acta*, **58**: 197–208. doi:10.1016/0016-7037(94)90457-X.
- Edmond, J.M., Palmer, M.R., Measures, C.I., Grant, B., and Stallard, R.F. 1995. The fluvial geochemistry and denudation rate of the Guayana Shield in Venezuela, Colombia, and Brazil. *Geochim. Cosmochim. Acta*, **59**(16): 3301–3325. doi:10.1016/0016-7037(95)00128-M.
- Edmond, J.M., Palmer, M.R., Measures, C.I., Brown, E.T., and Huh, Y. 1996. Fluvial geochemistry of the eastern slope of the

Geochim. Cosmochim. Acta, **36**(8): 825–865. doi:10.1016/0016-7037(72)90053-1.

Trivedi, J.R., Pande, K., Krishnaswami, S., and Sarin, M.M. 1995.
St isotopes in rivers of India and Pakistan: a reconnaissance

Table B1. Freshwater, diadromous, and marine fish species examined in this study ordered by family and common name.

| Freshwater | | Diadromous | | Marine | |
|------------------------|-------------------------------|------------------------|---------------------------------|-------------------------|---------------------------------|
| Common name | Species | Common name | Species | Common name | Species |
| Longnose sucker | <i>Catostomus commersoni</i> | European eel | <i>Anguilla anguilla</i> | Sablefish | <i>Anchoa mitchilli</i> |
| Black crappie | <i>Pomoxis nigromaculatus</i> | Barramundi | <i>Lateolabrax orientalis</i> | Chihuil | <i>Baetis alpestris</i> |
| Green sunfish | <i>Lepomis microlophus</i> | American shad | <i>Alosa sapidissima</i> | Fourspot herring | <i>Urophycis regia</i> |
| Smallmouth bass | <i>Micropterus dolomieu</i> | Blueback herring | <i>Alosa aestivalis</i> | Pacific herring | <i>Clupea pallasii</i> |
| Prickly sculpin | <i>Cottus bairdii</i> | Hickory shad | <i>Alosa edulis</i> | Antlered sculpin | <i>Esox niger</i> |
| Slimy sculpin | <i>Cottus cognatus</i> | Atlantic tarpon | <i>Leiostomus xanthurus</i> | Arctic staghorn sculpin | <i>Urophycis cirrata</i> |
| Lake chub | <i>Chesteria bicolor</i> | Ninespine stickleback | <i>Pungitius pungitius</i> | Fourhorn sculpin | <i>Urophycis adspersa</i> |
| Northern pike | <i>Esox lucius</i> | Threespine stickleback | <i>Gasterosteus aculeatus</i> | Giant wrymouth | <i>Cottus taca</i> |
| Burbot | <i>Lota lota</i> | Striped bass | <i>Morone saxatilis</i> | Pacific ladyfish | <i>Esox pacificus</i> |
| Threespine stickleback | <i>Gasterosteus aculeatus</i> | Rainbow smelt | <i>Osmerus mordax</i> | Arctic cod | <i>Boreogadus saida</i> |
| Channel catfish | <i>Ictalurus punctatus</i> | Arctic cisco | <i>Coregonus artedii</i> | Pacific cod | <i>Gadus macrocephalus</i> |
| Striped bass | <i>Morone saxatilis</i> | Bering cisco | <i>Coregonus alpinus</i> | Saffron cod | <i>Eleginus gracilis</i> |
| Yellow perch | <i>Perca flavescens</i> | Broad whitefish | <i>Coregonus nasus</i> | Greybar grunt | <i>Acanthaluteres fulvus</i> |
| Trout-perch | <i>Percina variegata</i> | Chinook salmon | <i>Oncorhynchus tshawytscha</i> | Grass emperor | <i>Etropus perca</i> |
| Arctic char | <i>Salvelinus alpinus</i> | Coho salmon | <i>Oncorhynchus kisutch</i> | Pacific red snapper | <i>Lutjanus fulviflamma</i> |
| Arctic grayling | <i>Thymallus arcticus</i> | Dolly Varden | <i>Salvelinus malma</i> | Whitson's grenadier | <i>Macrurus whitsoni</i> |
| Broad whitefish | <i>Coregonus nasus</i> | Humpback whitefish | <i>Coregonus hoyi</i> | Antarctic toothfish | <i>Dissostichus mawsoni</i> |
| Dolly Varden | <i>Salvelinus malma</i> | Inconnu | <i>Stenodus leucichthys</i> | Patagonian toothfish | <i>Dissostichus eleginoides</i> |
| Humpback whitefish | <i>Coregonus hoyi</i> | Least cisco | <i>Coregonus adaei</i> | Arctic flounder | <i>Paralichthys arctica</i> |
| Inconnu | <i>Stenodus leucichthys</i> | Sockeye salmon | <i>Oncorhynchus nerka</i> | Bering flounder | <i>Paralichthys berlandieri</i> |
| Kokanee | <i>Oncorhynchus keta</i> | Steelhead | <i>Oncorhynchus mykiss</i> | Pacific halibut | <i>Paralichthys oblongus</i> |
| Lake trout | <i>Salvelinus namaycush</i> | | | Yellowfin croaker | <i>Paralichthys oblongus</i> |
| Lake whitefish | <i>Coregonus clupeaformis</i> | | | Bigeye tuna | <i>Thunnus obesus</i> |
| Least cisco | <i>Coregonus adaei</i> | | | Yellowfin tuna | <i>Thunnus albacares</i> |
| Rainbow trout | <i>Oncorhynchus mykiss</i> | | | Canary rockfish | <i>Sebastes inniger</i> |
| Round whitefish | <i>Pomoxis canadensis</i> | | | Quillback rockfish | <i>Sebastes maliger</i> |
| Freshwater drum | <i>Ambloplites rupestris</i> | | | Rougheye rockfish | <i>Sebastes rosenblatti</i> |
| Alaska blackfish | <i>Dalmanella</i> | | | Yelloweye rockfish | <i>Sebastes rosenblatti</i> |
| | | | | Pacific graysby | <i>Cepranichthys argentea</i> |
| | | | | Yellowtail barracuda | <i>Seriola lalandi</i> |
| | | | | Slender eelblenny | <i>Parablennius taylori</i> |
| | | | | Stout eelblenny | <i>Acanthaluteres</i> |