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# Otoliths in archaeology: Methods, applications and future prospects

Morgan C.F. Disspain [a,*], Sean Ulm [b], Bronwyn M. Gillanders [a]

[a] Southern Seas Ecology Laboratories, School of Biological Sciences, University of Adelaide, SA 5005, Australia
[b] College of Arts, Society and Education, School of Arts and Social Sciences, PO Box 6811, James Cook University, Cairns, QLD 4870, Australia

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ABSTRACT

Otoliths are small structures found in the inner ear of teleost fish that act as organs of equilibrium and as direction and sound detectors. They possess unique characteristics that set them apart from other skeletal structures, notably a continuous growth structure deposited on a daily basis. While otolith analyses are widely employed in modern fisheries studies, they have slowly been increasing within archaeological and palaeoenvironmental research. This paper overviews the development and future prospects of otolith studies in archaeology. The main methods of analysis are outlined and major advances and research in each area detailed. In spite of some limitations, the benefits and unique information that otolith analyses can provide ensure that otoliths should be an important part of archaeological research. Continuing development of methods and technologies within this area will serve to further increase the importance and use of otoliths, while raising the profile of this unique resource.



## 1. Introduction

Otoliths are small structures found in the inner ear of teleost fish that act as organs of equilibrium and as direction and sound detectors (Popper and Fay, 2011). The three pairs of otoliths are termed the 'sagittae', 'lapilli' and 'asterisci', and are each contained within individual vestibules (Fig. 1) (Campana, 2004). They form in the embryonic stages of the fish, grow continuously throughout its life, and are composed of alternating layers of calcium carbonate (usually in the mineral form aragonite) and protein, which are deposited on a daily basis (Campana and Neilson, 1985; Pannella, 1971; Payan et al., 2004).

Otoliths possess unique characteristics that set them apart from all other skeletal structures. Otolith growth is continuous and is maintained even through periods when somatic growth is virtually nonexistent (Campana, 1990; Secor and Dean, 1989). As they form, otoliths absorb elements from the ambient water, which vary in relation to environmental conditions, such as salinity and temperature. They are acellular, meaning that once the material in otoliths is deposited, it is generally not reworked or resorbed (Campana and Neilson, 1985); otolith chemistry is thus a function of the environmental conditions experienced by the fish. This is a very important property of the otolith for palaeoenvironmental and archaeological applications. Their chemical composition affords the possibility of environmental reconstruction that, when matched with otolith biochronologies, can allow the lifetime of an individual fish to be placed retrospectively within time and space (Campana and Thorrold, 2001:37).

A large array of data are able to be recovered from otoliths, including species identification, age and growth studies, seasonality, radiocarbon dating and trace element and isotope analysis, which are discussed in this paper. Information gained from such analyses can address broad and often key archaeological issues. Otolith studies frequently contribute to answering questions focusing on changes in fish population structures, including examining impacts of intense human predation, environmental change and habitat destruction. The determination of ecological baselines is an essential step toward restoring native fish populations to pre-industrialised fishing levels, and as fisheries catch records generally only provide information from the last hundred years or so, otoliths, along with other fish remains, hold vital information frequently used for establishing knowledge of ancient fish stocks. There are some issues intrinsic to using anthropogenically compiled assemblages (Reitz, 2004), and Indigenous populations often had notable impacts on faunal populations (Holdaway and Jacomb, 2000; Mannino and Thomas, 2002; Wragg, 1995); however, it is undeniable that impacts experienced after the industrialisation of fishing have been unparalleled in human history. Otoliths also provide a wide range of information regarding the past occupants of a site; human subsistence strategies, fishing methods and technologies, trade routes, seasonality of site usage, and past human responses to environmental changes can all be examined through the analysis of these small carbonate structures.

Otolith analyses are widely employed in modern fisheries studies (for recent overviews, see Begg et al., 2005; Campana, 2005; Elsdon

* Corresponding author.
*E-mail address:* morgan.disspain@adelaide.edu.au (M.C.F. Disspain).

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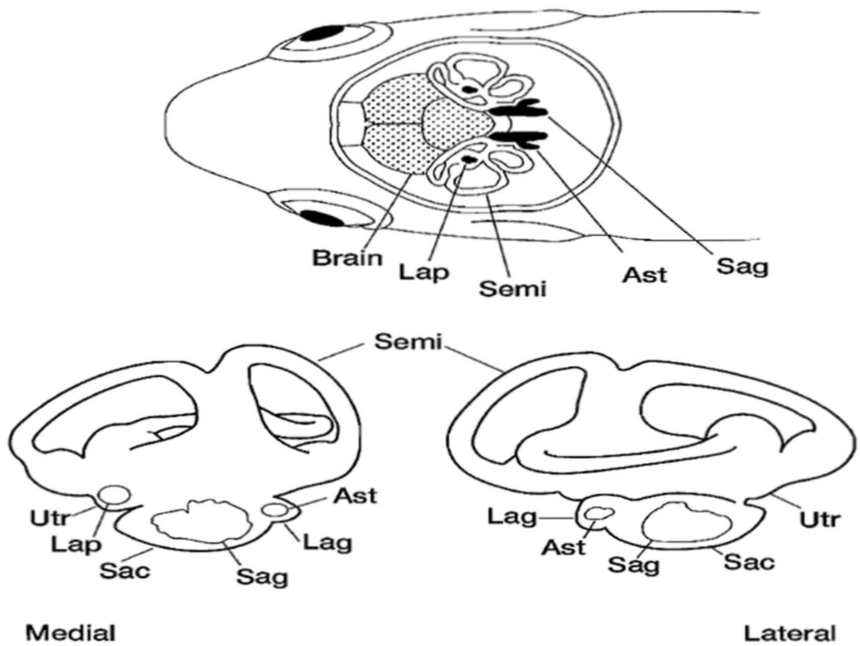


**Fig. 1.** Schematic of the location of the inner ear and three pairs of otoliths in the skull of a generalized teleost. *Top*, Dorsal view of the inner ear and otoliths in relation to the brain in a cutaway of a fish skull (modified from Secor et al., 1992). *Bottom*, Position of otoliths and otolith chambers in the inner ear of the teleost *Trichogaster* (*modified from* Popper and Hoxter, 1981). Ast, asteriscus; Lag, lagena; Lap, lapillus; Sac, sacculus; Sag, sagitta; Semi, semi-circular canal of labyrinth; Utr, utriculus (used with permission from Campana, 2004:2).

et al., 2008; Sturrock et al., 2012), and have been slowly increasing in archaeological applications. In 1891, otoliths were excavated from an archaeological site in Rio Grande do Sul, Brazil, and identified to species through comparisons with modern samples collected from fish in nearby streams (Ihering, 1891 in Fitch, 1972). Despite these promising beginnings, otolith analysis seems to be absent from archaeological literature until the mid-20th century, when discussions of otoliths from archaeological sites start to re-appear (e.g., Niehoff, 1952; Priegel, 1963; Shumway et al., 1961; Witt, 1960). Initially, these studies focused on species identification based on otolith shape, and size and age of the fish based on otolith size. The development of advanced analytical techniques over the recent past, including trace element and isotope analyses, as well as radiocarbon dating, has encouraged an expansion of these techniques, including archaeological and palaeoenvironmental applications.

A decade ago, Campana (2005) found that papers involving otoliths across all disciplines were being published at five times the rate they were in the 1970s; however, the areas of both environmental reconstruction (modern and ancient) and 'fossil' otoliths each made up <1% of the 862 papers published between 1999 and early 2004. A basic search of online databases, such as Web of Science, shows that while publications focusing on fish otoliths have increased over the past two decades, and archaeological papers within these have also steadily increased, they are still a relatively small area of research.

Despite some earlier reviews of otoliths in archaeology (Campana, 1999, 2005; Casteel, 1976b; Van Neer, 2000; Weisler, 1993) and coverage of otoliths in general icthyoarchaeology texts, no specialist overview on the state of the art of otolith analysis applications in archaeology has appeared for more than a decade. As such, this paper overviews the development of otolith studies in archaeology, building on past reviews and discussing recent technological developments. The main methods of analysis are outlined and major advances and significant studies in each area discussed. There are some limitations to the review; the publications included in this paper are all written in English, therefore, a significant amount of research and developments that have been published in non-English languages have been excluded. In addition, there has been an attempt to avoid "grey literature" (unpublished reports) and focus on peer-reviewed publications, which may have excluded some important research, but such literature is not always widely available. We do not hope to include every publication, but rather provide examples of the type of research that can be undertaken on otoliths. Despite these limitations, this paper provides a broad review of the current state of archaeological analyses of fish otoliths.

## 2. Sample collection and preservation

While the numbers of otoliths recovered during archaeological excavations can be low, or even non-existent at some sites, others contain significant assemblages from numerous or single fish species (Gabriel et al., 2012; Scartascini and Volpedo, 2013). Otoliths do require certain site conditions to survive in the archaeological record; their aragonite structure makes them more susceptible to deterioration than bone in some situations. The alkaline matrix of shell middens provide some of the best conditions for preservation (Andrus, 2011) and waterlogged sites such as cesspits or large deep refuse pits limit the impact of acid rain percolation, allowing for preservation of the otoliths of some taxa (Van Neer et al., 2002). Well preserved assemblages of otoliths have also been collected from other sites, such as earth mounds (Disspain et al., 2012a), lunettes and hearths (Long et al., 2014).

In order to enhance collecting otoliths from sites, wet sieving methods are advocated (Casteel, 1976a; Ross and Duffy, 2000). The sieve size used during collection will impact the size and number of fish remains collected from a site, and potentially taxa or species identification (James, 1997; Nagaoka, 2005; Ross and Duffy, 2000; Ulm, 2002; Weisler, 1993). Zohar and Belmaker (2005) demonstrated that taxonomic diversity within a fishbone assemblage from Arrawarra-I, a coastal midden site in Australia, was higher when sieved through a 1 mm mesh, as opposed to a 6 mm or 3 mm mesh. As otoliths can vary greatly in size dependent on the species and size of the fish (see Furlani et al., 2007 for examples), Casteel (1976a) advocated wet-sieving samples and sorting with low-power magnification to ensure a comprehensive collection of fish remains.

Sites with large quantities of fish bone can sometimes be devoid of otoliths (e.g., Butler and Chatters, 1994). This can be attributed to a number of factors including discard methods; fish heads may be removed at the time of catch, and returned to the water, or may be removed at the time of cooking and thrown into a fire where burning