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Full Length Research Paper

The genetic mineralogical characteristics of fish otoliths and their environmental typomorphism

Li Shengrong[1]*, Du Fengqin[1], Yan Lina[1], Cao Ye[1], Luo Junyan[1], Gao Yonghua[2], Yang Liangfeng[3] and Tong Jinggui[4]

[1]State Key Laboratory of Geological Processes and Mineral Resources, China University of Geosciences,Beijing 100083,China.
[2]Department of Materials Science and Engineering, Tsinghua University, Beijing 100084, China.
[3]The Geological Museum of China, Beijing 100034, China.
[4]Shenzhen College of Polytechnic, Shenzhen 518055, China.

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Otolith is a typical biomineral carrier growing on insides of fish skull with prominent zoning structure formed by alternating layers of protein and calcium carbonate around the nucleus. The zoning number and the thickness of the rhythmic zone can reflect the age and the growing velocity. The $\delta^{18}O$ values of the calcium carbonate are indicators of the temperature of the water where the fish lives. The geometry, color, common and trace elements, oxygen and carbon isotopes of the zones can be employed effectively to classify the species, trace the source, migration habits, nutrition level of the fish and the variation of the ocean environment, in order to predict the environmental variation trend of related waters and make strategic plan for fishery production. Thermoluminescence technique can be taken as a new tool in the investigation of fish otolith to describe the heavy metal pollution of related waters, and the thermoluminescence parameters can be used to deduce the source and manage fishery resources.

Key words: Fish otoliths, age, temperature, species, migration, water environment.

INTRODUCTION

Otoliths of fishes are paired metabolically inert concentric deposits in which alternating layers of protein and calcium carbonate grow around a nucleus and are formed by daily growth increments of calcium carbonate, used for balance and/or hearing in all teleost fishes (Campana and Neilson, 1985). All teleost fishes have three pairs of otoliths namely, sagittae, asteriscae and lappillae. Otoliths zoning structure had been studied from the biostatistics angle by many scientists to get the information about fish age, feeding and growth history, recruitment and migration, mortality and stock structure, and so on (Campana and Neilson, 1985; Song et al., 2006). The relationship between the chemical composition in the zoning structure of otoliths and ambient environmental factors such as elemental composition, temperature and salinity were studied (Campana, 1999, Thorrold et al., 1997; Elsdon and Bronwyn, 2002; Zacherl and Georges, 2003; Martin and Thorrold, 2004). Recently, some authors have tried to demonstrate that otoliths are a potential proxy for monitoring changes in water quality (Yang et al., 2006; Li et al., 2008; Gao et al., 2008; Luo et al., 2008; Yan et al., 2008). But there are still problems, that is, how ambient environmental and internal factors of fish control the chemical composition, crystal structure and texture of the calcium carbonate in the otolith, and what relationship among the ambient environmental factors and various characteristics of calcium carbonate exist. Like minerals formed by geological proceses, calcium carbonate in fish otoliths contain abundant genetic and environmental information, and

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*Corresponding author. E-mail: lisr@cugb.edu.cn.

Abbreviations: NAA, Neutron activation analyses; **EMPA,** electric microprobe analysis; **LA-ICP-MS,** laser ablation inductively coupled plasma mass spectrometry.

study of its typomorphism is important to biological, mineralogical, oceanographical and environmental research, and to fishery production as well as the inspection and protection of human environment.

As typical biomineral carriers and with typical microstructure, fish otoliths have many common properties with those abiological minerals. Studying otoliths by employing mineralogical methodology is possible and advantageous, especially for the study of genetic and environmental mineralogy of fish otoliths. Only few mineralogists, however, are concerned with the in-depth study of fish otoliths. From a mineralogist's point of view, the authors partially summarizes previous literatures and part of the authors' research results, with the aim to arouse the interest of mineralogists to participate in the study of biominerals, and introduce some newly found effective methods in the study of environmental biominerals.

TYPOMORPHISM OF FISH OTOLITH'S SHAPE AND MICROMORPHOLOGY

The shape of fish otolith means the otolith's whole external shape, and the micromorphology is applied to the shape, width and transparency of otolith growth increment. Typomorphism means the characteristics which indicate certain forming condition.

Growth increments make up a natural time series in otolith surfaces or cross sections. Since the discovery of daily growth layers in otoliths (Pannella, 1971), further researches reveal that growth increments are common in fish otoliths (Kawakami et al., 1998; Campana, 1999; 2001; Crook, 2004), which is one of the most important discoveries in fish biology since 1970.

AGE AND GROWTH PERIOD JUDGEMENT

Under optical microscope and electrical microscope, the center of otolith is primordium (equivalent to the growth nuclear of mineral crystal), out of the primordium are many orderly arranged rings (daily growth layers, equivalent to zonings of mineral). Some translucent rings make up a translucent zone, and some opaque rings make up an opaque zone. A pair of translucent-opaque zones forms a yearly growth increment. Generally, the otoliths and the daily increments of young fish are round in shape with smooth rings and margins, whereas the old ones are pyriform or elliptic with primordium departing from the center and with indented or irregular rings and margins (Xiang et al., 1997).According to experimental researches of barracuda otoliths (Li et al., 1993), the number of daily growth layers of more than 80% of the samples is only 2 days less than the actual days after hatch.

It is clear that the daily growth rings are important evidence for judgement of fish growth period.

INFERING WATER ENVIRONMENT AND FISH PRODUCTION AREA

The daily increments of otoliths change regularly with the growth of the fish and the ambient water environment. The width of daily increment increases when the fish is older than one month with strong feeding ability, and when food is rich in summer and autumn, and when fish grows rapidly. When the salinity of ambient water where fish lives changes, thick rings will grow in otoliths.

Morphology of otolith of sea bass was applied to identify Japanese *Lateolabrax japonicus* and Chinese *Lateolabrax maculates* (Ye et al., 2007). Significant differences in relation of otolith weight and otolith length were found between the two populations.

A new observation made by some authors showed that the relation between weights of carp sagittae and carp body had difference in fresh waters of South China and Australia plain (Crook, 2004) (Figure 1). It is obviously an interesting research subject, whether the relation between weights of otolith and fish body can be taken as evidence for tracing fish origin or producing area, which deserves further research in depth.

TYPOMORPHISM OF FISH OTOLITH'S CHEMICAL COMPOSITION

INDICATOR OF WATER CHEMISTRY AND GEOLOGICAL BACKGROUND

The chemistry of otolith is the direct result of ambient water chemistry. It is already known that more than 30 elements exist in otoliths including not only the common ones but also many rare earth elements, dispersed elements, noble elements and base metal elements. The concentrations of these elements in otoliths are somewhat or strongly related with the abundance of these elements in the ambient waters. Analyses of otolith chemistry are useful in the chemical evaluation of waters where the fish lives (Thorrold et al., 1998). The authors' neutron activation analyses (NAA) of the carp otoliths from the Baiyangdian Lake and the Miyun Reservoir of North China (10 samples respectively) gave a result of 33 metal content. Almost all the metals in the carp otoliths from Baiyangdian Lake are one order of magnitude richer than those from Miyun Reservoir, which are consistent with the analysis result of the respective water chemistry (Figure 2). Mathematical analyses of the NAA data give useful environmental information (Yang et al., 2006).

Strontium and calcium contents in carbonate minerals from various sea animals are good indicators of sea water environment (Anadon et al., 2002). $D_{Sr} = [Sr/Ca]_{otolith}/[Sr/Ca]_{water}$ have been used to study the response of otolith to aquatic environmental change. Although, a few researchers suggest that Sr/Ca value of otolith is subject to temperature and fish growth velocity

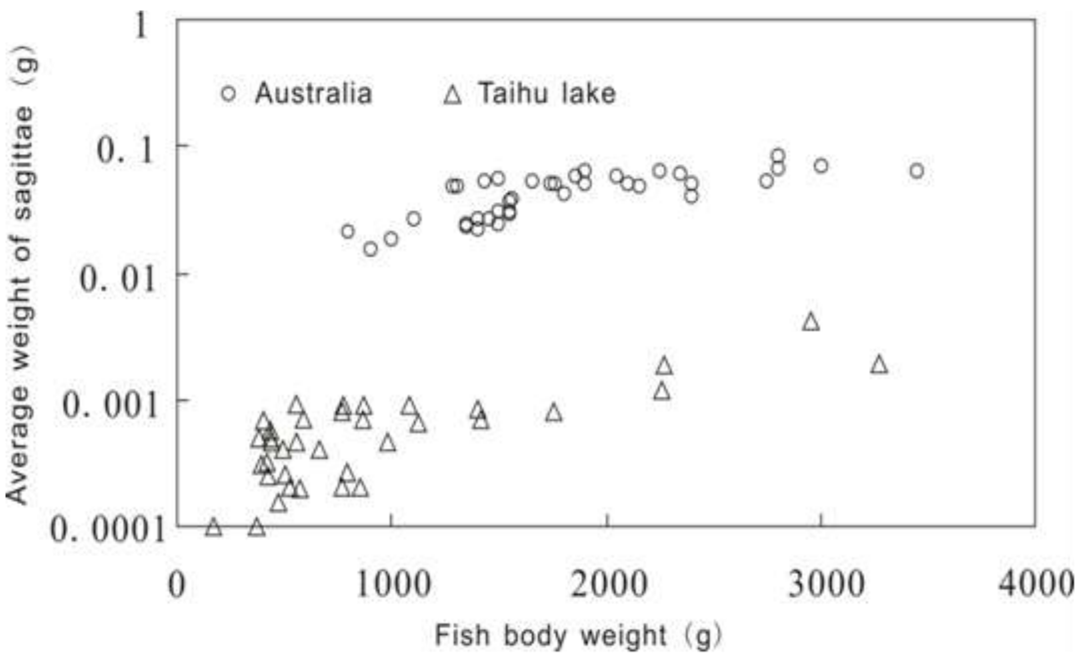

Figure 1. Plots of weights between carp bodies and sagittae from Taihu Lake, South China and Mullay River, Australia (the Australian data are from Crook, 2004).

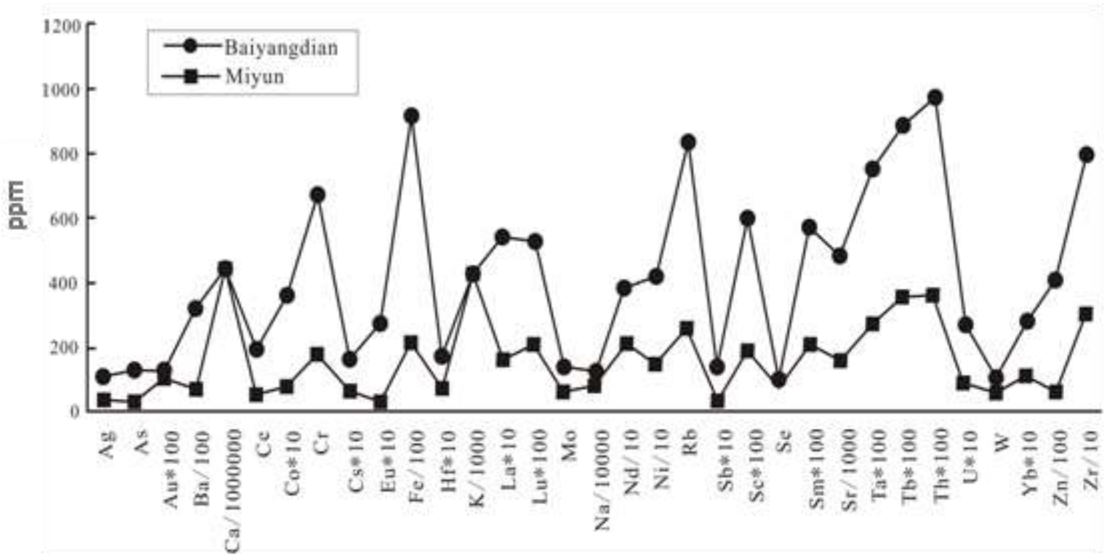

Figure 2. Comparison of relative concentration of elements in carp lappillaes from Baiyangdian Lake and Miyun Reservoir.

(Friedland et al., 1998), others argue that this value is only the function of water chemistry (Tzeng, 1994; Bath et al., 2000); or the geological background of the waters (Bacon et al., 2004).

Tanganyika Lake in east Africa is surrounded by 4 countries. The sagittal otoliths of two fish species, *Stolothrissa tanganicae* and *Limnothrissa miodon*, show clear differences in Sr/Ca and Ba/Ca values between their southern and northern lake populations. Differences also exist among those from the sub-basins in the north lake. This discovery is valuable for fishery management, especially in areas involving multilateral relationship.

A Sr/Ca-Cr/Ca diagram plotted with electric micro-probe analyses of the carp otoliths from Baiyangdian Lake and Miyun Reservoir (11 samples for each area) shows that the data are significantly differentiated on the diagram as two plotting areas with nearly no superposition (Figure 3). This can be an indicator for tracing

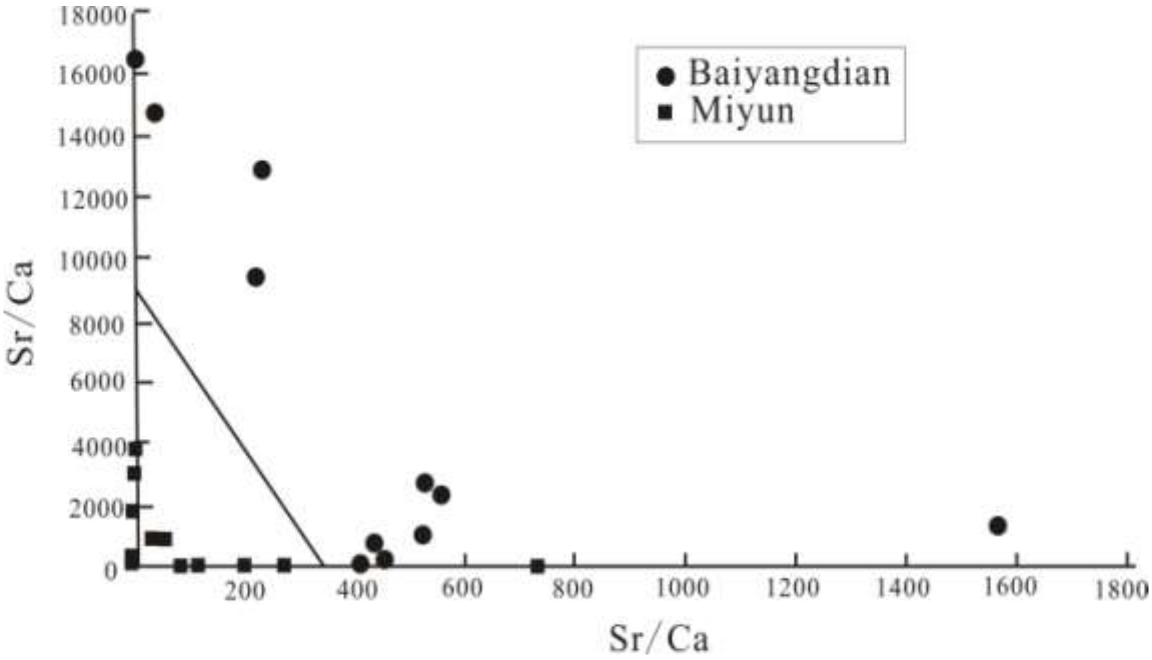

Figure 3. Sr/Ca-Cr/Ca plot for carp lappillaes from Baiyangdian Lake and Miyun Reservoir.

the origin of fishes and for displaying the relationship between otolith and water chemistry.

INDICATOR OF FISH LIVING HISTORY AND ENVIRONMENT CHANGE

It is particularly interesting to note that the daily rings in fish otolith keep forming after growth of the fish body ceased, and that once the rings are deposited, their chemistry (element content and isotopic fractionation) will be unchangeable. For this reason, the chemistry of different growth rings in the otolith can trustily record the change of water chemistry during the whole life of the fish.

The environmental change is most prominent in the life of migrating fish. Systematically measuring the chemistry of the otolith from the primordium to the margin by electric microprobe analysis (EMPA) and laser ablation inductively coupled plasma mass spectrometry (LA-ICP-MS) can supply useful information on the living habit and the migrating path of the fish. It is noticed that the strontium in the otolith of Japanese eel *Anguilla japonica* increases gradually when the eel lives in the sea and sharply decreases when the eel migrates to fresh water and afterward keeps in low level for a long time (Tzeng, 1994). Previously, only few elements in otoliths such as Ca, Sr, K, Na, Mg, Si, P, S and Fe were studied, many other trace elements, especially such toxic heavy metals as Hg, Cr, Pb, As and U, are scarcely studied.

Our systematic LA-ICP-MS study on the otolith composition of carps from Miyun Reservoir (supplying drink water for Beijing, the capital city of China) shows that such heavy metals as Cr, Cu, Pb, Zn, Ba and Al were quite rich in the otolith in the years 1997 to 1998, their contents decrease gradually since the summer 1998 till 2003 (Figure 4), and some of the elements are noticed with a little increase in 2004. This result is consistent with the water quality protection reinforced by the city government since the end of last century, and it also gives an alarm signal to prevent the water quality deterioration.

TYPOMORPHISM OF FISH OTOLITH'S ISOTOPIC COMPOSITION

FISH OTOLITH'S ISOTOPIC THERMOMETER

The use of oxygen isotopic composition in biogenic carbonates is well established as a proxy for reconstruction of temperatures (Devereux, 1967; Patterson et al., 1993), especially in ocean settings without large changes in water salinity (Gao, 2002; Gao and Beamish, 2003). Vital effect or biologically induced oxygen isotope disequilibrium fractionation is recognized not to be the rule. As a result, the oxygen isotopic composition ($\delta^{18}O$) of otolith aragonite can be used as a measure of temperature. Researchers observed that $\delta^{18}O$ values of otoliths tend to decrease with increasing temperature (Kalish, 1991) and the estimate of 1‰ $\delta^{18}O$ variation corresponds to about 5°C in the temperature of seawater at constant salinity (Gao, 1997).

Fossil otolith$\delta^{18}O$ record can be a good proxy of

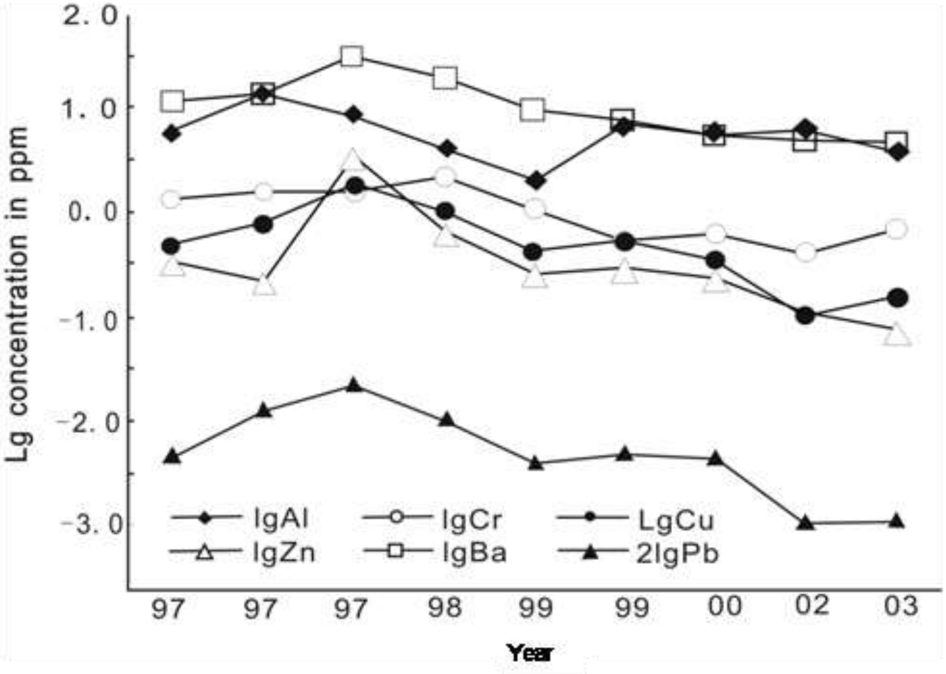

Figure 4. The 6-years (1997 to 2003) variation in relative concentrations of element Cr, Cu, Pb, Zn, Ba and Al in carp lappillae sample M05 from Miyun Reservoir.

paleotemperature. Andrus et al. (2002) found that in the mid-Holocene (about 6000 a B. P.), the sea surface temperature in Peru was 3 to 4°C higher than that at present.

PROXY FOR FISH STOCKS AND MIGRATION PATTERNS

Researches indicates that the fish otoliths from different habitat areas or water masses show different isotopic composition (Gao and Beamish, 1999) and that the migration patterns and stocks of the fish can be discriminated from the otolith isotopes (Nelson, 1989; Gao, 2002). Some researchers even suggested that the change of migration patterns and routes might account for the population declines of salmonids in the North Pacific in response to the global warming events (Welch, 1998). It is noticed, however, that only few isotopes, such as carbon, oxygen and nitrogen isotopes are measured and studied till now.

PROXY FOR WATER ENVIRONMENT CHANGE

In order to probe environmental change from single otolith isotopes, microsampling or microprobe analysis approaches are essential. Otolith microsampling technique was developed at the end of the last century (Gao, 1999). Microprobe isotope analysis was available recently through the use of LA-ICP-MS. By using these methods, annual and intra-annual or seasonal scales isotopic data can be measured. Previous literatures have already documented quite a few isotopic data of different annual increments in fish otoliths, which are much useful in the tracing of water environmental changes. The use of LA-ICP-MS in this concern will be a great progress.

TYPOMORPHISM OF FISH OTOLITH THERMOLUMINESCENCE

A tentative study of otolith thermoluminescence was made by the authors recently. Our work demonstrated that some of the thermoluminescence parameters of otoliths can be employed to discriminate among water masses with or without heavy metal pollution. Baiyangdian Lake, which is inhomogeneously polluted by heavy metals, shows much wider half-widths of carp otolith thermoluminescence peaks than those obtained from Miyun Reservoir, the drinking water source of Beijing, the capital city of China (Figure 5).

CONCLUSION

Previous researches have made it clear that fish otolith can be a good environmental proxy for the water mass where the fish lives. The morphology, micromorphology,

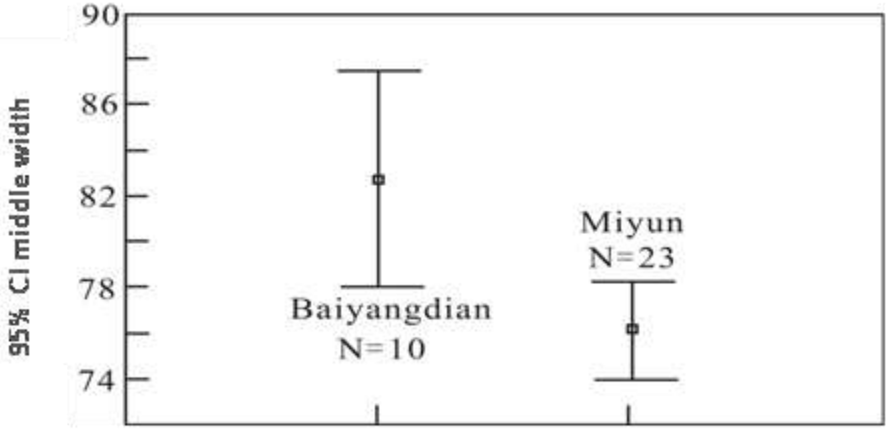

Figure 5. Comparison of thermoluminescence parameters (middle width of glow curve crest) for carp lappillaes from Baiyangdian Lake and Miyun Reservoir.

common and trace elements, oxygen and carbon isotopes and thermoluninescence of fish otoliths can be employed effectively to classify the species, to trace the source, migration habits and nutrition level of the fish. Information of water temperature, heavy metal concentration, over-nutrition condition and their variation are cordially recorded in fish otoliths. It is possible to predict the environmental variation trend of related water and make strategic plan for fishery production by using otolith data.

It is well-known that direct water analysis can be affected by the weather changes, and one time analysis, therefore, can only give a result on the water without undergoing sudden weather change. In summer or autumn, the weather change is very often. In this case, frequent sampling and analyses are necessary for evaluating annual or seasonal environment of the water. Whole otoliths of one year old fishes can be a good tool for evaluating annual environment of the water, and those of one season old fishes are good for seasonal evaluation. Besides, analysing few otoliths of old fishes (many fish species live as long as more than 50 years) with LA-ICP-MS, a systematic environmental data of the water can be obtained. In another aspect, the otolith samples can be safely stored for further studies in future, in water samples, however, cannot be kept unchangeably. In comparison with direct water analysis, water environment monitoring through fish otolith study has quite a few advantages.

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REFERENCES

Anadon P, Utrilla R, Vazquez A (2002). Mineralogy and Sr-Mg geochemistry of charophyte carbonaes: a new tool for paleolimnological research. J. Earth. Planet. Sci. Lett. 197: 205-214.

Andrus CFT, Crowe DE, Sandweiss DH, Reitz EJ, Romanek CS (2002). Otolith $\delta^{18}O$ record of mid-Holocene sea surface temperatures in Peru. Science, 295(5559): 1508-1511.

Bacon CR, Weber PK, Larsen KA, Reisenbichlen R, Fitzpatrick JA, Wooden JL (2004). Migration and rearing histories of Chinook salmon (*Oncorhynchus tshawytscha*) determined by ion microprobe Sr isotope and Sr/Ca transects of otoliths. Can. J. Fish. Aquat. Sci. 61: 2425-2439.

Bath GE, Thorrold SR, Jones CM, Campana SE, McLaren JW, Lam JWH (2000). Strontium and barium uptake in aragonitic otoliths of marine fish. Geochim. Cosmochim. Acta. 64: 1705-1714.

Campana SE (2001). Accuracy precision and quality control in age determination, including a review of the use and abuse of age validation methods. J. Fish Biol. 59: 197-242.

Campana SE (1999). Chemistry and composition of fish otoliths: pathways, mechanisms and applications. Mar. Ecol. Prog. Ser. 188: 263-297.

Campana SE, Neilson JD (1985). Microstructure of fish otoliths. Can. J. Fish. Aquat. Sci. 42: 1014-1032.

Crook D (2004). Contribution of the Barmah-Millewa floodplain lakes to carp populations in the mid-River Murray: Arthur Rylah Institute for Environmental Research, Department of Sustainability and Environment, Heidelberg, Victoria. (Final report to Barmah-Millewa Forum).

Devereux I (1967). Temperature measurements from oxygen isotope ratios of fish otoliths. Science, 155: 1684-1685.

Elsdon TS, Bronwyn MG (2002). Interactive Effects of Temperature and Salinity on Otolith Chemistry: Challenges for Determining Environmental Histories of Fish. Can. J. Fish. Aquat. Sci. 59: 1796-1808.

Friedland KD, Reddin DG, Shimizu N, Haas RE, Youngson AF (1998). Strontium: calcium ratios in Atlantic salmon (Salmo salar) otoliths and observations on growth and maturation. Can. J. Fish. Aquat. Sci. 55: 1158-1168.

Gao YW (2002). Regime shift signatures from stable oxygen isotopic records of otoliths of Atlantic cod (Gadus morhua). Isotopes Environ.

Health Stud. 38: 100-113.

Gao YW (1999). Microsampling of fish otoliths: a comparison between DM 2800 and Dremel in stable isotope analysis. Environ. Biol. Fish. 55: 443-448.

Gao YW (1997). Stable isotope analyses in otoliths of cod (*Gadus morhua* L. 1758): implication for long-term environmental changes in the Canadian Atlantic. Ph. D. Thesis, McMaster University, Hamilton. pp. 1-96.

Gao YW, Beamish RJ (1999). Isotopic composition of otoliths as a chemical tracer in population identification of sockeye salmon (*Oncorhynchus nerka*). Can. J. Fish. Aquat. Sci. 56: 2062-2068.

Gao YW, Beamish RJ (2003). Stable isotope variations in otoliths of Pacific halibut (*Hippoglossus stenolepis*) and implications of the possible 1990 regime shift. Fish. Res. 60: 393-404.

Kalish JM (1991). ^{13}C and ^{18}O isotopic disequilibria in fish otoliths: metabolic and kinetic effects. Mar. Ecol. Prog. Ser. 75: 191-203.

Kawakami Y, Mochioka N, Morishita K, Tajima T, Nakagawa H, Toh H and Nakazone A (1998). Factors influencing otolith strontium/calcium ratios in *Anguilla japonica* elvers. Environ. Biol. Fishes, 52: 299-303.

Li CH, Sha XS, You F, Yang CW, Huang RD (1993). Study on the formation of daily increments in otoliths of fry barracuda and age identification of its natural speciases. Oceanol. Limnol. Sinica. 24(4): 345-349.

Li SR, Xu H, Shen, JF, Li GW, Zhang XB (2008). On the connotation and methodology of environmental-biological mineralogy. Earth Sci. Frontiers. (in Chinese with English abstract). 15(6): 1-10.

Luo JY, Li SR, Shen JF (2008). The influential factors of strontium and barium enrichment in otolith and their response to the environment. Earth Sci. Frontiers. (in Chinese with English abstract). 15(6): 18-24.

Martin GB, Thorrold SR (2004). Temperature and Salinity Effects on Stronitium Incorporation in Otoliths of Larval Spot (leiostomus Xanthurus). Can. J. Fish. Aquat. Sci. 61: 34-42.

Nelson CS (1989). Potential use of oxygen and carbon isotopic composition of otoliths to identify migratory and non-migratory stocks of the New Zealand common smelt: a pilot study. N. Z. J. Mar. Freshwater Res. 23: 337-344.

Pannella G (1971). Fish otoliths: daily growth layers and periodical patterns. Science, 173: 1124-1126.

Patterson WP (1993). Continental paleothermometry and seasonality using the isotopic composition of aragonitic otoliths of freshwater fishes. In Climate Change in Continental Isotopic Records (Edited by Swart P, Lohmann KC, McKenzie J and Savin S). Geophys. Monogr. 78: 191-202.

Song ZB, Fu ZD, Yue BS, Zhao EM (2006). Otolith microstructure of larval Gymnocypris potanini Herzenstein from the Minjiang River in China. Environ. Biol. Fish. 75: 431-438.

Thorrold SR (1998). Accurate classificationof nursery areas of juvenile weakfish *(Cynoscion regalis)* based on chemical signatures in otoliths. Mar. Ecol. Prog. Ser. 173: 253-265.

Thorrold SR, Campana SE, Jones CM (1997). Factors determining δ13C and δ18O fractionation in aragonitic otoliths of marine fish. Geochim. Cosmochim. Ac. 61: 2909-2919.

Tzeng WN (1994). Temperature effects on the incorporation of strontium in otolith of Japanese eel *Anguilla japonica.* J. Fish Biol. 45: 1055-1066.

Welch DW (1998). δ^{13}C-δ^{15}N values as indicatiors of trophic position and competitive overlap for pacific salmon (Oncorhynchus spp.). Fish. Oceanogr. 2: 11-23.

Xiang DC, He Z, Zhu J, Shen KM, Ran JC, Zheng X, Liu YZ (1997). Study on the daily increments of crucian otolith, J. Southwest China Uni. Agriculture, (in Chinese with English abstract),19(5): 451-454.

Yan LN, Li SR, Luo JY, Du FQ, Ma GL, Wang YL, Wang W (2008). Tentative application of computed tomograpraphy to the study of carp otoliths and their responses to environmental variations. Earth Sci. Frontiers. 15(6): 025-031(in Chinese with English abstract).

Yang LF, Li SR, Luo JY, Gao YH, Tong JG, Cao Y, Shen JF (2006). Microchemical characteristics of carp otoliths from two different water environments and their indication significance for environmental changes, Ac. Petrolog. mineralog. (in Chinese with English abstract), 25(6): 511-517.

Ye ZJ, Meng XM, Gao TX, Yang YH, Wang YJ (2007). The geographical differentiation in otolith morphology of sea bass: *Lateolabrax Japonicus* and *L. Maculates*. Oceanolog. Limnolog. Sinica. 38(4): 356-360.

Zacherl AC, Georges A (2003). Barium and Strontium Uptake Into Larval Protoconchs and Statoliths of the Marine Neogastropod Kelletia Kelletii. Geochim. Cosmochim. Ac. 67: 4091-4099.