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Fossil otoliths, from the Gulf of Kutch, Western India, as a paleo-archive for the mid- to late-Holocene environment

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Abundantly available catfish otoliths excavated from the ruins of the Indus civilization, in the coastal regions of Western India, are expected to preserve a detailed paleoclimatological record of the mid- to late-Holocene. In this study, we analyzed saltwater catfish otoliths recovered from the Gulf of Kutch, Western India. Stable isotopes (oxygen and carbon) and elemental ratios (Ba/Ca and Sr/Ca) were measured by isotope ratio mass spectrometry (IRMS) and high-resolution laser ablation inductively coupled plasma mass spectrometry (LA-ICP-MS), respectively. Oxygen isotopes of a modern otolith ($\delta^{18}O$) indicates the interval when the catfish would have dwelt in the sea and appear to record seasonal temperature variability with a precision of 1 C°. Calculated temperatures from $\delta^{18}O$ of a fossil otolith dated to 4.3 cal ka BP indicates that the minimum temperature in winter was ~2.5 C° lower than that of the present. Although comparison to alkenone results from the northwestern Arabian Sea indicates potential temperature underestimation, further measurements of modern and fossil samples would lead to more precise reconstruction of temperature history during mid- to late- Holocene.

1. Introduction

Reconstruction of Western Indian climate is important to understand the relationships between climate variability and the rise and fall of the Indus civilization around 4.2 ka. A number of studies reported that severe environmental changes occurred simultaneously in different parts of the world, such as East Asia, Europe, North America, and Western India (Walker et al., 2012). Widespread aridification caused by the abrupt weakening of Indian monsoons is associated with the decline of the Indus civilization that had flourished in Western India (Staubwasser et al., 2003; Berkelhammer et al., 2012; Dixit et al., 2014). However, the degree of synchronous global climate change remains unclear because some paleoenvironmental reconstructions from various proxies do not always show drastic change at ca. 4.2 ka (e.g. Doose-Rolinski et al., 2001; Fleitmann et al., 2003, 2007; Staubwasser et al., 2003; Prasad and Enzel, 2006; Berkelhammer et al., 2012; Dixit et al., 2014). As there are many Indus period sites that existed before and after 4.2 ka around the coastal regions of the Gulf of Kutch, Western India (MacDonald, 2011), this is a key region to study.

Climate reconstructions in Western India are also important to understand the mechanism of the Indian monsoon. Western India is a particularly sensitive region to monsoon precipitation because of a very steep meridional isohyet gradient with a humid area in the south and a semi-arid area in the north (Prasad and Enzel, 2006). To date, climate reconstructions from ca. 4.2 ka are limited to inland regions of Western India (e.g. Prasad and Enzel, 2006; Dixit et al.,

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2014). By reconstructing the climate in the coastal region, we can not only obtain insights on regional climate change of Western India but also outline its relationship to the Indian monsoons.

In paleoclimatology and paleoceanography, fossilized biominerals of calcifying organisms such as corals and mollusks are widely used (e.g., Yokoyama et al., 2011; Seki et al., 2012; Hirabayashi et al., 2013; Kubota et al., 2014). Organisms with incremental growth rings enable us to reconstruct high-resolution records (e.g. in seasonal timescales) by microanalysis of chemical signatures along the growth axis (i.e. sclerochronology; e.g. Morrongiello et al., 2012; Kawakubo et al., 2014). However, fossil corals and shellfish around 4.2 ka are rarely found in the coast of Western India. Therefore, fish otoliths, excavated abundantly (Chen et al., 2011) from the Indus ruins, are an important potential resource to conduct paleoenvironmental research. Otoliths are common to all teleost fish and are calcified structures that typically exhibit growth rings due to incremental formation. Therefore, chemical analyses along the growth axis of otolith can provide continuous high-resolution records of various parameters (Campana, 1999).

It is known from laboratory experiments that oxygen isotope fractionation in otoliths is independent from kinetic and metabolic effects and primarily thermodynamic in nature (Patterson et al., 1993; Thorrold et al., 1997; Høie et al., 2004; Long et al., 2014). Hence, otolith oxygen isotopes ($\delta^{18}O_o$) have been used as a proxy for water temperature and $\delta^{18}O$ of the water body ($\delta^{18}O_w$). For instance, when a fish dwelt in the sea where $\delta^{18}O_w$ is relatively stable, $\delta^{18}O_o$ is a high-resolution paleothermometer of the seawater on seasonal to interannual timescales (Surge and Walker, 2005). For freshwater fish, $\delta^{18}O_o$ has been used to reconstruct changes in rainfall amount and storm intensity (Walker and Surge, 2006). However, some migratory fishes experience large changes in $\delta^{18}O_w$ during their life histories (e.g. from the river to the sea; Carpenter et al., 2003), which makes it necessary to identify the sections of otolith that correspond to fresh and seawater in order to use $\delta^{18}O_o$ as a paleothermometer.

Ba/Ca and Sr/Ca ratios of otoliths have been used to estimate habitats of fish by utilizing geochemical differences between water bodies (Campana, 1999). The values of Ba/Ca and Sr/Ca in the water bodies ($(Ba/Ca)_w$, $(Sr/Ca)_w$) are distinctly different between marine and riverine/brackish water; in general, $(Ba/Ca)_w$ of riverine/brackish water is higher than that of the seawater, while $(Sr/Ca)_w$ of riverine/brackish water is lower than that of the seawater. The values of $(Ba/Ca)_w$ and $(Sr/Ca)_w$ of seawater can be regarded as constant because of the long residence times of strontium, barium, and calcium relative to the timescale of ocean circulation (Millero, 2005). Otolith Ba/Ca and Sr/Ca ratios are influenced by temperature, salinity, and chemical compositions of the ambient water bodies (Campana, 1999).

Marine catfish otoliths are the largest among those excavated from the ruins, and they enable us to obtain long and high-resolution records. However, the lack of ecological information of the catfish in the Gulf of Kutch hampers paleoenvironmental reconstructions. Therefore, this study has been designed to tackle the following three issues through high-resolution geochemical analyses of modern and fossil otoliths: (1) to understand catfish ecology; (2) to determine an appropriate $\delta^{18}O_o$-temperature equation; (3) to estimate sea surface temperature (SST) at ca. 4.3 ka.

2. Methods

2.1. Study area

The Gulf of Kutch stretches east to west by more than 100 km and is very shallow, with a typical depth range of 10–20 m and a maximum of 40 m (Fig. 1). The eastern gulf opens into the high saline marshy area, the Little Rann of Kutch, which was inundated from 6 ka to 2 ka (Ramaswamy et al., 2007). The maximum and minimum temperatures offshore at the closest grid point from the mouth of the Gulf (23.3°N, 67.5°E) from 2006 to 2010 were ~30 °C in July–August and 24 °C in January–February, respectively (Figs. 1 and 2a). The Gulf is well mixed, and the temperature does not change vertically (Varkey et al., 1977). The salinity at the site (23.3°N, 67.5°E) shows subtle seasonal variation ranging as small as 0.4 psu (Fig. 2b). On the other hand, the salinity in the inner part of the Gulf is generally higher than that of the open ocean, over 40 in some cases (Vethamony et al., 2007). Almost 90% of annual precipitation occurs in the monsoon season (May–October) when the intertropical convergence zone passes over the Indian subcontinent (Fig. 2c). The total amount of rainfall varies substantially year-to-year, ranging from 500 to 1000 mm. Monthly-averaged seawater temperature and salinity data were obtained from the Global Data Assimilation System (GODAS, http://iridl.ldeo.columbia.edu/SOURCES/.CMA/.BCC/.GODAS/) (Liu et al., 2005). Monthly rainfall data in Saurashtra and Kutch were obtained from the Open Government Data Platform in India (http://data.gov.in).

A limited number of seawater $\delta^{18}O$ ($\delta^{18}O_{SW}$) data from inside the Gulf are available. Summer $\delta^{18}O_{SW}$ is ~0.3‰ higher than that in winter (0.61‰ in December and 0.93‰ in May; Chakraborty and Ramesh, 1998). This is probably because of a gradual intensification of evaporation during the dry season in winter, which increases $\delta^{18}O_{SW}$ to maximum prior to the arrival of the summer monsoon. A forty-two year coral record indicates pronounced interannual variability of $\delta^{18}O_{SW}$ (Chakraborty and Ramesh, 1998).

2.2. Catfish ecology and samples

A fossil sample (BSR7) was excavated in Bagasra village (23°3′30″N 70°37′10″E), on the southeastern shore of the Gulf of Kutch in Maliya Taluka of Rajkot District, Gujarat (Fig. 1), and it appears to be an ariid catfish. This was compared to a modern catfish (*Siluriformes*, *Ariidae*), referred to as sample SNP27, that was

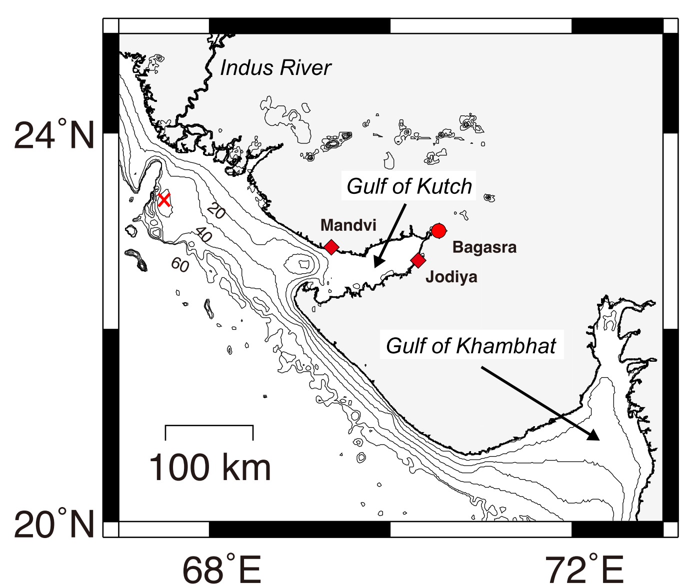

Fig. 1. Gulf of Kutch, Western India. Modern samples were obtained from fisheries of Jodiya or Mandvi. Fossil samples were obtained from a ruin in Bagasra. The cross represents the location where seawater temperature and salinity were observed.