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# Migration history of an ariid Indian catfish reconstructed by otolith Sr/Ca and $\delta^{18}$O micro-analysis

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Understanding catfish ecology is important because catfish constitute one of the largest fish stocks in the coastal Indo-Pacific regions. Recent technological advances have enabled the use of biological electric sensors to understand fish ecology, but their application requires catch and release. Fish otoliths can record ecological changes, and oxygen isotopes and Sr/Ca ratios along the growth direction are independently used to reconstruct the migration history of the fish. Here we report high-resolution measurements of both oxygen isotopes and Sr/Ca ratios of a modern otolith from a marine catfish (*Plicofollis tenuispinis*) collected from the Gulf of Khambhat, western India. Both sets of data suggest that the catfish migrated from an estuarine environment to the sea during its lifetime. Migration history of the catfish was estimated with monthly resolution aided by numerical modeling. Potential applications of this analysis as an environmental recorder for variables such as temperature and water chemistry are examined.

Keywords: otolith, oxygen isotope, carbon isotope, Sr/Ca, Ba/Ca

## INTRODUCTION

Otoliths, the ear stones of fish, consist of aragonite crystals similar to the skeletons of other calcifying organisms (e.g., corals and mollusks). Geochemical analysis of otoliths has a wide range of applications such as paleoenvironmental reconstruction (Andrus *et al*., 2002a, b; Surge and Walker, 2005; Kerr *et al*., 2007), estimation of horizontal and vertical migration histories of fish (Carpenter *et al*., 2003; Lin *et al*., 2012), and determination of hatching sites and habitats within estuaries (Amano *et al*., 2013; Tanner *et al*., 2011). Incremental and regular growth of otoliths and recent developments in micro-analytical techniques enable spatiotemporal high-resolution data to be obtained from biogenic carbonates (Sakai, 2009; Sakai and Kodan, 2011; Kawakubo *et al*., 2014; Sinclair *et al*., 1998). Notably, otolith oxygen isotope ratios ($\delta^{18}$O) are deposited in isotopic equilibrium with ambient water values, making it one of the best recorders of fish ecology and habitat (Patterson *et al*., 1993; Thorrold *et al*., 1997; Campana, 1999). Trace elements in otoliths (e.g., Sr/Ca, Ba/Ca) also carry signatures of both physiological and environmental processes throughout the life history of the fish (Campana *et al*., 1999; Elsdon *et al*., 2008).

Today, catfish occupy an important position as a fish stock in the coastal areas of Indo-Pacific regions (Menon, 2003). The otolith analyzed in this study was obtained from a catfish (order Siluirofrmes) in the family Arridae. Their otoliths are characteristically large, often as much as 1 cm long (Chen *et al*., 2011; Dan, 1980), and hence are well suited to provide high-resolution ecological and climatological data. We analyzed $\delta^{18}$O and element/Ca ratios in the same otolith of a catfish collected off the coast of western India to estimate its migration history and to assess the potential of this analysis to be used as an environmental recorder.

## MATERIALS AND METHODS

*Climatology of Gujarat*

The study region is located in the Gujarat state in western India (Fig. 1). Gujarat is a large peninsula lying

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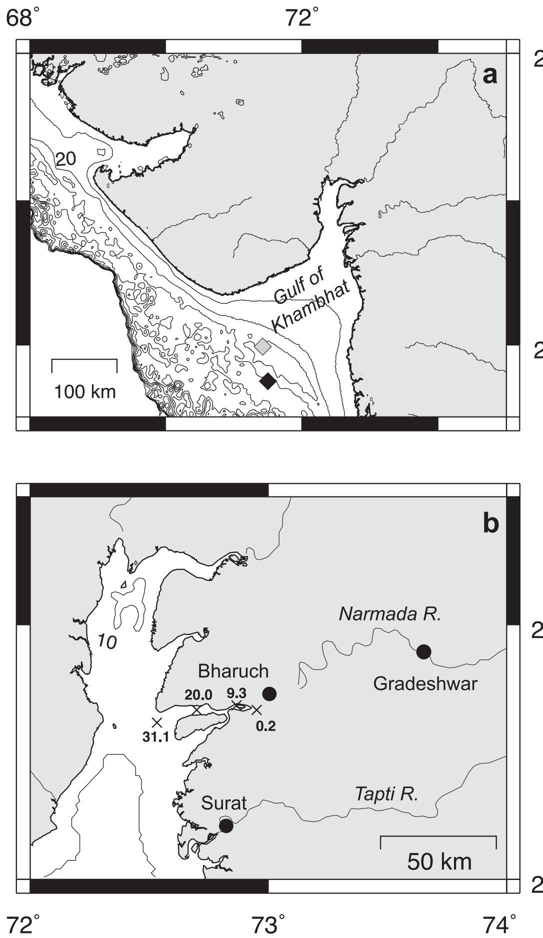


*Fig. 1. (a) Geographical map of Gujarat with a depth counter. Gray and black diamonds indicate data points of monthly averaged temperature and salinity of GODAS and annual averaged $\delta^{18}O$ of GISS, respectively. (b) An enlarged view of the Gulf of Khambhat. Four crosses with numbers indicate salinity measured in March 2007 in the Narmada Estuary (Rahaman and Singh, 2012).*

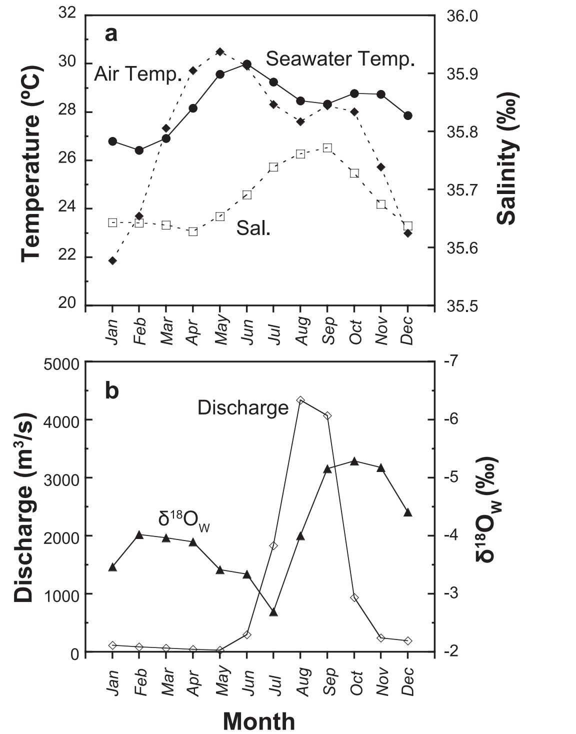


*Fig. 2. Meteorological and oceanographic settings of Gujarat. (a) Monthly averaged temperature (closed circles with line) and salinity (open rectangles with line) in the surface mixed layer (0–40 m) during 2001–2009. Monthly averaged air temperature (closed diamonds with dashed line) in Surat during 2000–2008. (b) Monthly averaged discharge of the Narmada River (open diamonds) during 1949–1979. Monthly averaged $\delta^{18}O_{FW}$ of the Narmada measured at Gradeshwar during July 2002–July 2004 (closed triangles).*

between two gulfs (the Gulf of Kutch in the north and the Gulf of Khambhat in the south). Gujarat belongs to a subtropical climate zone. The sea surface temperature (SST) in the Gulf of Khambhat reaches its minimum value (26.5°C) in February and maximum value in June (30°C) (Fig. 2) with a seasonal range of 3.5°C. In contrast, the air temperature in Surat varies from 22 to 30.5°C and its seasonal range is about twice that of its SST (Figs. 1b and 2a). A bimodal local maximum with secondary peaks in September to November is a characteristic feature in the temperature variations (Fig. 2a).

Sea surface salinity (SSS) fluctuates a little seasonally and inter-annually at the mouth of the Gulf (approximately 0.1 psu) (Fig. 2a), whereas SSS in the Gulf varies largely due to river discharge (Rao *et al*., 2009; Rahaman and Singh, 2012). Most freshwater that enters the Gulf of Khambhat comes from direct rainfall and runoff from the Narmada River. Almost 90% of annual precipitation occurs in the monsoon season (May–October) when the inter-tropical convergence zone passes over the Indian subcontinent, corresponding to an increase in the river discharge measured at Gradeshwar (Figs. 1b and 2b). During the monsoon season, a low-salinity water plume with a massive sediment particle load is observed in instrumental and satellite data (Rao *et al*., 2009; Rahaman and Singh, 2012). Seawater $\delta^{18}O$ ($\delta^{18}O_{SW}$) is stable in the upper 50 m (0.6‰, Fig. 1a) reflecting little seasonality in SSS. In contrast, the seasonality of river water $\delta^{18}O$ ($\delta^{18}O_{FW}$) is large and its behavior is complicated. At Gradeshwar in the Narmada River, $\delta^{18}O_{FW}$ varies from –5‰ to –3‰ seasonally (Bhattacharya, unpublished data) (Fig. 2b), which suggests $\delta^{18}O$ of estuarine water in the Gulf also changes dramatically depending on mixing of these waters.

Monthly averaged seawater temperature and salinity data are obtained from the Global Data Assimilation System (GODAS; http://iridl.ldeo.columbia.edu/SOURCES/.CMA/.BCC/.GODAS/), and monthly averaged air temperature in Surat is obtained from the National Climatological Data Center (http://www.ncdc.noaa.gov). River discharge in the Narmada River and $\delta^{18}O_{SW}$ are obtained from the River Discharge Database (http://www.sage.wisc.edu/riverdata/) and Godard Institute for Space Studies (GISS; http://iridl.ldeo.columbia.edu/SOURCES/.NASA/.GISS/), respectively.

*Otolith and ecology of Plicofollis tenuispinis*

Three samples of an ariid catfish were obtained in Bharuch in March 2009 (BRH-20, 21, and 22). The catfish had been captured alive in the Gulf of Khambhat by a local fisherman (Fig. 1b). The catfish were dissected immediately after capture and the saggital otoliths were removed from skulls. After being cleaned with tap water, the otoliths were dried and stored.

Siluriformes includes 37 recognized families of catfish distributed widely and particularly in freshwater environments (Sullivan *et al*., 2006). Only two families predominantly contain marine species: Plotosidae and the Arridae. Arridae, or sea catfish (called *Khagi* in the local language of Gujarat (Menon, 2003)), include approximately 150 species that inhabit marine, brackish, and freshwater environments in tropical and subtropical continental shelves worldwide (Betancur-R *et al*., 2007). There are five types of ariids currently consumed by humans in western India. They are, in order of relative abundance, *Plicofollis dussumieri* (45%), *P. tenuispinis* (16%), *Nemapteryx caelata* (12%), *Netuma thalassina* (12%), and *Osteogeneiosus militaris* (8%) (Menon, 2003). They live in marine and estuarine (in some case, riverine) waters and their habitat depth ranges from the surface to about 200 m, with preferential concentration on muddy seafloors of depth 30–70 m (Menon, 2003). Species such as *P. dussumieri*, *P. tenuispinis*, and *Net. thalassina* exhibit vertical and horizontal migration during the adult/breeding/spawning phases of their life cycles (Menon, 2003). They usually feed on crustaceans, fish, and mollusks. Spawning seasons in ariid catfish vary by genus, but a prolonged period of about 5 months is generally reported (Menon, 2003; Dan, 1977).

The appearance of the catfish, along with the geometric features and the number of growth bands in the otoliths, suggest that BRH-20, 21, and 22 can be identified as *P. tenuispinis* (Chen *et al*., 2011; Dan, 1977, 1980). The spawning season of *P. tenuispinis* is reported to range from May to September and the male catfish mouthbrood their offspring for about 5 months (Dan, 1977). They reach sexual maturity at age 1–2 years (Dan, 1977). Longevity is 3–4 years and they can reach a maximum body length of approximately 45 cm (Dan, 1977, 1980).

*Thin section*

One otolith sample (BRH-22) was attached to the bottom of a disposable 30 mL plastic cup, which was filled with a polyester solidifier and dried for 24 h at room temperature. It was further heated to 50°C for 24 h to cure the epoxy completely. The otolith was bisected with a rock saw across the minor axis of growth through the core, revealing clear incremental growth features. A thin section was made after surface polishing with silicon carbide (SiC) abrasives on a glass plate until growth bands were seen clearly under transmitted light microscope (Fig. 3a). Once the thickness of the otolith was reduced to about 280 $\mu$m, it was rinsed ultrasonically and dried at room temperature.

*Analytical methods*

X-ray diffraction analysis was performed before trace element and isotopic analyses to check for any alteration in otolith mineralogy. Carbonate powder was collected and calcite content was quantified. The results confirmed that the otolith consisted of pure aragonite (<2% calcite).

High-resolution subsampling of BRH-22 was conducted using a computer-controlled micromilling device with a three-dimensional positioning stage under a fixed drill (GEOMILL326; Sakai, 2009). Sampling traverses were parallel to growth features from the edge to the core of the otolith (Fig. 3a). The otolith was cut at 34 $\mu$m intervals on average and small amounts (20–100 $\mu$g) of powdered carbonate (100 samples) were collected using a micro-powder-collecting apparatus (Kyushu-Danji; Sakai and Kodan, 2011). Oxygen and carbon isotopic compositions ($\delta^{13}C$) of obtained subsamples were determined using an isotope ratio mass spectrometer (GV Instruments IsoPrime) with an automated carbonate reaction system (Multiprep) at the Japan Agency for Marine-Earth Science and Technology. Values of $\delta^{18}O$ and $\delta^{13}C$ are reported with respect to the Vienna Pee Dee Belemnite (VPDB) standard using standard delta notation in permil (Craig, 1957). Analytical precision for the in-house carbonate standard was better than 0.06‰.

Element/Ca analysis of BRH-22 was performed using a high-resolution inductively coupled plasma mass spectrometer (HR-ICPMS; Thermo Scientific Element-XR) coupled to a Resonetics 193 nm excimer laser ablation system installed at the Atmosphere and Ocean Research Institute (Obrochta *et al*., 2014). Measurement conditions are summarized in Table 1. Before measurement, the thin section was cleaned again in distilled water to remove surface contamination and dried overnight in a 50°C oven. A transect was set from the edge to the core of the otolith (Fig. 3a) and ablation of the otolith was made using a circle slit (112 $\mu$m in diameter) at an energy density of 50 mJ and a pulse rate of 5 Hz. The thin section was moved with a speed of 10 $\mu$m/s and the ab-

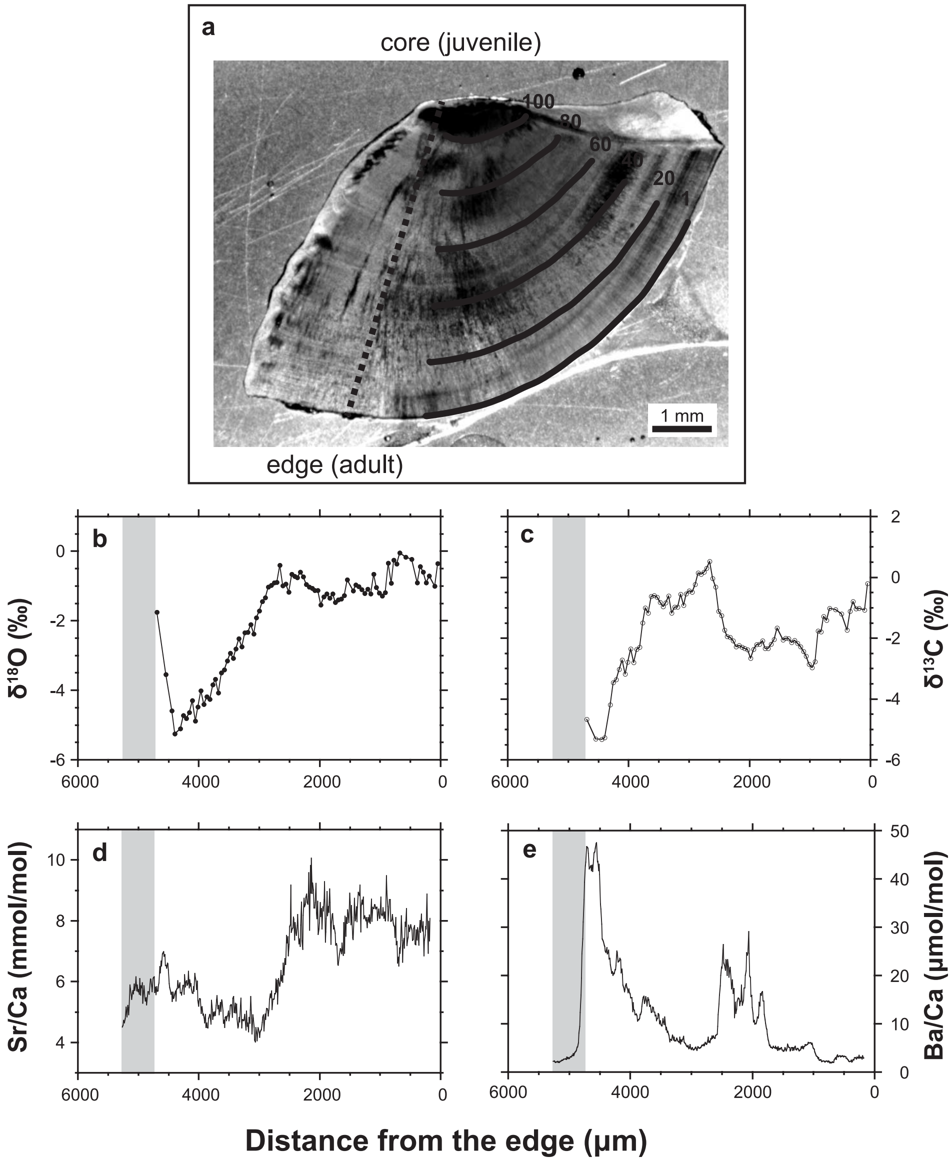


*Fig. 3. (a) Photograph of the BRH-22 thin section under transmission light microscope. Solid and dashed lines represent where isotopes and element/Ca ratios were measured using IRMS and laser ablation HR-ICPMS, respectively. Numbers indicate order of sampling paths. (b)–(e) Measured isotopes and element/Ca ratios. Gray shadows indicate the opaque zone of the otolith near the core; thus, continuity of the growth is ambiguous.*

lated material was continuously introduced via He gas stream to the HR-ICPMS. A pressed powder of carbonate material (JCp-1) and a glass standard (NIST SRM614) were used as standards. Measured isotopes were $^{43}$Ca, $^{86}$Sr, and $^{137}$Ba. Element/Ca ratios were calculated in comparison to certified values of JCp-1 for Sr/Ca and Ba/Ca (Okai *et al.*, 2002). We found good reproducibility along different trajectories and a reversed trajectory (from the core to the edge) within the same otolith (not shown). The analyses at the start and the end part of the traverse (approximately 100 $\mu$m) were discarded since they showed some unexpected spikes, which may be due to materials from the resin used to fix the otolith.

## Results

$\delta^{18}$O of BRH-22 showed large variability near the core, that is, at the beginning of its growth history (Fig. 3b). It abruptly decreased from –2‰ to –5‰ between 4,700 and 4,500 $\mu$m and then gradually increased to –0.5‰ until 2,700 $\mu$m. Between 2,700 and 0 $\mu$m, it fluctuated between 0‰ and –1‰. The $\delta^{13}$C results showed a gradual increase

*Table 1. Details of the laser ablation system and HR-ICPMS operating parameters used in this study*

| | |
|---|---|
| ***Laser ablation system*** | |
| Wavelength | 193 nm (ArF) |
| Repetition rate | 5 Hz |
| Energy | 50 mJ |
| Spot size | 112 $\mu$m |
| Mixing chamber | He (0.5 L/min) |
| Scan speed | 10 $\mu$m/s |
| ***HR-ICPMS*** | |
| Resolution | low |
| Gas flow | |
| Coolant | 16 L/min |
| Auxiliary | 1.0 L/min |
| Sample | 1.1 L/min |
| Cone | Nickel |
| Detection modes | Analog (Ca, Sr, Ba) |
| Sample time | 10 ms |
| Samples/peak | 5 (25% of mass window) |

between 4,500 and 2,700 $\mu$m, similar to $\delta^{18}$O (Figs. 3b and c). After reaching the maximum value (0.5‰) at 2,700 $\mu$m, it rapidly decreased to –2‰ and then fluctuated between –3‰ and 0‰.

Two plateaus with small fluctuations are seen in the Sr/Ca of BRH-22 (Fig. 3d). The first plateau, between 4,700 and 3,000 $\mu$m, is about 5 mmol/mol and the second one between 2,500 and 0 $\mu$m is about 8 mmol/mol. The two plateaus were separated by a sudden increase in Sr/Ca between 3,000 and 2,500 $\mu$m. Ba/Ca of BRH-22 showed two peaks (Fig. 3e). The first sudden increase to 45 $\mu$mol/mol began at 4,800 $\mu$m, followed by a gradual decrease into the background value of approximately 5 $\mu$mol/mol. The beginning of the first increase corresponded to an opaque zone in the otolith. The second one began at 2,600 $\mu$m, at half the amplitude of the first one.

The otolith was generally transparent, with some opaque growth bands; there was a large opaque zone around the core (5,200–4,700 $\mu$m; Fig. 3a). As the growth direction and its continuity are in question, we do not consider the element/Ca ratios in this opaque zone in the subsequent discussions.

## Discussion

### *Variability of $\delta^{18}$O and Sr/Ca and fish migration*

The large increase in $\delta^{18}$O of BRH-22 seen between 4,500 $\mu$m (*ca.* –5‰) and 2,700 $\mu$m (*ca.* –1‰) can be interpreted as being due primarily to changes in $\delta^{18}$O of the ambient water ($\delta^{18}O_W$), not to changes in the local water temperature around the catfish, because the required temperature change would have to be as high as 20°C (Grossman and Ku, 1986; Thorrold *et al.*, 1997; Patterson *et al.*, 1993). There is no water mass that has a temperature as high as 50°C around the Gulf of Khambhat; however, a possible effect of ambient water $\delta^{18}$O is reasonable since $\delta^{18}O_W$ at the mouth of the Gulf of Khambhat is 0.6‰ and that of the Narmada River is –3.9‰ on average (Fig. 2b).

Although otolith Sr/Ca has also been reported as a temperature recorder (Campana, 1999; Bath *et al.*, 2000; Elsdon *et al.*, 2008), the rapid increase of 3 mmol/mol of BRH-22 between 3,000 and 2,500 $\mu$m cannot be attributed to short-term temperature fluctuations. Rather, it suggests the timing at which the catfish entered seawater, since the Sr/Ca value of global seawater is 8.75 mmol/mol (Millero, 2005), which is much larger than that of the Narmada River (2.61 mmol/mol; Dessert *et al.*, 2001). Although there is some uncertainty in absolute Sr/Ca value in different water masses and its seasonality in the Narmada River, we note that Sr/Ca of river water is generally lower than that of seawater (see a compilation of Brown and Severin, 2009). Otolith Sr/Ca of other diadromous fish is widely used to track movements between rivers and the sea (e.g., Secor and Rooker, 2000; Kerr *et al.*, 2007; Brown and Severin, 2009). Culture experiments of various taxa of both juvenile and adult fish have confirmed that otolith Sr/Ca variability reflects water Sr/Ca composition (Bath *et al.*, 2000; Elsdon and Gillanders, 2003, 2004, 2005; Zimmerman, 2005; Walther and Thorrold, 2006).

Thus, both $\delta^{18}$O and Sr/Ca in the otolith indicate that BRH-22 migrated during its life from the river/estuary to the seawater before it was eventually captured at sea. However, the exact timings of shifts in the two proxies of BRH-22 do not agree; $\delta^{18}$O indicates a shift at 4,500–3,000 $\mu$m, whereas Sr/Ca indicates 3,000–2,500 $\mu$m (Figs. 3b and d). In the next section, we will introduce a simple mixing model and discuss how to explain this lag.

### *A mixing model*

Before introducing a model to interpret the difference between the $\delta^{18}$O and Sr/Ca signals, we assumed the following:

(1) The partition coefficient of Sr/Ca ($D_{Sr}$ = $(Sr/Ca)_{otolith}/(Sr/Ca)_{water}$) is dependent on temperature but independent of salinity and absolute Sr/Ca value of water.

(2) $\delta^{18}$O of the otolith precipitates with known relationships between $\delta^{18}$O of aragonite and temperature.

(3) The changes in $\delta^{18}$O and Sr/Ca of water are instantaneously incorporated into the otolith.

(4) The otolith grows continuously with no hiatus and at an almost constant growth rate.

We assume a mixing process of two end member water masses: seawater and freshwater. As the exact river where

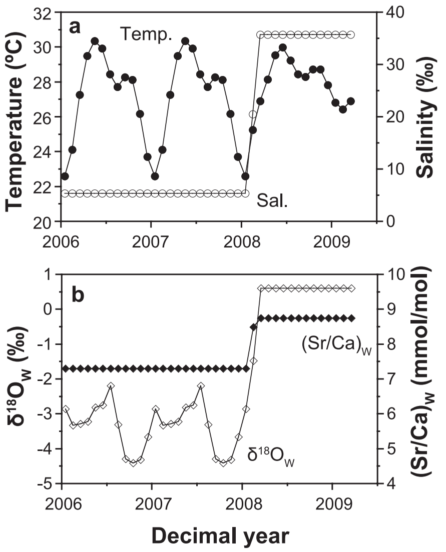


*Fig. 4. Representatives of parameters used in the mixing model. (a) Monthly averaged temperature (closed circles) and salinity (open circles) of the water where the catfish was believed to have lived. (b) Monthly averaged $\delta^{18}O$ (open diamonds) and Sr/Ca (closed diamonds) of the water where the catfish was believed to have lived.*

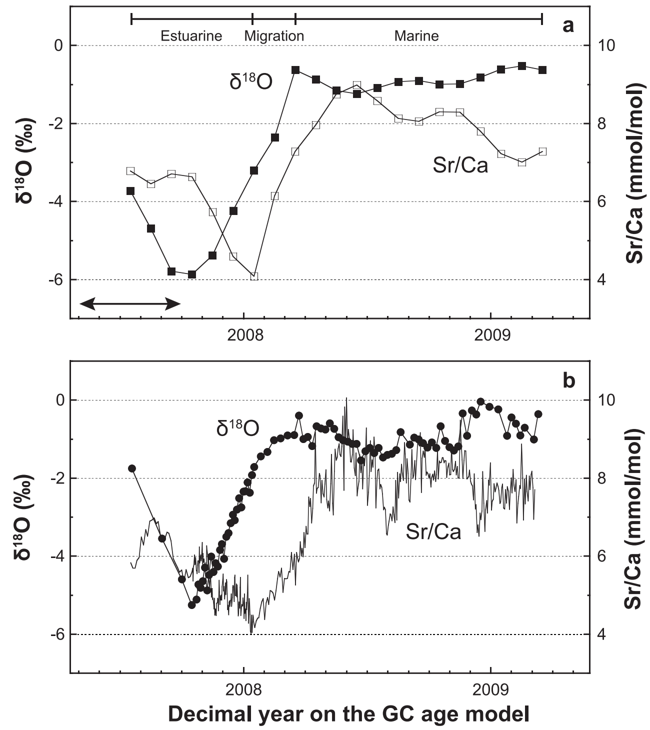


*Fig. 5. Comparison between the (a) modeled and (b) measured $\delta^{18}O$ (rectangles and circles, respectively) and Sr/Ca (open rectangles and a thick line, respectively) variation on the GC age model. The arrow indicates the estimated hatchery season for P. tenuispinis (Dan, 1977).*

the fish lived at the start is not known, chemical properties of the Narmada River (constituting the largest runoff into the Gulf) are assumed to represent the freshwater end member values. However, since there are only fragmentary records of water temperature for the Narmada River, monthly averaged air temperature in Surat during 2000–2008 are used instead for calculation (Figs. 1b and 4). Salinity, temperature, and $\delta^{18}O$ are mixed conservatively (Figs. 4a and b), where the mixing ratio is defined as 0 representing the seawater, and 1 representing the freshwater. Sr/Ca of the mixed water mass is calculated through conservative mixing of known Ca and Sr concentration of each end member (Fig. 4b or see Brown and Severine, 2009). No inter-annual variations of $\delta^{18}O_W$, Sr/Ca of water, and temperature are assumed in the model, because observation of these variables in this region is not sufficient to reproduce them. $\delta^{18}O_{SW}$ is kept constant because both seasonality and inter-annual variation is negligibly small (less than 0.04‰) when it is calculated using a known $\delta^{18}O_{SW}$-SSS relationship in the Arabian Sea (Dahl and Oppo, 2006). Similarly, Sr/Ca of the seawater is kept constant because its variation is negligible, reflecting the long residence time of strontium and calcium in the ocean. The expected $\delta^{18}O$ of the otolith was calculated using the $\delta^{18}O$-temperature equation for biogenic aragonites given by Grossmann and Ku (1986). Conversion of $\delta^{18}O$ values from the VPDB scale to the VSMOW scale was accomplished using the equation by Coplen (1988). According to assumption 1, $D_{Sr}$ is calculated from the measured Sr/Ca in otolith and the known Sr/Ca value for seawater. $D_{Sr}$ for ariid catfish in this study is roughly calculated to be 0.95, which is somewhat larger than that of previously reported values (i.e., 0.15–0.75; Dorval *et al*., 2007; Campana, 1999; Brown and Severine, 2009). Temperature sensitivity of $D_{Sr}$, often discussed in the literature (Campana, 1999; Bath *et al*., 2000; Elsdon *et al*., 2008), is estimated by comparing the amplitude of the variation in measured Sr/Ca in otolith with the seasonal amplitude of SST. The maximum and minimum values of Sr/Ca between 2,500 and 0 $\mu$m are used in this calculation, since this portion corresponds to the time when the fish lived in seawater. It is calculated to be 0.067 mmol/mol/°C, consistent with previously determined values (0–0.1 mmol/mol/°C between temperatures of 20–30°C) (Campana, 1999). We used these values for all Sr/Ca calculations, irrespective of salinity (i.e., mixing ratio) and life stage of the fish (i.e., juvenile or adult).

Other relevant variables in this context are the timing and the quantities of water involved in the mixing of the two end members. As the migration behavior of *P. tenuispinis* is not well understood, we freely adjusted related variables such as mixing ratio, timing, and duration of the mixing to see their effects on the expected $\delta^{18}O$ and Sr/Ca variations. The timing of changes in proxies in otolith is constrained by the following:

(a) The age of the catfish is less than 3 years, according to the otolith length-body size relationship (Dan, 1980).

(b) The end of otolith growth was March 2009, when the catfish was caught.

(c) As the hatching season of *P. tenuispinis* is independently determined to be within May to September (Dan, 1977), the start of the record should be around these months.

We modified the variables to find a reasonable migration scenario after iterating the calculation. The most probable mixing scenario is shown in Fig. 4, where the mixing ratio of freshwater to seawater varied from 0.85 (brackish water; salinity equal to 5.4 psu) to 0 (seawater; salinity equal to 35.7 psu) for two months beginning in January 2008. Expected $\delta^{18}O$ and Sr/Ca variations that reflect changes in the water chemistry are shown in Fig. 5a. It reproduces well the time lag in the beginning of large increases in $\delta^{18}O$ and Sr/Ca, in which $\delta^{18}O$ precedes Sr/Ca by 3 months. The reason might be due to the dominant effect of seasonality in $\delta^{18}O_W$ with secondary effects from temperature decreases during winter. In this scenario, the catfish lived in the sea from March 2008 to March 2009 and thus the otolith record roughly covers a year in the marine environment (Figs. 4 and 5a). Considering the salinity gradient in the pre-monsoon season (cf., data obtained in March 2007 by Rahaman and Singh, 2012), this would be equivalent to a migration of roughly 50 km if the catfish moved from the mouth of the Narmada River estuary to the seawater in the Gulf (Fig. 1b).

In this model, we do not consider the possibility of delay between environmental element/Ca changes and their incorporation in the otolith. For example, delays of 30–60 days and 20 days in Sr/Ca are observed for Japanese eel and black bream, respectively (Yokouchi *et al.*, 2011; Elsdon and Gillanders, 2005). Another issue pertains to the factors that determine the mechanism of Sr incorporation into the otolith. Brown and Severin (2009) pointed out that variables other than temperature and water chemistry may be operative and that data on Sr/Ca ratio of marine fish otoliths show significant variations despite homogeneity of seawater Sr/Ca and stable SST. Changes in $D_{Sr}$ in different salinity may relate to hypotonicity of fish bodies (Brown and Severin, 2009; Zimmerman, 2005). Additionally, some ontogenic effects on Sr/Ca incorporations (Brown and Severin, 2009; Secor and Rooker, 2000) are also possible. In the model, seasonality in Sr/Ca of water is also not considered. Large variations in annual rainfall and subsequent river discharge may result in cycles of concentrations of dissolved solutes, which could affect seasonality in Sr/Ca of riverine and estuarine water. Considering the mixing curve of Sr/Ca of water, seasonality could be a potentially important parameter when salinity is less than approximately 5 psu. Although these issues should be evaluated in future work, for a more general representation of migration behavior of diadromous fish, the model proposed here seems to reflect the life history of *P. tenuispinis* well.

*Table 2. Tie-points of the GC age model*

| Distance from the edge ($\mu$m) | Month/year | Description |
|---|---|---|
| 4,700 | Jul/2007 | Start of growth banding (End of isotope measurements) |
| 4,400 | Oct/2007 | Minimum value in $\delta^{18}O$ |
| 3,000 | Jan/2008 | Minimum value in Sr/Ca (Start of migration) |
| 2,700 | Mar/2008 | Local maximum in $\delta^{18}O$ (End of migration) |
| 0 | Mar/2009 | Catfish capture (Start of measurements) |

*Reconstruction of the life history of the catfish*

We utilized the chronological tie-points corresponding to the distinct transitions in $\delta^{18}O$ and Sr/Ca variability to construct the migration history of the *P. tenuispinis* specimen, with a monthly resolution (geochemically-derived age model; hereinafter, the GC age model). Tie-points in this age model are summarized in Table 2. The lowest values of $\delta^{18}O$ and Sr/Ca correspond to October 2007 and January 2008, respectively (Figs. 4 and 5). The local maximum in $\delta^{18}O$ coincides with March 2008, when the migration was completed. The GC age model is in good agreement with a previously published model age based on the body and otolith size of *Tachysurus tenuispinis*, which is a synonym of *P. tenuispinis* (Dan, 1977, 1980). In the previous age model, a 5,000 $\mu$m long otolith would belong to a catfish that lives for about 2 years and has a body size of about 30 cm. In the present case, the birth of the catfish is inferred to be prior to July 2007, according to the GC age model. The breeding season of *P. tenuispinis* is from May to September (Fig. 5a) (Dan, 1977); thus, the birth of the catfish can be between May and July 2007, the exact time being dependent on unknown growth pattern of the opaque zone near the otolith core.

To summarize, the life history of the catfish can be inferred from $\delta^{18}O$ and Sr/Ca variability and the mixing model. It seems to have been born between May and July 2007, in estuarine water with a salinity of approximately 5 psu. Then it migrated (January to March 2008) by about 50 km toward the sea. It then lived in seawater for almost 1 year and was finally captured by a local fisherman in

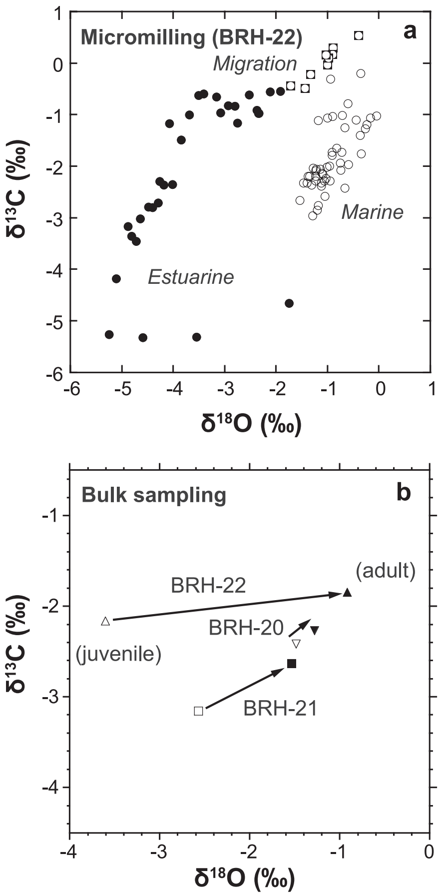


*Fig. 6. A cross plot of $\delta^{18}O$ versus $\delta^{13}C$. (a) Micro-milled BRH-22. Three main stages are depicted: estuarine migration and marine. (b) Bulk-sampled BRH-20 and 21 (reversed triangles and squares, respectively). Values of $\delta^{18}O$ and $\delta^{13}C$ for BRH-22 (triangles) are calculated using high-resolution micromilling data. Arrows indicate time shift from the juvenile phase (near the core, opened symbols) to the adult phase (near the edge, closed symbols).*

March 2009, at age 2 years. Had it not been captured it would have likely lived for an additional 1 or 2 years, after spawning in estuarine waters, since it is reported that the longevity of *P. tenuispinis* is 3–4 years (Dan, 1977, 1980).

*Ba/Ca variability*

We can infer that the overall decreasing trend in Ba/Ca is attributable to the migration of the catfish from the river to the sea. Barium is relatively abundant in riverine and estuarine waters, compared to seawater (Coffey *et al*., 1997). Thus, otolith Ba/Ca can be potentially useful for tracing migrations of diadromous fish, similar to the way Sr/Ca is useful (Dorval *et al*., 2007; Bath *et al*., 2000; Elsdon and Gillanders, 2003, 2004). The Ba/Ca value just before capture of the fish is about 3 $\mu$mol/mol, corresponding to marine water values (Gillanders, 2005; Milton and Chenery, 2001; Bath *et al*., 2000). The first excursion of Ba/Ca in the otolith is seen in July–December 2007, suggesting an entrance into river/estuarine water, which coincides with the monsoon season when the Narmada River has high discharge and deposits large amounts of terrigenous material into the Gulf of Khambhat (Fig. 2b). On the other hand, the second peak found in the otolith is difficult to interpret, because the period corresponds to the time when the fish was living in seawater. It may reflect a period of complex interaction between the seawater and suspended particles and/or sediments before it was introduced into the fish body (Coffey *et al*., 1997). As chemical behavior of Ba in estuarine waters is more complex than that of Sr and cannot be approximated by a conservative mixing process (Coffey *et al*., 1997; Rahaman and Singh, 2012), we do not further discuss otolith Ba/Ca variability.

*Migration history recorded in coupled $\delta^{18}O$ and $\delta^{13}C$*

According to the above migration scenario, there are three main phases during the life of the catfish, namely the *estuarine* stage, *migration* stage, and *marine* stage (Figs. 5 and 6a). During the *estuarine* stage, $\delta^{18}$O and $\delta^{13}$C show large variability (Figs. 5 and 6a) comprising of a sharp decrease from 4,700–4,500 $\mu$m in $\delta^{18}$O but no significant change in $\delta^{13}$C. This supports our main hypothesis that otolith $\delta^{18}$O variation is due mainly to large seasonality in $\delta^{18}O_W$ (Figs. 2b and 4b). Other parts of the isotopic data can be interpreted by complex interactions among various factors, including temperature effects on these isotopes; large seasonality in $\delta^{18}O_W$ as well as $\delta^{13}$C of dissolved inorganic carbon ($\delta^{13}C_{DIC}$); and biological controls on $\delta^{13}$C that are related to diet (Nonogaki *et al*., 2007), growth rate (Thorrold *et al*., 1997), and incorporation of metabolic carbon (Schwarcz *et al*., 1998).

The *migration* stage is characterized by a positive correlation between $\delta^{18}$O and $\delta^{13}$C ($R^2$ = 0.90, n = 9) (Fig. 6a), suggesting that the migration of the fish recorded in the otolith during its life cycle can be described as a simple mixing process governing $\delta^{18}O_W$ and $\delta^{13}C_{DIC}$ (McConnaughey and Gillikin, 2008). When the migration terminated in March 2008, corresponding to a fish age of approximately 1 year, body size was about 20 cm (Dan, 1980). The correlation between $\delta^{18}$O and $\delta^{13}$C breaks down during the *marine* stage (Figs. 3 and 6a), indicating minimal influence from kinetic-related isotope fractionation (McConnaughey, 1989). Large variability in $\delta^{13}$C can be explained by a combination of three factors, namely variations in $\delta^{13}C_{DIC}$, temperature, and metabolic effects (Schwarcz *et al*., 1998; Thorrold *et al*., 1997; Nonogaki *et al*., 2007). Finally, the catfish reached a length of approximately 30 cm at an age of approximately

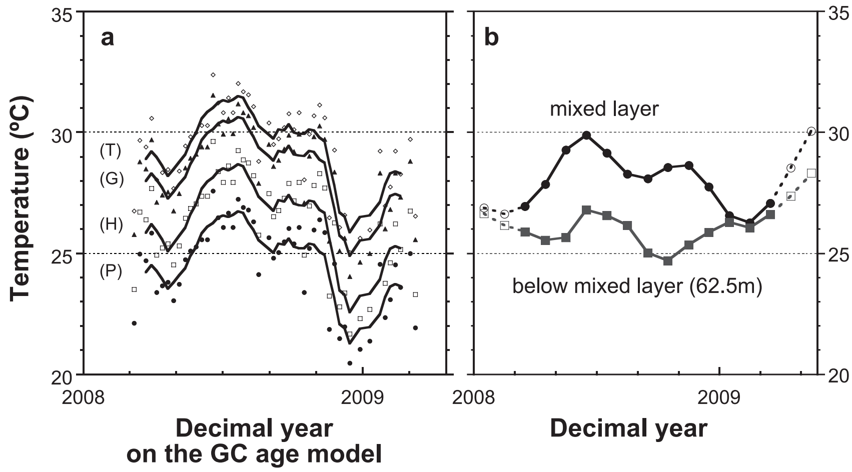


*Fig. 7. Comparison of estimated temperature from otolith $\delta^{18}O$ and measured temperature. (a) Estimated temperature using the equations by Thorrold et al. (1997) (open diamonds), Grossmann and Ku (1986) (closed triangles), Høie et al. (2004) (open rectangles), and Patterson et al. (1993) (closed circles). Dots are original data points and lines are 5-year moving averages. (b) Monthly averaged seawater temperature at the mouth of the Gulf of Khambhat at depths of 0–40 m (black circles) and 67.5 m (gray rectangles).*

2 years (Dan, 1980). This is consistent with the fact that the sexual maturity of the *P. tenuispinis* specimen when it reached body size 27.5 cm was independently proposed based on gonad measurements (Dan, 1977). It is reported that a maximum value in $\delta^{13}$C in otoliths in Atlantic cod is an indicator of sexual maturity (Schwarcz *et al*., 1998). Thus, the otolith record in the present study shows that *P. tenuispinis* did not reach sexual maturity when the migration terminated (Figs. 3 and 6a). This observation is supported by the fact that the catfish was captured at sea, not in an estuary, which is where *P. tenuispinis* brood their offspring (Dan, 1977, 1980).

In order to see reproducibility of $\delta^{18}$O and $\delta^{13}$C increases during migration of *P. tenuispinis*, we employed bulk subsampling for BRH-20 and BRH-21. We collected powder of portions near cores and edges of halved otoliths using a dental drill and measured $\delta^{18}$O and $\delta^{13}$C. Bulk subsampling enables us to obtain representative values for juvenile and adult phases of the catfish. $\delta^{18}$O ($\delta^{13}$C) values of BRH-20 and BRH-21 increased through ontogeny by 0.21‰ (0.15‰) and 1.04‰ (0.53‰), respectively (Fig. 6b). Although magnitude of the changes are different, the pattern of change is similar among the three specimens (Fig. 6b). The relatively smaller magnitude of $\delta^{18}$O increases of BRH-20 compared with BRH-21 and BRH-22 may reflect the smaller proportions in otoliths corresponding to *estuarine* stage relative to *marine* stage. Thus results of bulk subsampling further lend support to migration of *P. tenuispinis*.

### *Implication for $\delta^{18}O$ otolith as a paleothermometer*

The reported temperature dependency of otolith Sr/Ca is based on an empirical assumption (Campana, 1999). Here we employed a previously reported $\delta^{18}$O-temperature equation to obtain water temperatures during the *marine* phase because this is more robust and based on thermodynamic theory (Fig. 7a). It is reported that $\delta^{18}$O of otoliths is not significantly affected by vital effects (Thorrold *et al*., 1997; Campana, 1999; Patterson *et al*., 1993) and that the observed low variability in $\delta^{18}O_{SW}$ in the study region increases the reliability of this thermometer. The equations proposed by Grossmann and Ku (1986) and Thorrold *et al*. (1997) reconstruct instrumental SST well; however, those by Patterson *et al*. (1993) and Høie *et al*. (2004) underestimate SST by as much as 2–4°C (Fig. 7). The discrepancy might be attributable to the method used to obtain the equations. The equation by Høie *et al*. (2004) was derived by rearing cod (*Gadus morhua*) in a cold temperature (6–10°C) environment, whereas the one by Patterson *et al*. (1993) was established by compilation of $\delta^{18}$O for various freshwater fish that live in a wide range of temperatures (3.2–30.3°C). Thus these compilations are heavily biased toward fish that live in temperatures less than approximately 20°C. Such low temperatures differ substantially from the SST range around Gujarat (26–30°C) and therefore we used the equation proposed by Thorrold *et al*. (1997), which was obtained by rearing Atlantic croakers (*Micropogonias undulatus*) in temperatures of 18–25°C, a range spanning the average SST in Gujarat. However, the equation by Thorrold *et al*. (1997) overestimates the maximum temperature in May by as much as about 2°C (Fig. 7). Although the equation by Grossmann and Ku (1986) was originally obtained with biogenic aragonites other than otoliths (in foraminifera, gastropods, and scaphopods), it seems to be most suitable for temperature reconstruction using otoliths of catfish that live in subtropical regions (e.g., Andrus *et al.*, 2002a). The equation by Grossmann and Ku (1986) gives a correct maximum temperature, but underestimates the minimum temperature by 1°C (Fig. 7).

Since the difference in slopes of the various $\delta^{18}$O-temperature equations is minimal (Grossmann and Ku, 1986; Patterson *et al.*, 1993; Thorrold *et al.*, 1997; Høie *et al.*, 2004), the reconstructed seasonal amplitude of temperature must be robust if there is no substantial change in $\delta^{18}O_{SW}$. We observe that the timing of the minimum temperature reconstructed from $\delta^{18}$O of the otolith precedes that of the instrumental SST by approximately 2 months (Fig. 7). This could be due either to an error in the GC age model or to fish movement into colder waters. In the GC age model, we assume that the growth rate of the otolith during the *marine* phase is constant. If the maximum value in $\delta^{18}$O corresponds to the minimum temperature in winter (February 2009), it follows that the otolith would have grown by approximately 500 $\mu$m in 1 month. This interpretation seems unreasonable since it implies a growth rate twice as large as the monthly average during the *marine* phase. On the contrary, as suggested by case study of vertical migration of grenadiers (Lin *et al.*, 2012), *P. tenuispinis* might have migrated to deeper waters during the period from December 2008 and January 2009. We note that vertical migration of ariid catfish, which can live at approximately 200 m depth (Menon, 2003), is very common. Given that the mixed layer in this region is roughly 40 m, it seems that the *P. tenuispinis* specimen moved more than about 60 m vertically, to where water temperature is several degrees colder than SST (Fig. 7b). This implies that we must keep in mind the possibility of underestimation in temperature reconstruction from $\delta^{18}$O of fossil otoliths, in studying paleoenvironments when study sites are deeper than the mixed layer.

## Conclusions

We analyzed $\delta^{18}$O and Sr/Ca in the otolith of an Indian catfish (*P. tenuispinis*). Both records suggested that the fish migrated from the river to the sea and lived there until capture. A model that assumed a conservative mixing process of two end member water bodies (freshwater and seawater), including water chemistry and incorporation of trace elements and isotopes into the otolith, was able to successfully reconstruct the migration history of the catfish in question. The inferred scenario is in good agreement with the known ecology and growth patterns of *P. tenuispinis*. In addition, otolith Ba/Ca and $\delta^{13}$C records are discussed. Water temperature when the fish lived in seawater was reconstructed using the $\delta^{18}$O-temperature equation of Grossmann and Ku (1986) for biogenic aragonite, which agrees well with observed SSTs in the region. The data also suggest that the fish migrated temporally to waters deeper than the mixed layer in the study region.

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