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Otoliths as indicators for fish behaviour and procurement strategies of hunter-gatherers in North Patagonia

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A B S T R A C T

This study evaluates the potential use of archaeological otoliths of *Genidens barbus* (Cuvier and Valenciennes) as a tool to study fish behavior and hunter-gatherers procurement strategies on the North Patagonian coast. The studied samples come from the San Antonio archaeological locality dated at ca. 1000-800 ^{14}C yr BP (Late Holocene). To assess whether exposure to fire significantly affects the otolith Sr:Ca and Ba:Ca ratios, burned and unburned modern *lapilli* otoliths have been analyzed by Laser Ablation Inductively Coupled Plasma Mass Spectrometry and no statistically significant differences were found between the results of both treatments. Core-to-edge chemical time series were carried out on ancient otoliths (ca. 1000 ^{14}C yr BP) in order to study the fish life history. Three amphidromous patterns were found for ancient samples. The capture environments and seasons inferred by the otolith edge chemistry and marginal increase, respectively, suggest a location in high salinity water (estuary and sea) in summer. Finally, to estimate the size of archaeological fish, a linear regression between total length and otolith length was constructed using 70 modern catfish otoliths. The size variability (358–610 mm) might indicate the use of non-selective capture techniques, probably nets, by hunter-gatherer groups.

1. Introduction

The chemistry of modern otoliths has been widely used as a natural tag to describe environmental use and to study the population structure of fish [1, 2, 3, 4, 5]. Otoliths are calcified accretions, mainly in the form of aragonite, located in the ear of the teleostean fish [6, 7]. Otolith constantly incorporates dissolved material (carbon, calcium and other trace elements) from the surrounding environment or from the diet throughout ontogeny [6, 8]. In this sense, the elements that are deposited in the core correspond to early stages of life, while those that are incorporated in the edge correspond to recent periods. In studies on the life history of diadromous fish, migration between environments with different salinities is frequently investigated using Sr:Ca and Ba:Ca geochemical tags, which are positively and negatively related to salinity respectively [9, 10, 11].

Regarding archaeology and paleontology, elemental and isotopic ratios (oxygen, carbon) have been employed for paleoenvironmental reconstructions and to study the ontogenetic history of fishes [12, 13, 14]. However, there are relatively few archaeological studies on reconstructions of life history through otolith chemistry because they require prior knowledge of the relationship between otolith composition and environmental parameters [12, 13, 15]. Moreover, it is common in archaeological studies to collect samples that have been cooked (burned otoliths); therefore, additional experimental works to confirm the stability of elemental ratios should be performed [16, 17]. The analysis of fish size is often employed in archaeological research to infer fishing techniques used by indigenous people. Otolith has been very useful for this purpose, because often it is possible to estimate the archaeological fish size using a mathematical function that relates the otolith weight or size with the fish size of modern samples [e.g. [18]]. Additionally, when the otoliths are well-preserved, the edge increment analysis can provide information about the season of death [19].

Although otoliths from other species (e.g. *Micropogonias furnieri* (Desmarest, 1823)) have been studied in Northeastern Patagonia [20, 21], no studies on Silurids have been performed yet. Silurids of the Ariidae family are the most common species in modern and ancient coastal environments from the Southwestern Atlantic Ocean [22]. In the North-eastern Patagonia, profuse assemblages of *Genidens barbus*

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(Lacépède, 1803), which is currently one of the most abundant species, were recovered (e.g. archaeological otoliths specimens) from archaeological deposits (dated to the Late Holocene), particularly related to the mouth of the Colorado River [23]. Moreover, this species inhabits coastal waters, estuaries and lagoons and exhibits annual movements between environments with different salinities (e.g. anadromous behavior) [5]. In the last decade, the otolith chemistry has allowed to reveal different biological aspects of *G. barbus* such as nursery areas [24, 25], stock discrimination [8, 25, 26] and life history [5, 27]. These studies [8] have shown a direct relationship between the surrounding environment (water composition, salinity) and otolith chemistry, suggesting that especially Sr:Ca, but also Ba:Ca, are good habitat indicators.

The general objective of this work is to evaluate the potential use of archaeological otoliths of *Genidens barbus* as a tool to study the ancient fish behavior and hunter-gatherers procurement strategies on the North Patagonian coast. Particularly the case of the Late Holocene San Antonio archaeological locality from the Pampa-Patagonia transition (Figure 1) is addressed. This study discusses: 1) the potential use of the microchemistry of otoliths exposed to fire (cooked) as habitat indicators, 2) the capability of the otolith microchemistry to reveal the environmental use of archaeological catfish throughout the ontogeny and, 3) the capability of the otolith (microchemistry and annual marks) to estimate sizes, fishing environments and seasonality of catches.

2. Material and methods

2.1. Ecological setting

The eastern Pampa-Patagonia transition (Figure 1) is traversed by the Colorado River and belongs to the so-called "Arid Diagonal" [28]. The local environment corresponds to a warm and dry steppe with semiarid-arid climate, with a mean annual rainfall of 466 mm [29]. Regarding animal and plant species, and given the subject of this paper, only fish will be described thoroughly. Vegetation belongs to the "Distrito del Caldén" and "Provincia del Espinal", although vegetal communities of the "Provincia del Monte" are also recorded [30]. C3 flora predominates although C4 and CAM species are also present in a smaller proportion [31]. Regarding zoogeography, the area is located in the "Subregión Patagónica", "Distrito Patagónico". Ichthyogeographically,

the area belongs to the "Andino-Cuyana" province, represented by Patagonian catfish (*Hatcheria macraei* (Girard, 1855)), velvety catfish (*Olivaichthys cuyanus,* Ringuelet, 1965) and perch (*Percichthys trucha*, Cuvier and Valenciennes, 1840) [32]. There is an overlap in the distribution of freshwater fish species from the Austral and Brasílica subregions between the mouths of the Colorado and Negro rivers [33]. The largest richness of fish species is related to the Colorado River estuary, in which several euryhaline marine species including *Genidens barbus* are present [23]. According to the information provided above, the eastern Pampa-Patagonia transition is characterized as a region of high biological productivity and environmental variability that are consistent with the properties of an ecotone [31, 34].

2.2. The archaeology of the lower Colorado river

Archaeological research in the eastern Pampa-Patagonia transition (Figure 1) has allowed to generate information in several lines of inquiry such as lithic and pottery technology, subsistence, settlement systems, mobility, paleodiets, decorated portable items, mortuary practices, among others (e.g. [35]). All ^{14}C dates were calibrated using Calib Rev.7.1 [36] and the southern hemisphere calibration curve (SHCal13, [37]). The ages are expressed in calendar years at a two-sigma confidence level. Dates mentioned in the text represent the median probability in cal. BP ages. The chronology of the human occupations belongs to the Middle and Late Holocene (ca. 6300–250 ^{14}C yr BP; ca. 7210-287 cal. yr BP) [38]. Among the recorded sites, the San Antonio archaeological locality is the only place related with coastal settlements where residential camps of hunter-gatherers were found [38]. The locality, composed of six archaeological sites, is located c. 4 km from the current Atlantic coast (39°39′34″ S – 62°09′36″ W). The San Antonio 1 and 2 sites, separated only by 700 m (Figure 1), have been systematically studied and present similar stratigraphic sequences [35, 39, 40]. They are located on low aeolian sand dunes partially affected by deflation processes that produced blowouts, overlying alluvial and marine deposits. On the basis of the sedimentary information provided by the excavation of nine test pits from San Antonio 1 and 2 sites, an idealized stratigraphic column was built (Figure 2). The marine basal units contain fossiliferous material such as *Heleobia australis*, *Tagelus plebeius* (in "life position") and *Adelomedon* sp. *Heleobia australis* was dated at 1833 ± 46 ^{14}C yr BP while
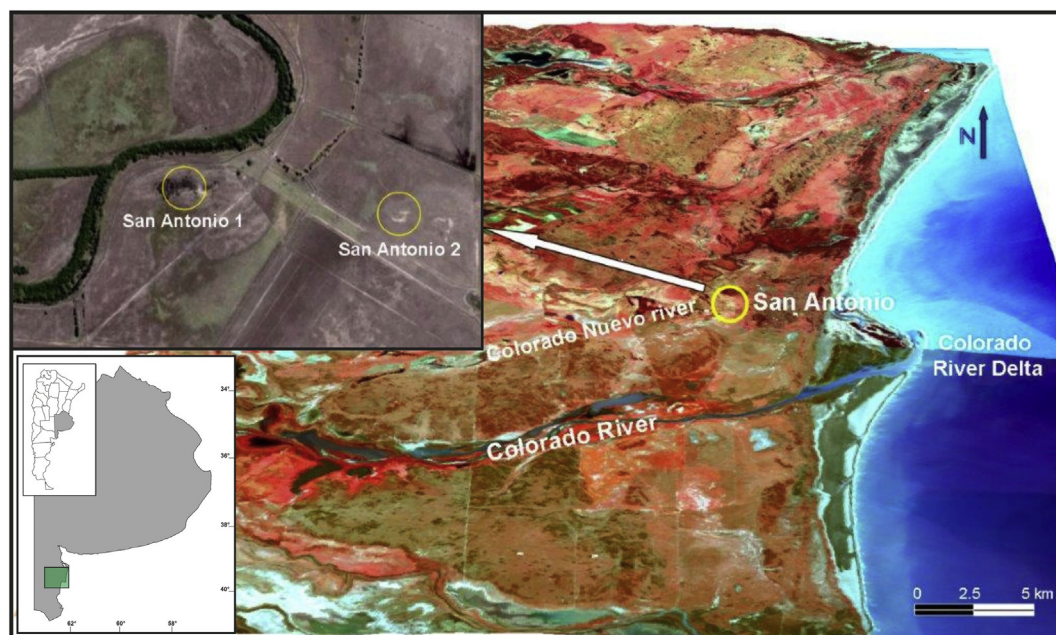

Figure 1. Mouth of the Colorado River and its delta (3D view based on SRTM3 digital model + Aster image (VNIR 1, 2 and 3N bands). Location of San Antonio 1 and 2 sites next to the Rio Colorado Nuevo (taken and modified from Martínez and Martínez [40]). The distance between these sites is 700 m.
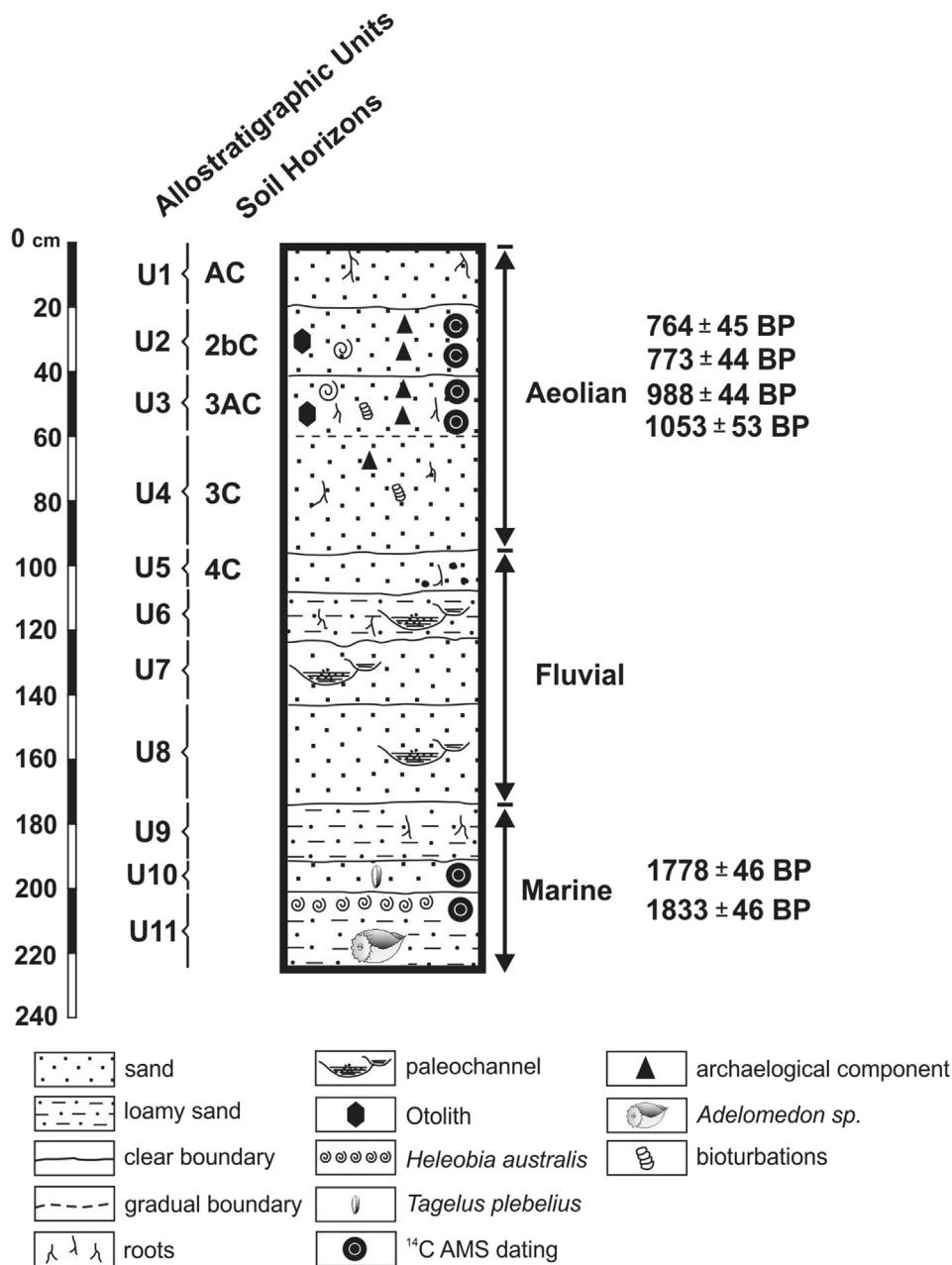
Figure 2. Idealized stratigraphic profile that shows, among other characteristics, otoliths provenience and their chronology (taken and modified from Martínez and Martínez [38, 40]) from SA1 or SA2 (Figure 1).

T. plebeius yielded an age of 1778 ± 36 ^{14}C yr BP [38] (without reservoir effect correction). Clearly at c. 1800 ^{14}C yr BP what today are sandy mantles corresponded to a costal marine environment, which included tidal flats, sandy barrier islands and coastal lagoons [38, 40]. Thus, marine deposits that belong to Holocene ingressions underlie fluvial and aeolian deposits (Figure 2). The overlying alluvial facies correspond to an old meandering system composed of alternating processes of lateral and vertical accretion (e.g. Figure 2, backswamps). The upper stratigraphic units consist of four aeolian sand deposits. A buried soil horizon (e.g. Figure 2, 2bC) was identified in aeolian Unit 2 at both sites. From these aeolian deposits, Units 2 and 3 commonly include archaeological materials and are treated as an archaeological component. Four ages were obtained from bones coming from these units: 773 ± 44 ^{14}C yr BP/673 cal. yr BP (*Lama guanicoe*), 988 ± 44 ^{14}C yr BP/853 cal. yr BP (*L. guanicoe*), 764 ± 45 ^{14}C yr BP/666 cal. yr BP (*L. guanicoe*) and 1053 ± 53 ^{14}C yr BP/911 cal. yr BP (*Homo sapiens*) [38]. As a result, the

archaeological component associated with pedogenetic horizons, where the otoliths are coming from, has a chronological range of ca. 1000-800 ^{14}C yr BP [35].

The archaeological materials recovered in San Antonio locality come from stratigraphic and superficial contexts. The most common artifacts are small stemless triangular projectile points, scrapers, a variety of lithic debris and raw materials, bone tools and pottery. No material culture associated with fishing techniques (e.g. weights, hooks, etc.) has been recorded. The exploited fauna included marine fish (*G. barbus*, *M. furnieri*, *Myliobatis* sp, Chondrichthyes and *Sciaenidae* indet) freshwater fish (*Percichthys* sp), and artiodactyls (*L. guanicoe*) [23, 41]. Some specimens of these species present cut marks, fractures and thermal alteration that indicate human consumption [35]. In addition, the presence of thousands of fragments of shells belonging to *Mesodesma* sp. also indicates that was part of the diet [39]. These sites are interpreted as domestic, residential bases, seasonally used (spring

and summer) mainly for fish procurement, processing and consumption [39].

Genidens barbus otoliths (Figure 3c and d) were identified by using modern collections. The otoliths sample (N = 15) analyzed in this paper comes from test pit #5 of the San Antonio 1 site, which has the highest frequency of fish remains of all sites in the locality (number of identified specimens (NISP), ca. 3000). The marine species are present in higher frequencies; among them the sea catfish fully dominates the assemblages of the entire locality (NISP = 2743; minimum number of individuals (MNI) = 549; Table 1) and presents clear evidence of human exploitation (cutmarks and thermal alterations; [41]).

2.3. Effect of exposure to fire on otolith chemistry

To assess whether exposure to fire significantly affects the otolith composition (Sr:Ca and Ba:Ca ratios), modern *lapilli* otoliths of *G. barbus* were employed (Figure 3c and d). Thirteen fish were caught in the Argentine Atlantic coast (Mar de las Pampas, Buenos Aires; 37°21′44″ S - 57°02′5.27″ W) with hooks at salinity of 27. The total fish length (TL in mm) was recorded and the otoliths were removed. Right otoliths were embedded in epoxy resin and sectioned transversely through the core. The anterior half of each otolith was extracted from the resin and burned with a Bunsen burner until it reached an amber color (Figure 3b), to be embedded again in resin. It should be noted that the method used in this work probably involved temperatures greater than traditional cooking and probably does not represent exactly the cooking conditions, but rather, a more extreme fire exposure. Subsequently, both halves (burned and unburned) were sectioned (containing the core) to a thickness of 1000 μm using a Buehler Isomet low speed saw (Hong Kong, China) (Figure 3a and b). Finally, Sr:Ca and Ba:Ca ratios were measured in the last growth area (outermost 100 μm) and compared between both treatments (see below).

2.3.1. Fish total length estimation

To estimate the size of archaeological fish, a linear regression between total length (TL, in mm) and otolith length (OL in mm) was constructed using 70 modern catfish otoliths (fish total length range: 240–837 mm). These otoliths belong to fish collected at the Río de la Plata Estuary (Argentina) between 2010 and 2015. The ventral face of each right archaeological and modern otolith was photographed using a Nikon Coolpix L110 digital camera at the same focal length. All images were taken with a black background with a 1 × 1 cm scale. Otolith length was measured in all pictures by using an image processing system (Image-Pro Plus 4.5).

2.3.2. Fish life history, environment and season of catch

Archaeological otolith sections (thickness: 1000 μm) were obtained as described above. Core-to-edge otolith measurement (Sr:Ca and Ba:Ca)

transects were carried out (Figure 3e) in order to study the fish life history. Transition thresholds (otolith Sr:Ca values) between freshwater-estuary and estuary-sea habitats were used to interpret the fish movement patterns through ontogeny. We estimate the sea reference values using the edge Sr:Ca ratio (last 50 μm, Figure 3) of the modern otoliths from the North Patagonian coast (N = 13) caught at a salinity of ~27. These values were contrasted with those reported previously by Avigliano et al. [5]. Moreover, *G. barbus* Sr:Ca reference values between 1.0 and 2.8 mmol/mol for freshwater were reported by Avigliano et al. [5]. Salinity thresholds based on otolith Ba:Ca ratio were not used because it is known that this is strongly susceptible to factors such as freshwater inputs or water composition, and they may vary according to the geological characteristics of the estuaries [5].

The Sr:Ca reference values and the core-to-edge Sr:Ca transects were plotted together in order to facilitate the interpretation of fish movement through life time. Habitat patterns were classified in amphidromous types: a, b and c, according to Avigliano et al. [5]. Amphidromous type a is defined as fish spawned in freshwater and moved at least once to a marine environment (like anadromous behavior), while the type b corresponds to individuals spawned in freshwater that migrate to brackish water (semi-anadromous, fish do not use marine environment). The type c is defined as individuals spawned in estuarine water that migrate to freshwater or marine environments. In addition, the Sr:Ca ratios of the archaeological otolith edges (50 μm) were compared with the modern reference values to estimate the possible fishing environments.

In order to infer the season of catch, the hyaline or opaque areas of the otolith edge were examined [19]. According to Reis [42] the ring formation in *G. barbus* has an annual periodicity: the complete hyaline edge is formed in December (summer) (Figure 3f), while the maximum width of the last opaque zone is observed between September and October (spring) (Figure 3g). In this regard, the presence of hyaline or opaque areas was examined by observing the archaeological otolith sections immersed in water under a stereo-microscope (Leica EZ4-HD, Singapore) with transmitted light (40X).

2.4. Trace elemental analysis

Archaeological and modern otolith sections were fixed to glass slides using epoxy resin and polished using 9 μm-grit sandpaper. After polishing, sections were rinsed with distilled water and sonicated for 5 min in Milli-Q water (resistivity of 18.2 mOhm/cm).

The isotopes ^{138}Ba, ^{88}Sr and ^{43}Ca were measured by Laser Ablation Inductively Coupled Plasma Mass Spectrometry (LA-ICP-MS). The laser system consisted of a 193 nm ArF Excimer laser (Photon Machines Analyte G2) coupled to an ICP-QMS Agilent 7700 (Santa Clara, USA). A circular aperture of 50 μm was used at 10 μm/s (repetition rate: 10 Hz; fluence: 5 J/cm^2). Helium was used as the carrier gas (flow: 800 ml/min) in the laser ablation cell and Ar was added before entering the ICP, which

Table 1. Abundance of fish species from the study area (taken and modified from Stoessel [48]). References: NISP: number of identified specimens; MNI: minimum number of individuals (Lyman 1994).

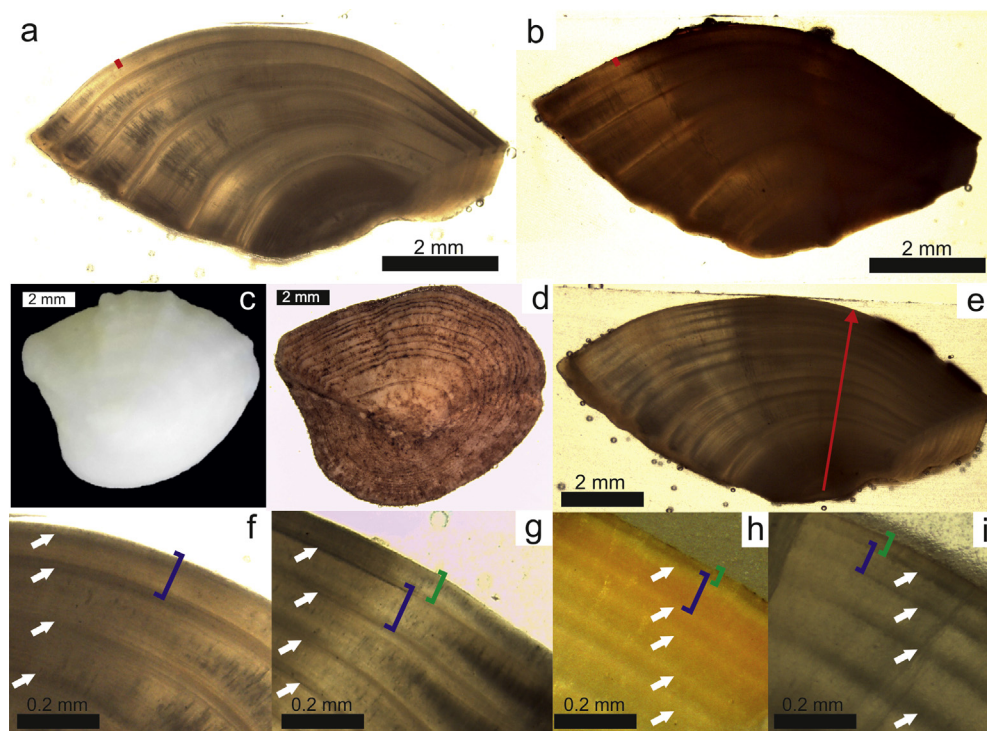| Taxa	San Antonio locality		
	NISP	NISP%	MNI
Teleostei			
Genidens barbus (catfish)	2743	82.15	549
Micropogonias furnieri (white croaker)	254	7.60	80
Pogonias cromis (black drum)	8	0.23	2
Percichthys sp. (perch)	205	6.13	15
Sciaenidae indet.	75	2.24	3
Chondrichthyes			
Myliobatis sp. (eagle ray)	25	0.74	3
Chondrichthyes indet.	29	0.86	5
Total	**3339**	**100**	**657**

Figure 3. *Genidens barbus* otoliths. a) Section of an unburned modern otolith. b) Section of a burned modern otolith. c) Modern otolith from Rio de la Plata Estuary, Argentina. d) Ancient otolith from San Antonio 1. e) Transect of the Sr:Ca and Ba:Ca measurement by LA-ICPMS. f) Complete *annuli* of the modern otolith edge from a catfish caught in January. g) Incomplete *annuli* of the modern otolith edge from an individual caught in October. Small (h) and large (i) marginal increments in ancient otoliths. Purple and green square brackets represent the last complete *annuli* and the marginal increment, respectively.

was operated at a power of 1600 W. MACS-3 (trace elements in synthetic calcium carbonate, Geology, Geophysics, and Geochemistry Science Center, USA) and NIST 612 (trace elements in glass, National Institute of Standards and Technology, USA) reference materials, analyzed in triplicate every 10 samples, were used as primary and secondary standards, respectively (Jochum et al., 2011; Pearce et al., 1997). The ^{238}U/^{232}Th (<1.2) and ^{232}Th^{16}O/^{232}Th (<0.40 %) ratios in NIST 612 were used for monitoring the plasma robustness. Moreover, elemental quantification was carried out using ^{43}Ca (38.3 weight % in the otoliths) as internal standard (Yoshinaga et al., 2000). Reference materials' recoveries showed acceptable values for ^{138}Ba (98 %) and ^{88}Sr (115%). Subsequently, elemental concentrations were expressed as molar ratios in relation to Ca (Sr:Ca and Ba:Ca in mmol/mol and μmol/mol, respectively).

2.5. Statistics

Linear regression analysis was employed to assess the elemental relationship between burned and unburned samples (last ~50 μm). In addition, a student *T*-test was performed to detect whether the slope of the linear best-fit was equal to 1 and then test for the occurrence of a difference in elemental signature. Mann-Whitney U test was performed to analyze the elemental differences between burned and unburned samples. The size of the archaeological fish was estimated using a linear equation based on data from modern catfish. All estimates were made considering a 95% confidence interval.

3. Results

3.1. Effect of exposure to fire on otolith chemistry

Modern otolith edge Sr:Ca ratio was 4.47 ± 0.39 and 4.31 ± 0.24 mmol/mol, while Ba:Ca was $5.6 \times 10^{-3} \pm 1.1 \times 10^{-3}$ and $6.1 \times 10^{-3} \pm 6.4 \times 10^{-4}$ μmol/mol for burned and unburned samples, respectively. No significant differences were found in the Sr:Ca (H = 114, p = 0.49) and Ba:Ca (H = 93, p = 0.36) ratios between both treatments.

A significant linear relationship was found for Sr:Ca (R^2 = 0.78; F = 27, p-value = 0.0008) and Ba:Ca (R^2 = 0.54; F = 8, p-value = 0.024) between burned and unburned samples (Figure 4). The slopes obtained were not significantly different from 1 (Sr:Ca = 1.2 and Ba:Ca = 0.94, p > 0.05).
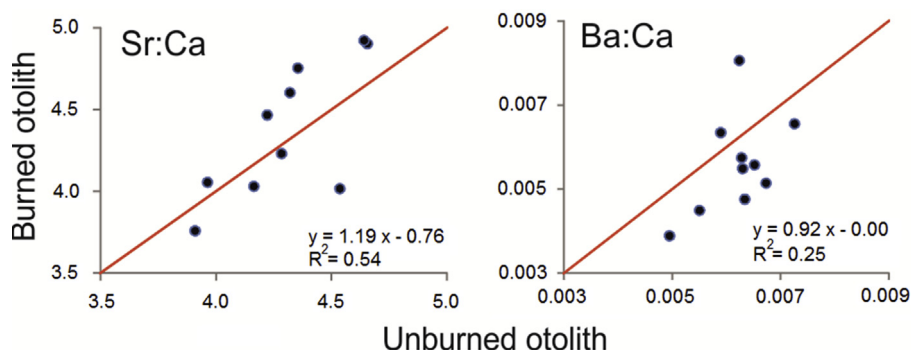

Figure 4. Otolith edge Sr:Ca linear relationship between burned and unburned otoliths.

3.2. Fish total length estimation

Considering the modern fish, a significant linear relationship ($R^2 = 0.86$, $F = 407$; p-value $= 0.0001$) was found between total length otolith and fish total length, where the equation slope was 64.6 and the ordinate was 325.6 mm. The estimated total length of the archaeological fish ranged from 358 to 610 mm (mean $\pm$ SD: 446 $\pm$ 71 mm, Table 2).

3.3. Fish life history, environment and season of catch

Otolith Sr:Ca ratio ranged from 1.38 to 9.09 mmol/mol. For all samples, the core Sr:Ca ratio matched reference values for freshwater or estuary (Figure 5). According to the Sr:Ca profiles, the amphidromous pattern type a, b and c were found in 53% (N = 8), 13% (N = 2) and 33% (N = 5) of the archaeological samples, respectively (Figure 5).

Ba:Ca ratio varied between 0.0072 and 0.43 µmol/mol. Peaks of Ba:Ca ratio were observed in the otolith core followed by a marked drop throughout the life time.

Around 53% (N = 8) of the archaeological otolith edges were within the estuarine range (3.09–3.87 mmol/mol) of Sr:Ca values, while 26.7% (N = 4) were within Sr:Ca range (3.92–4.42 mmol/mol) for salinity~27 (Figure 6, Table 2). The remaining 20% (N = 3) were higher (4.61–5.64 mmol/mol) than that reference range (Figure 5, Table 2).

The marginal increase of the archaeological otoliths showed a thin opaque zone (very close to the hyaline zone) for 14 samples (~93%) (Figure 3h), which suggests that exploitation occurred during the summer months, after December (maybe from December to March). Only one sample had a marginal increase around 50% (opaque edge), suggesting a potential capture in winter-spring (Figure 3i).

4. Discussion

4.1. Effect of exposure to fire on otolith chemistry

Disspain et al [17] examined the effects of six traditional processing and cooking methods on chemical composition of *Argyrosomus japonicus* otoliths. The cooking methods included exposure to temperatures from 49 to 939 °C during 20 min. In that study, Sr:Ca and Ba:Ca did not differed significantly among treatments, indicating that these ratios could be used in palaeo-research.

The effect of cooking on the otolith elemental composition was also tested in other ariids like *B. marinus* [16]. Based on six *lapilli* otoliths, Andrus and Crowe [16] reported that otolith composition could be altered after using five different methods such as boiling in seawater and

freshwater, roasting and direct burning in hardwood coals to simulate cooking. In particular, these authors reported that the Sr variation was lower than that of other elements, such as P and Na, suggesting greater stability related to inclusion in the aragonite matrix. Nevertheless, they used only one sample (N = 1) for each method (five cooking methods and one otolith control) and made comparisons among left and right otolith. According to Disspain et al. [17], variations reported by Andrus and Crowe [16] may be related to fish anomalies or variations in preparation or storage methods. Here, we have performed the experiments on the same otolith by dividing it in a half untreated and the other burned, discarding potential physiological differences between right and left. Similar to Disspain et al. [17], our results show that there are no statistically significant differences between the control and the burned samples.

4.2. Fish life history

Movement patterns were inferred using Sr:Ca estimated reference values (mean $\pm$ SD, 4.32 $\pm$ 0.24 mmol/mol) for salinity of ~27. These values were consistent with those reported by Avigliano et al. [5] for *G. barbus* from the Brazilian coast (mean $\pm$ SD, 4.32 $\pm$ 0.83 mmol/mol).

The range of otolith Sr:Ca ratio found in this paper was also comparable with that reported for modern catfish (0.90 - 9.83 mmol/mol [5]), while the range of Ba:Ca was different between modern (0.0072 - 0.43 µmol/mol [5]) and ancient (0.00013 - 0.10 µmol/mol) fish. In modern fish, otolith Ba:Ca is highly variable among estuaries [24, 26]. The incorporation of Ba:Ca in otoliths of *G. barbus* is highly sensitive to its availability in water, being less potent as an indicator of salinity than the Sr:Ca ratio [5, 8].

Life history patterns of the ancient catfish were very comparable with those reported for modern fish [5, 27]. Herein, we have found the three migratory patterns (Figure 5) reported for the species [5, 27], while the freshwater resident pattern has not been found. In modern catfish, the freshwater resident pattern is uncommon, and was only reported in some specimens from the Patos Lagoon (Brazil) [5, 27].

G. barbus perform amphidromous and reproductive migrations from the sea to upstream in spring (September–November), moving to regions of relatively low salinity such as rivers, lagoons or estuaries [5, 43, 44]. After the reproductive event, the fish returns to the lower area of estuaries and open sea waters from December [43, 44], just when the otolith annual mark is completed [42]. In this sense, the capture environments and seasons inferred in this paper are consistent, because they suggest a location in water masses with relatively high salinity in summer (maybe after December).

Estuarine catches (salinity <27) suggest the presence of water masses with relatively low salinity in the study area (estuaries or rivers). This is

Table 2. Metadata of the otoliths (OL, otolith length) and edge Sr:Ca (mean $\pm$ SD) results. Different estimates are also shown (fish total size plus confidence interval (CI), fishing season and environment).

| ID	OL (mm)	Estimated TL (mm)	CI (mm)	Marginal increment (%)	Capture season	Edge Sr:Ca (mmol/mol)	Capture environment
1	12.37	473.6	379.6–567.6	15	summer	3.62 $\pm$ 0.55	estuary
2	10.57	357.4	262.1–452.7	15	summer	4.00 $\pm$ 0.16	sea
3	13.50	546.1	452.1–640.0	15	summer	3.87 $\pm$ 0.63	estuary
4	10.96	382.4	287.5–477.3	20	summer	3.92 $\pm$ 0.43	sea
5	11.18	396.8	302.1–491.5	15	summer	3.66 $\pm$ 0.48	estuary
6	11.71	431.0	336.7–525.4	15	summer	4.08 $\pm$ 0.32	sea
7	14.47	609.0	514.7–703.3	15	summer	3.11 $\pm$ 0.26	estuary
8	10.61	359.9	264.7–455.2	15	summer	3.36 $\pm$ 0.24	estuary
9	11.94	445.3	351.1–539.5	15	summer	3.09 $\pm$ 0.45	estuary
10	11.71	430.9	336.6–525.2	0	summer	3.78 $\pm$ 0.49	estuary
11	11.95	446.5	352.3–540.7	15	summer	3.81 $\pm$ 0.64	estuary
12	11.09	390.8	296.0–485.6	15	summer	4.42 $\pm$ 0.35	sea
13	12.96	511.5	417.6–605.4	0	summer	4.96 $\pm$ 0.97	sea
14	12.52	483.4	389.4–577.3	15	summer	5.46 $\pm$ 0.64	sea
15	11.44	413.1	318.6–507.6	50	winter-spring	4.61 $\pm$ 0.24	sea
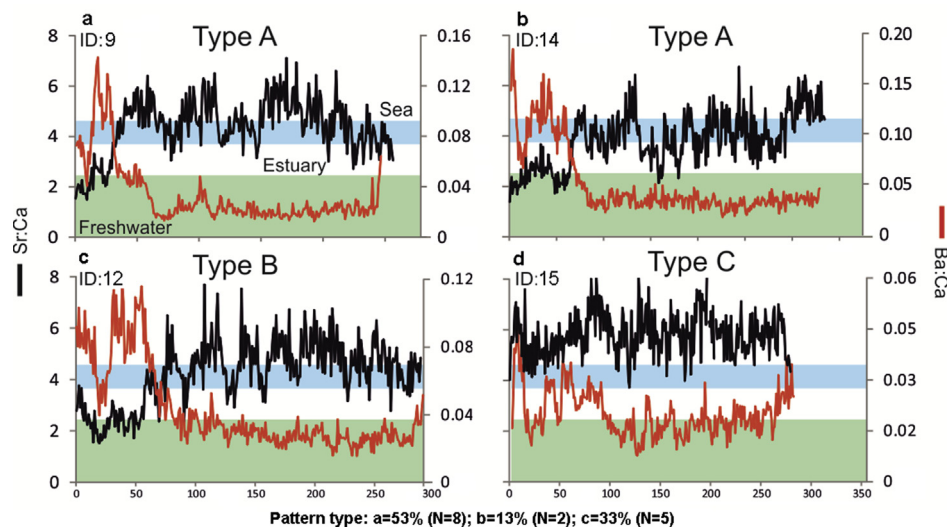
Figure 5. Otolith microchemical profiles of *Genidens barbus* from core to edge. The green and blue areas indicate freshwater and saltwater (~27) use, respectively. Type a, b and c corresponds to different amphidromous patterns.
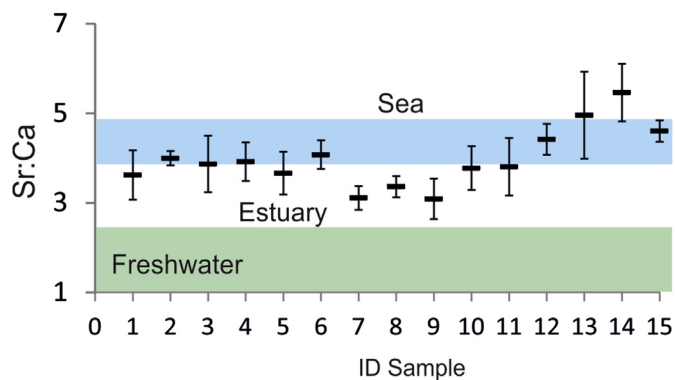

Figure 6. Mean (±SD) otolith edge Sr:Ca of *Genidens barbus*. The green and blue areas indicate freshwater and saltwater (~27) use, respectively.

supported by the presence of anadromous specimens, which use these systems for reproductive purposes [5]. In modern catfish, it has been reported that adult migrants are strongly related to the area of breeding or spawning (rivers or estuaries) throughout life [24, 25], and even homing has been suggested [24].

4.3. Archaeological implications

In the archaeological locality of San Antonio, on the basis of the overwhelming presence of eurihaline marine species, especially catfish, Martínez et al. [39] proposed that these residential bases had been seasonally occupied during spring and early summer. Results obtained in this paper are in agreement with the seasonal pattern of capture and allow to better adjust the period of fishing to December–March. Only one specimen indicates a winter-spring capture, which could show a relatively flexible seasonal occupation, for example, being able to occur in some cases earlier (e.g. spring).

Obtained results indicates a significant variability in sizes of catfish (Table 2) representing both juvenile and adult individuals. As shown in Table 1, despite the abundance of *G. barbus* other fish species have also been captured. Variability in sizes and species diversity indicates the use of non-selective capture techniques, probably nets. The same technique was proposed for obtaining perch in the inland portion of the study area [45]. As previously mentioned no material culture associated with

fishing techniques has been recorded in the archaeological record at San Antonio, which makes it difficult to assign the captures to particular techniques. This situation contrasts with evidence obtained in neighboring areas such as the north and west coast of the San Matías Gulf where net-weights [20] and even fishing stone structures that work as weirs or fish traps [46] have been recorded.

Despite the absence of material culture related with fishing, the ethology of *G. barbus* in association with the mouth of the river and estuary could promote the capture of some marine specimens relatively easily and without employing complex technical devices. Some chronicles described particularities related to the acquisition of fish in the study area. In this sense, by 1870, the farmer Teófilo Gomila was a captive of the indigenous people. When he escaped, on the road along the lower course of the Colorado river he reached its mouth and commented that the sea: "…penetrates the beach in the low parts of the sandbanks, forming streams and small lagoons, where an incredible quantity of fish of all sizes enters (…). Exquisite fish of all kinds demanded no more than gathering them when the sea withdrew (…) and they were stranded…" (translated from de Jong and Satas [47], page 140).

5. Final remarks

Our results suggest that the chemical composition of *G. barbus* burned otoliths could be considered to study different archaeological aspects. From the biological point of view, the migratory patterns of the ancient fish were comparable with the modern ones.

From an archaeological perspective two main aspects deserve to be highlighted. Results obtained in this paper were useful to confirm the seasonal capture (December–March) of fish already proposed for the San Antonio locality throughout other lines of evidences. On the other hand, the diversity in specimen's sizes of *G. barbus* allowed to propose the use of nets as a non-selective capture techniques in zones related with an estuary-sea range.

Declarations

Author contribution statement

Esteban Avigliano: Conceived and designed the experiments; Performed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper.

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