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The Importance of Fish Otoliths in Pacific Island Archaeofaunal Analysis

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ABSTRACT

Analysis of fish archaeofaunas is commonly restricted to a limited set of routinely identified 'diagnostic' bones that has biased the richness and diversity of identified taxa. Fish otoliths increase the number of diagnostic bones, thus reducing identification biases; permit family, genus, and species-level identifications; and provide information on seasonality through incremental growth structures, and aging and size estimation of individuals. Otolith studies are reviewed; scanning electron micrographs of reference and archaeological specimens are illustrated; and the utility of fish otoliths is demonstrated by analysing two assemblages from the Hawaiian Islands. Results provide the first identification of mullet, an historically important, but previously unrecognised taxon from archaeological sites in Hawai'i. Additionally, a broader range of family and species-level identifications were possible. The importance of developing a catalogue of SEMicrographs of fish otoliths is stressed, as well as sampling cultural deposits with 3.2 mm or finer mesh sieves to maximise recovery of otoliths.

Keywords: OCEANIA, FAUNAL ANALYSIS, FISH, OTOLITHS, SEM.

INTRODUCTION

Fish bones are the most abundant vertebrate faunal class in Pacific island middens and form the basis for inferring diet, subsistence practices, and fishing strategies throughout prehistory. It is contended that the common practice of restricting the skeletal elements examined to a limited set of 'diagnostic' fish bones (e.g., dentaries, premaxillae, maxillae, pharyngeal clusters, scutes, dorsal spines, quadrates, articulars, and certain vertebrae [Leach 1976, 1989; Sutton 1979]) can result in biases that inadequately reflect the range and frequency of fish taxa present in a sample. This systematic bias has compounded the problems in interpreting Oceanic fish bone assemblages. (Screen size has also played a fundamental role [Nichol 1988]). By providing faunal analysts with a greater number of identifiable fish elements, the problem is lessened, but not eliminated (Butler 1988: 109; see also Sutton 1979: 345). This paper demonstrates that fish otoliths (three pairs of hard, calcareous bodies found in the neurocranium) add a new dimension to the identification and analysis of Oceanic fish faunas by (1) increasing the number of elements used for identifications; (2) identifying a wider range of taxa, some of which have not been previously reported; (3) providing the possibility of discovering seasonality indicators through otolith incremental growth structures; (4) aging individuals, ascertaining life history and population structure for some taxa; and, perhaps most importantly, (5) facilitating more genus and species-level identifications. This latter point is especially important since "very

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few tropical fish can be reliably identified to species or even genus" (Leach and Davidson 1988: 10).

Otoliths can aid identification of species that should be prevalent, but are rarely recognised from Pacific island middens. One need only mention the bewildering absence of flounder (*Rhombosolea* sp.) and eels from most prehistoric New Zealand sites where ethnohistoric and ecological data suggest that these species were abundant and important food resources (Armitage *et al.* 1981: 51; Fyfe 1982: 160; Leach 1989; Marshall 1987: 55). Mullet (*Mugil cephalus*) and milkfish (*Chanos chanos*) are conspicuously absent from archaeological sites in Hawai'i (e.g., Goto 1986: 455), but were raised in hundreds of prehistoric fishponds on all the major Hawaiian Islands where annual production may have exceeded 1 million kg (Kikuchi 1976: 298). Bonefish (*Albula* spp.) are also unrecognised from most middens. Data presented here demonstrate that mullet and bonefish can be identified from prehistoric middens. Consequently, incorporating fish otoliths into established practices of faunal analysis will provide a fuller picture of prehistoric subsistence economies in Oceania.

In this paper I review otolith studies in fisheries research; present archaeological studies of these elements world-wide, focusing on Oceania; describe important attributes of otoliths; provide scanning electron micrographs of archaeological and reference otoliths; and demonstrate the value of otoliths to faunal studies through two Hawaiian case studies.

FISH OTOLITH ANALYSIS IN BROAD PERSPECTIVE

It is claimed that Aristotle knew of the existence of otoliths (Adams 1940: 499) and Cuvier recognised the taxonomic value of these elements in 1836 (Nolf 1985: 1). Otoliths occur in all vertebrates, yet are most distinctive among the teleost or bony fishes (Casteel 1976: 17). Teleost fish differ from other vertebrates in the enormous size of the otoliths relative to the size of the body (Blacker 1974: 68). These small ear stones weigh from a few milligrams to several grams and are taxon-specific at the family, genus, and often species level (Adams 1940; Blacker 1974; Harkonen 1986; Lavenberg, pers. comm. 1989; Morrow 1979; Nolf 1985). However, the otoliths of sharks and rays are highly variable in shape and can be used for taxonomy only with great difficulty (Harkonen 1986: 15).

Consisting primarily of calcium carbonate and organic matter in the crystal form of aragonite (Degens *et al.* 1969), three pairs of otoliths are found within the neurocranium of a fish's skull: sagitta (also known as saccular or sacculith), utricular (utriculith or lapillus), and lagenar (lagenalith or asteriscus; Fig. 1a, b). Because of their larger size, most research focuses on the sagitta (Fitch and Brownell 1968: 2562; Summerfelt and Hall 1987; but see Adams 1940).

The precise role and physiology of otoliths are poorly understood, but they are usually thought to be associated with motor activity and sound reception (Blacker 1974: 70; Casteel 1976: 17–18; Harkonen 1986: 14–15; Nolf 1985: 3).

Otoliths exhibit periodic growth zones and can be used in age determination of individual fish (e.g., Harkonen 1986: 14). In areas with marked seasonal variation, the primary pattern of growth rings, light or hyaline (narrow, winter) and dark or opaque (wide, summer), is most obvious (Blacker 1974; Nolf 1985: 5). Blacker stated that the physiological mechanisms of otolith growth are little understood (1974: 76), but suspected that the development of rings could be related to the season of heaviest feeding and period of greatest weight gain (Blacker 1974: 79; Casteel 1976: 31–35; Irie 1960). Pannella was one of the first to document daily growth rings exhibiting a bi-weekly and monthly periodicity.

CEREBELLUM

SEMICIRCULAR CANAL

UTRICULUS

SACCULUS

SAGITTA

LAGENA

SEMICIRCULAR CANALS

LAPILLUS

UTRICULUS

LAGENA

ASTERISCUS

SAGITTA

SACCULUS

DORSAL MARGIN

ANTIROSTRUM

SULCUS

ROSTRUM

POSTERIOR

ANTERIOR

OSTIUM

CAUDA
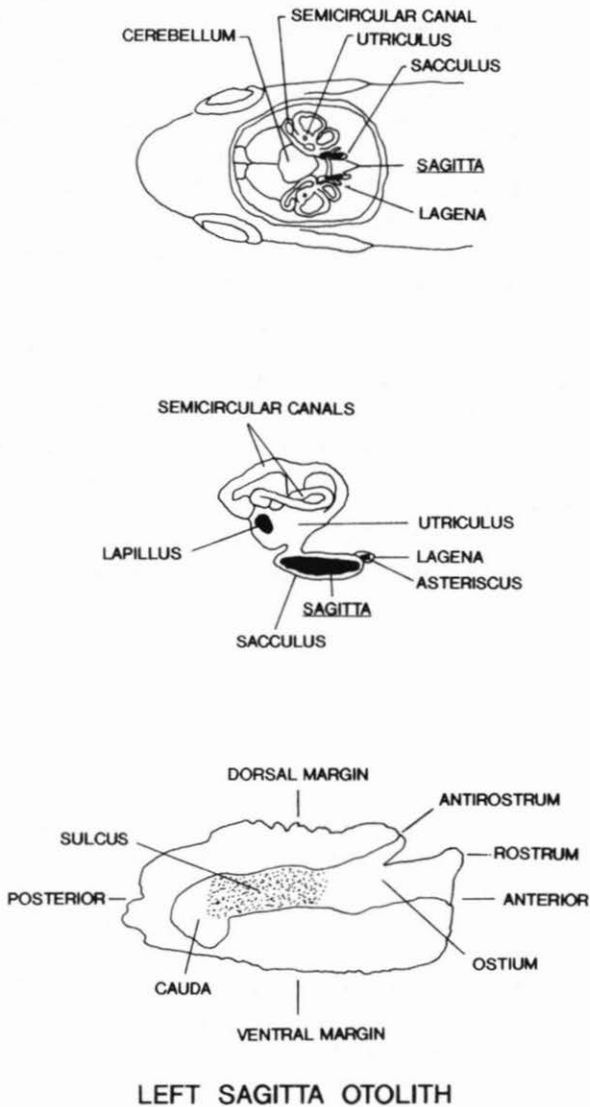
VENTRAL MARGIN

LEFT SAGITTA OTOLITH

Figure 1: Upper and middle: location of otoliths, shown in black, in the fish neurocranium (redrawn from Harkonen [1986: 15, 16]). Lower: morphological landmarks on the left sagitta otolith of the threadfin, *Polydactylus sexfilis*.

Furthermore, microscopic evidence suggests a relationship between rates of otolith calcification and reproduction; consequently, a record of spawning is left in the sagitta (Pannella 1971: 1126). As with shellfish, growth patterns are less clear in fish from tropical regions where seasonal variability is minor (Harkonen 1986: 14; Lowe-McConnell 1987: 241; Nolf 1985: 5; Sheppard 1985); However, growth models and life histories of the

Hawaiian snapper (*Pristipomoides filamentosus*) have been demonstrated recently (Radtke 1987), and otolith calcification may be useful for indicating spawning months.

In addition to determining season and age of death (Hales and Reitz 1992; Mellars and Wilkinson 1980; Reitz 1982), measurements of fish otoliths are used to reconstruct live fish weight and length (Balme 1983; Casteel 1974a,b; Reitz *et al.* 1987; Southward 1962; Witt 1960). A logarithmic relationship has been established for many species between otolith radius and fish length (e.g., Southward 1962), otolith length and total live weight (e.g., Casteel 1974a, b, 1976), otolith weight and live weight (e.g., Reitz *et al.* 1987), and otolith weight and fish fork length (Radtke 1987: 22–23). These relationships are valid within a single species, while there is a low correlation between otolith size and fish size across different genera (Fig. 2). Consequently, when considering all taxa, otolith size is not a valid indication of fish size.

Degens *et al.* (1969), using oxygen and carbon isotope data, have demonstrated that otoliths form in close equilibrium with the sea or freshwater bodies. They concluded that isotope values may help (1) to determine the mean water temperature where the fish lived; (2) to distinguish between freshwater and marine fish in ancient deposits; and (3) to reveal information on migratory tendencies (Degens *et al.* 1969: 105; Radtke 1987).
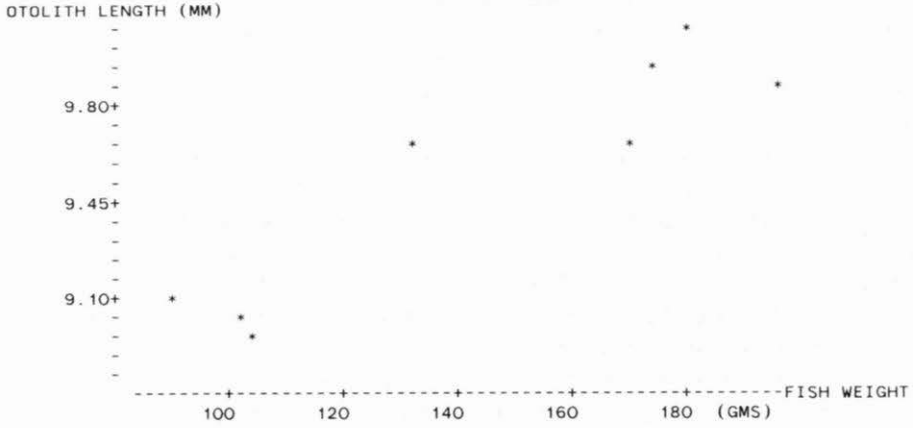
In summary, teleost otoliths are extremely useful for (1) identifying family, genus, and often species; (2) indicating age, spawning months, and season of death; (3) providing data on paleoenvironments, fish ecology, and biogeography; and (4) estimating weight and length of individual fish. These are all problems of interest to archaeologists, while paleontologists have also used otoliths for biostratigraphy (Nolf 1985: 27–29).

FISHERIES RESEARCH

Most data on otoliths have accumulated through fisheries research. Because fisheries biologists monitor the age structure of fish populations, otoliths are important for identifying fish taxa recovered from the stomachs of predators. They are used to reconstruct fish length and weight, and season and age of death of individual fish. Several excellent keys are available for important fisheries in the northeast Atlantic (Harkonen 1986), the Gulf of Alaska (Morrow 1979), and for identifying five species of Pacific salmon in North American waters (Casteel 1974c). Studies of individual taxa, such as the Pacific halibut (Southward 1962), illustrate otoliths and provide logarithms for reconstructing fish size. In contrast, research on otoliths from fish of the tropical Pacific is limited (e.g., Radtke 1987).
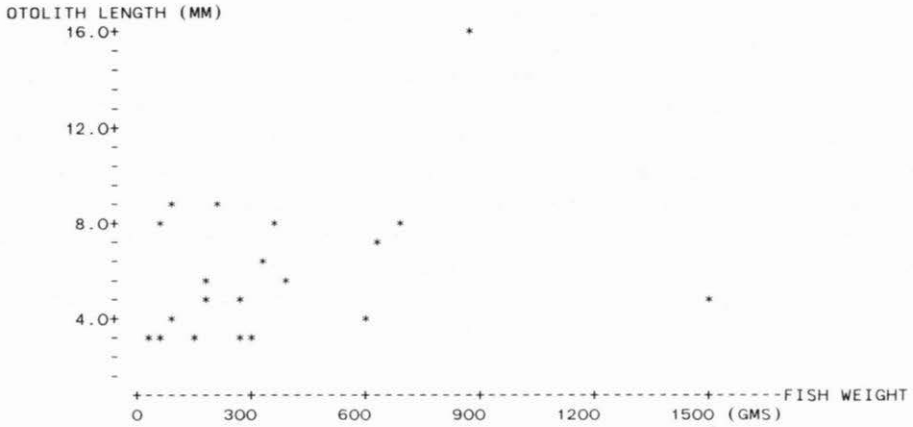
The significance of otolith research in fisheries management was firmly established by an important paper by Fitch and Brownell (1968) who analysed the feeding habits of cetaceans. Building from an earlier paper by Scott (1903), they identified 51 fish species in the stomachs of 17 cetaceans and, significantly, only two species of fish were identifiable without otoliths (Fitch and Brownell 1968: 2561). Along with cetacean research, fish otoliths are used to study the feeding habits of seals (Rae 1972; Spalding 1964) and sea birds (Ainley *et al.* 1981). Archaeologists, however, should be aware that recovering otoliths from prehistoric sites which also contain bones of cetaceans and sea birds may pose interpretive problems.

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SCATTERPLOT OF OTOLITH LENGTH AND FISH WEIGHT OF SAME SPECIES
-------------------------------------------------------------


OTOLITH LENGTH (MM)
        -                                                    *
        -                                               *
        -                                                         *
        -
  9.80+
        -                              *                   *
        -
        -
  9.45+
        -
        -
        -
        -
  9.10+    *
        -        *
        -           *
        -
        -
        ---------+---------+---------+---------+---------+-------FISH WEIGHT
               100       120       140       160       180  (GMS)

        Correlation of OTOLITH LENGTH and FISH WEIGHT= 0.914




SCATTERPLOT OF OTOLITH LENGTH AND FISH WEIGHT OF 20 DIFFERENT GENERA
-------------------------------------------------------------------


OTOLITH LENGTH (MM)
  16.0+                           *
     -
     -
     -
     -
  12.0+
     -
     -
     -
     -   *   *
   8.0+  *         *         *
     -                    *
     -        *      *
     -     *  *    *
   4.0+  *            *
     -  **   *   **
     -
     +---------+---------+---------+---------+---------+------FISH WEIGHT
     0       300       600       900      1200      1500  (GMS)

        Correlation of OTOLITH LENGTH and FISH WEIGHT= 0.305
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Figure 2: Scatterplots, demonstrating the high correlation between otolith length and fish weight within a species, *Myripristis argyromus* (upper), and the low correlation of otolith length and fish weight between 20 genera commonly found in tropical waters (lower). Consequently, big fish do not necessarily have large otoliths. All data from Table 1.

OTOLITH TAPHONOMY

Research on the feeding habits of seals has emphasised the importance of understanding the role of otolith preservation (taphonomy) in identification and reconstruction of fish length and weight from otolith measurements. It is important to understand the effects of predator digestive acids on otolith morphology and ascertain how otolith density and shape affect preservation. Other factors, such as post-depositional transportation of otoliths by water and wind, and decalcification of the sediment in which the otoliths are embedded, have been mentioned by Nolf (1985: 5).

Fisheries biologists have recognised some effects of gastro-intestinal acids of predators on otoliths, such as smoothing of surface features (Harkonen 1986: 32; Morrow 1979: 2; Nolf 1985: 5–6). Controlled experiments of feeding herring to seals have shown loss of surface topography of otoliths and, in some cases, holes have appeared in thinned areas of the otolith (Murie and Lavigne 1985: 294). Salmon otoliths, measuring 4 to 5 mm long, were fed to seals and showed little sign of digestion along the edges (Bigg and Fawcett 1985: 286). Examining the gut contents of cetaceans, Fitch and Brownell suggested that otoliths are slow to digest (1968) and that they are the densest structure in the body of teleost fishes and the most resistant to digestion. Amongst the indigenous human populations of Pacific islands, fish heads are considered desirable portions of the fish. Consequently, knowledge learned from controlled experiments with feeding fish to seals may have important implications on the taphonomy of otoliths processed by humans and give clues as to what we may expect to recover archaeologically. This is especially important when estimating live fish dimensions from otolith measurements.

A study relevant to archaeological otoliths was by Jones (1986) who fed haddock, mackerel, and herring to a pig, dog, and himself to document changes in otolith shape. Haddock otoliths found in the dog faeces showed evidence of digestion, as the ventral surface sculpturing was not apparent—the entire surface bore a distinctly polished appearance—and he noted a small size reduction (at least 2 mm in a 11.5 mm long otolith), making size estimation based on otolith length of haddock inaccurate (Jones 1986: 55).

Prime and Hammond (1985) noted that small, flat and irregularly shaped otoliths are more likely to be digested than otoliths with high area/volume ratios. Compiling data from a number of sources, Harkonen (1986: 31) ranked ten fish families as to high or low probability of digestion. It is of interest to Oceanic archaeologists that Scombridae had the highest chance of total digestion. This family includes such well-known taxa as the tunas (*Katsuwonus pelamis, Euthynnus yaito, Thunnus alalunga, Thunnus albacares, Thunnus obesus*) and mackerels (*Acanthocybium solandri, Scomber japonicus*, and *Auxis thazard*). Perhaps these taxa will be recoverable archaeologically only if the heads were not consumed.

ARCHAEOLOGICAL STUDIES OF OTOLITHS

Studies of otoliths recovered from archaeological sites have been hampered by the basic problems of recovery and misidentification. In many instances, teleost otoliths are thought to be mollusc opercula. Indeed, several Pacific archaeologists have confirmed this to me and Gifford, from his excavations in New Caledonia (Gifford and Shutler 1956), catalogued individual otoliths as mollusc opercula; many of these I identified as bonefish (*Albula* sp.).

Most archaeological studies of otoliths have, not unexpectedly, occurred in areas where there is also detailed knowledge of extant fisheries. For example, Mellars and Wilkinson (1980) measured 1742 sagittae from four late Mesolithic archaeological sites at Oronsay, Britain, to determine season of occupation. Seasonal aspects of coalfish (*Pollachius virens*) exploitation were determined by plotting the size distribution of archaeological otoliths. It was assumed that the size distribution of the reconstructed fish populations provided an accurate indication of the age of the fish and, assuming a uniform date of spawning, of the seasons when the fish were caught. Observations of modern populations justified this assumption, as well as the presence of other seasonally available food remains in the archaeological deposits.

Witt (1960) reconstructed the length and weight of freshwater drum (*Aplodinotus grunniens*), otoliths of which were found in four prehistoric middens in the midwest and southern United States. Individual fish size of the archaeological samples was calculated by reference to modern data. At some sites Witt found a decrease in fish size of the subfossil material when compared to modern samples which may relate to climatic and environmental variation (a cooling of water temperatures), aboriginal fishing methods, or chance (1960: 184).

PREVIOUS USE OF OTOLITHS IN OCEANIC FISH BONE ANALYSIS

My literature review identified only five published references to fish otoliths from archaeological sites in Oceania, including Australia. At the Nebira 4 site in central Papua, Allen (1972: 116) identified otoliths of catfish (Tachysuridae *Hexanemtichthys latirostris*) and suggested that their high occurrence probably distorted the relative importance of this species.

Probably because of the use of 1/4 inch (6.4 mm) sieves, Masse (1986: 95) commented that otoliths were absent from the Palau assemblages.

Frimigacci reported that otoliths were used to identify the species and relative sizes of fish from the New Caledonian site of Nessadiou (WBR-001) (1980: 9). Although he does not list the taxa, the fish were probably caught in the lagoon adjacent to the site and R. C. Green (pers. comm. 1990) suggests they could be Mullidae.

In his analysis of aboriginal fishing along the coast of New South Wales, Australia, Dyall (1980) identified bream (*Acanthopagrus australis*), snapper (*Chrysophrys guttulatus*), and whiting (*Sillago* sp.). He suggested that bream otoliths have a poor survival rate compared to snapper, and that whiting otoliths survive better than their dentaries (1980: 60), although he provides no supportive data.

Balme (1983) provides the most comprehensive treatment of otoliths in Oceania (see also Kefous 1977). Analysing over 1200 otoliths from four sites located near lakes and rivers in New South Wales, Australia, she reported the identification of golden perch (*Maguaria ambigua*) and cod (*Maccullochella* sp.). Importantly, fish otoliths were the dominant faunal element at one site (Balme 1983: 24). At another locale, much of the bone was fragmented except the otoliths, and Balme reported that "no fish bone survived but otoliths are well-preserved" at another site (1983: 26). She measured modern reference specimens to determine algorithms for estimating fish lengths from otolith measurements and applied the resulting equations to the archaeological material to estimate the sizes of fish that were caught. These data were then used to discuss fishing strategies.

The potential of otolith studies in Hawai'i has not been evaluated and the following study was formulated to assess the utility of using these elements for archaeofaunal analysis.

THE OTOLITH REFERENCE COLLECTION

The reference collection used in the following study contains sagitta otoliths of 24 species, from 21 genera and 14 families which represent 5.4% of the taxa known to inhabit the inshore and surface marine waters of Hawai'i (Appendix 1; Gosline and Brock 1960: 2–3). The otolith reference specimens were collected in Hawaiian waters; I caught most of the fish off the island of Moloka'i with gill nets. Identifications were made using the *Handbook of Hawaiian Fishes* (Gosline and Brock 1960). Specimens that could not be identified in the field were photographed with colour film and identified by Arnold Suzumoto (Department of Ichthyology, Bishop Museum).

To prepare the fish for the reference collection, the specimens were boiled for several minutes in water after which most of the soft tissue was removed. Then, the cranium was disarticulated as necessary to remove the sagittae which were then air-dried. Table 1 lists the otolith reference specimens, the total fish length, ungutted weight of collected fish, lengths and widths of sagittae, and ratios of otolith length to fish length, and otolith length to width. (The relationship of otolith length to width can be indicative of family-level classification [R. Lavenberg, pers. comm. 1989].) All otolith identifications made during this study were later confirmed by Dr. Robert Lavenberg, Section of Fishes, Natural History Museum of Los Angeles County, where more than one million otolith reference specimens are curated.

Otolith terminology (see Casteel 1976: 21–22; Harkonen 1986: 16–18; Morrow 1979: 2, 22) for the reference otoliths is described consistently for each taxon from a sample of from one to eight specimens. Figure 1c illustrates the important landmarks of sagitta otoliths. Because otoliths undergo ontological changes (Morrow 1979: 1; Nolf 1985), data described for subadults are noted and should be augmented in the future with samples from mature specimens.

Scanning electron micrographs were taken by the author for 16 reference specimens and 6 unidentified archaeological pieces (Figs 3–6). A JEOL 840A scanning electron microscope (SEM) was used at 5kV (bias 2), and working distance of 32 to 49 mm. After much experimentation with mounting mediums (silver paste, epoxy, and colloidal graphite), double-sided clear (Scotch) tape was found to be the best. Mounting stubs were ringed with silver paste to increase conductivity. The great advantage of using tape is that specimens can be removed easily. Unlike larger 'diagnostic' fish bones where the actual reference specimens are usually needed to make identifications, SEMicrographs of otoliths provide an excellent format for disseminating reference material to a wide audience. Harkonen (1986) provides an excellent reference for identifying fish otoliths of northeast Atlantic species; some illustrated families such as Belonidae, Serranidae, Carangidae, Mugilidae, Labridae, and Scombridae are also present in tropical Pacific waters. Developing a catalogue of otolith SEMicrographs of tropical fish species at different growth stages should be a priority.

TABLE 1
OTOLITH REFERENCE SPECIMENS

Taxon	Fish Length	Fish Wgt	Otolith Length	Otolith Wgt	Ratio 1	Ratio 2
Abudefduf sordidus	15.5	104	4.11	2.19	38	1.88
Acanthurus dussumieri	31.5	620	6.86	3.86	46	1.78
A. sandvicensis	14.0	70	3.36	2.08	42	1.62
A. sandvicensis	21.0	187	4.06	2.47	52	1.64
Albula glossodonta	38.0	383	12.36	6.59	31	1.88
A. glossodonta	47.5	869	15.65	6.69	30	2.34
Apogon menesemus	18.5	90	8.60	5.72	22	1.50
Calotomus sandvicensis	31.0	605	4.26	2.51	73	1.70
Caranx melampygus	30.0	263	5.01	2.20	60	2.28
Ctenochaetus strigosus	-	-	4.49	3.08	-	-
Holocentrus lacteoguttatus	13.5	49	2.84	1.61	48	1.76
Kuhlia sandvicensis	21.5	190	6.89	3.96	31	1.74
K. sandvicensis	26.0	216	8.46	3.45	31	2.45
Kyphosus cinerascens	22.0	327	6.14	2.60	36	2.36
Mugil cephalus	16.0	41	5.44	2.70	29	2.01
M. cephalus	34.5	359	8.25	3.21	42	2.57
Mulloidichthys auriflamma	24.5	177	4.57	2.91	54	1.57
Myripristis argyromus	15.0	89	9.11	6.00	17	1.52
M. argyromus	15.5	101	9.01	6.58	17	1.37
M. argyromus	16.5	103	8.94	6.42	19	1.39
M. argyromus	17.0	132	9.69	6.69	18	1.45
M. argyromus	19.0	174	9.94	6.74	19	1.47
M. argyromus	19.5	169	9.64	6.61	20	1.46
M. argyromus	19.5	180	10.08	6.81	19	1.48
M. argyromus	21.0	196	9.87	6.42	21	1.54
Naso annulatus	45.5	1501	4.84	4.83	94	1.00
N. unicornis	19.0	113	3.80	2.46	50	1.54
Parupeneus multifasciatus	22.0	139	3.74	3.12	59	1.20
Polydactylus sexfilis	32.0	533	7.91	3.57	40	2.22
P. sexfilis	43.5	678	8.22	3.52	53	2.34
P. sexfilis	45.0	1572	9.28	4.37	49	2.12
Priacanthus cruentatus	22.0	165	6.48	3.84	34	1.69
P. cruentatus	22.5	171	5.85	3.98	39	1.47
Scarus perspicillatus	-	-	6.87	5.09	-	-
Sphyraena helleri	57.0	842	12.24	5.14	47	2.38
Thalassoma ballieui	26.0	286	3.97	2.54	66	1.56
T. fuscum	27.0	309	3.57	2.13	76	1.68
Trachurops crumenophthalmus	15.5	28	3.30	2.02	47	1.63
Upeneus arge	33.0	386	5.98	3.27	55	1.83

Note: all otoliths measured with a Nikon Measurescope Model II to 1/1000 mm and rounded to 1/100 mm. All weights in grams. Fish length is total length in cm. Twenty-five different taxa represented. Ratio 1 = Otolith length to fish length. Ratio 2 = Otolith length to otolith width.
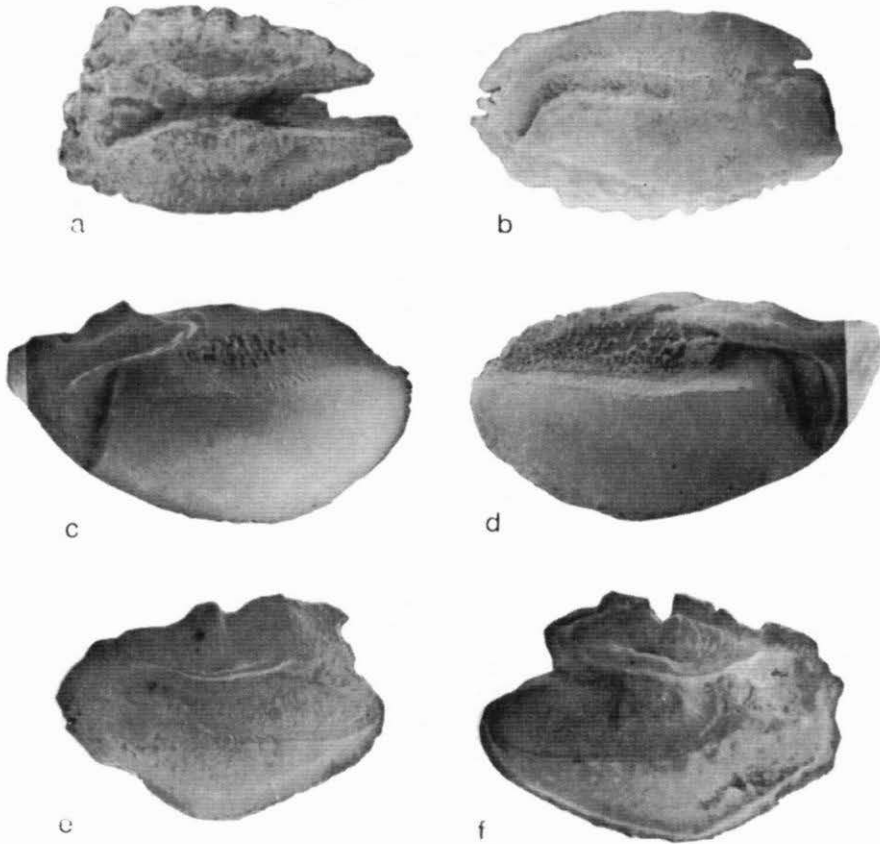
Figure 3: Scanning electron micrographs of saccular otoliths: a, *Naso unicornis* (left side of fish, reference); b, *Kuhlia sandvicensis* (left side, reference); c, *Albula glossodonta* (left side, archaeological); d, *Albula glossodonta* (right side, reference); e, *Apogon* sp. (left side, archaeological); f, *Apogon menesemus* (right side, reference). Specimens range in length from 3.80 to 15.65 mm).

CASE STUDIES

The following examples demonstrate the potential contribution of otoliths to our understanding of prehistoric fish use in Oceania. Most previous analyses rely on a restricted range of easily identifiable bone elements such as mouth parts, dorsal spines, caudal tangs, and scutes. Table 2 lists the fish families identified by these diagnostic bones and otoliths at two sites on the island of Moloka'i. Also presented are the families that frequent the marine waters adjacent to the archaeological sites. These fish are caught by a variety of methods (nets, spear, poison, traps, and hook) and were all eaten by Hawaiians (Buck 1957; Ii 1959; Kamakau 1976). Consequently, one should expect their bones to be present in the archaeological sites (considering, however, that taphonomic processes and bone densities may yield differential preservation of bone elements [Lyman 1984, 1985]). The expected
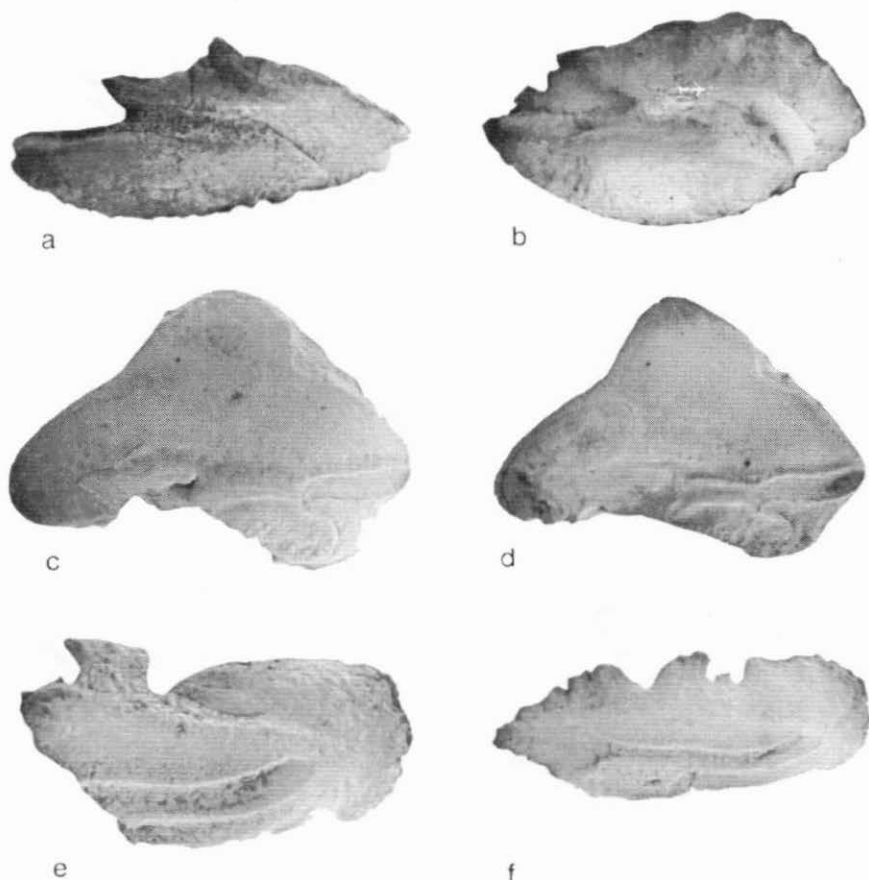
Figure 4: Scanning electron micrographs of saccular otoliths: a, *Caranx melampygus* (right side of fish, reference); b, *Trachurops crumenophthalmus* (right side, reference); c, *Myripristis* sp. (left side, archaeological); d, *Myripristis argyromus* (left side, reference); e, *Mugil cephalus* (right side, archaeological); f, *Mugil cephalus* (right side, reference). Specimens range in length from 3.30 to 14.15 mm.

taxa, then, provide a *general* gauge for monitoring the efficacy of fish faunal analysis.

Despite mention of the 'over-representation' of some taxa in archaeological assemblages (Allen 1972: 116; Davidson 1971: 93; Davidson and Leach 1988: 337; Kirch 1973, 1979: 136; Severance 1986: 38), scarcely a word is written of the 'ones that got away', either through the screens, because of post-depositional alterations (such as chemical weathering and breakage), or through our own limitations of what can be identified (but see Nichol and Wild 1984). The list of expected taxa for Moloka'i sites is derived from a recent coastal resources survey (United States Army Corps of Engineers 1984), personal observations, and the standard reference for the Hawaiian Islands (Gosline and Brock 1960). Despite this information, surveys and observations are subject to the limitations of sampling (for
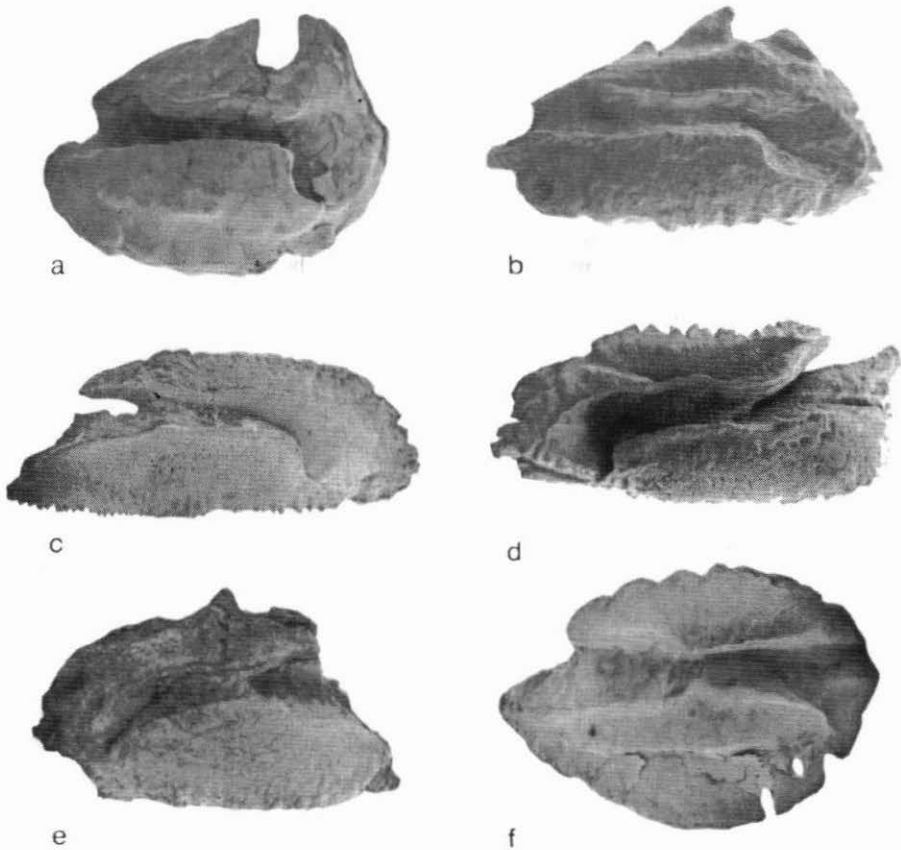
Figure 5: Scanning electron micrographs of saccular otoliths: a, *Parupeneus multifaciatus* (right side of fish, reference); b, *Upeneus arge* (right side, reference); c, *Kyphosus cinerascens* (right side, reference); d, *Polydactylus sexfilis* (left side, reference); e, *Abudefduf sordidus* (left side, reference); f, *Priacanthus cruentatus* (right side, reference). Specimens range in length from 3.74 to 9.28 mm.

Moloka'i, see Anzai *et al.* 1979; Sanderson and Solonsky 1980; and for a good review of sampling problems, Russell *et al.* 1978). The problems of adequately sampling the marine waters adjacent to the archaeological sites were reduced by the author undertaking several fishing sorties with gill nets. The use of gill nets, besides poisoning (Russell *et al.* 1978: 331), is a good technique for catching a wide range of fish taxa—both diurnal and nocturnal species—that inhabit inshore waters.

CASE STUDY 1

Along the south shore of Moloka'i is a broad fringing reef up to 1 km wide that hosts a diverse array of inshore fish species. The gently sloping nature of the reef, shallow waters, and freshwater springs issuing along the beach provided an ideal setting for construction of walled fishponds (Kikuchi 1976), an artificial aquacultural ecosystem for raising mullet (*Mugil cephalus*) and milkfish (*Chanos chanos*). Only the outer edge of the reef has luxuriant, live coral growth which supports Scaridae, Labridae, and other coral dwelling species, while the majority of the consolidated reef platform has a sandy surface with increasing amounts of terrigenous mud towards shore. These bottom types are ideal habitats for Mugilidae, Mullidae, and Albulidae.

A major settlement pattern study was conducted on the slopes above the south-central coastline at Kawela resulting in the discovery of 499 architectural features, including four fishponds (Weisler and Kirch 1985). A late prehistoric to proto-historic settlement was documented consisting of several dozen residential complexes, non-irrigated agricultural complexes, stone-tool manufacturing locales, and various religious features. The fish assemblage from a single habitation feature (site T-62) is discussed. The structure is situated on a calcareous sand hill, about 300 m from the coast, and consists of a stone-faced earthen terrace and levelled soil area *c.* 31.5 m square. A midden scatter extends about 10 m
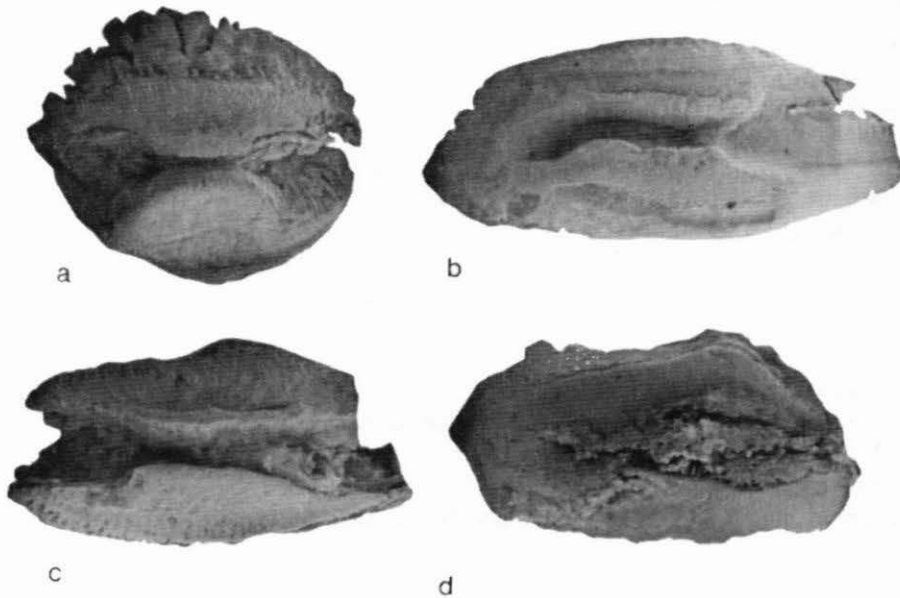

Figure 6: Scanning electron micrographs of saccular otoliths: a, *Scarus perspicillatus* (right side of fish, reference); b, *Sphyraena helleri* (left side, reference); c, *Thalassoma* sp. (left side, archaeological); d, Unidentified #1 (left side, archaeological). Specimens range in length from 6.87 to 12.24 mm.

downslope. Sixty-three metre-square units were surface collected and a 21.75 metre-square area was excavated (2.43 m^3). The site matrix was dry-screened through 6.4 and 3.2 mm sieves, bagged by screen fraction, and sorted in the lab. Table 3 presents the fish identified using diagnostic bones and otoliths; also note the NISP values for the 6.4 and 3.2 mm size classes in Figure 7.

TABLE 2

EXPECTED AND IDENTIFIED FISH FAMILIES AT SITES T-62 AND B6-66

| | Expected Taxon* | | Identified Taxon | | | |
| | | | Diagnostic Bones | | Otoliths | |
Taxon	T-62	B6-66	T-62	B6-66	T-62	B6-66
Acanthuridae	1,3	1,3	X	X	-	X
Albulidae	2,3	2,3	-	-	X	-
Apongidae	3	3	-	-	X	-
Balistidae	3	2,3	X	X	-	-
Carangidae	3	3	-	X	-	-
Chaetodontidae	1	3	-	-	-	-
Chanidae	3	-	-	-	-	-
Diodontidae	-	2	-	X	-	-
Holocentridae	1–3	1–3	X	-	X	X
Kuhliidae	-	2	-	-	-	-
Kyphosidae	3	1–3	-	-	-	-
Labridae	1–3	1–3	X	X	X	-
Mugilidae	2,3	-	-	-	X	-
Mullidae	2,3	1–3	-	-	-	-
Polynemidae	-	2	-	-	-	-
Pomacentridae	1,3	1,3	-	-	-	-
Priacanthidae	3	3	-	-	-	-
Scaridae	1,3	1,3	X	X	-	X
Sphyraenidae	-	2	-	-	-	-

* Expected taxa are those:
    (1) reported in the Moloka'i Island Coastal Resources Inventory (1984);
    (2) observed personally;
    (3) cited by Gosline and Brock (1960).
Families identified only by otoliths at one or both sites are highlighted.

TABLE 3
FISH BONE IDENTIFICATIONS FROM SITE T-62

Taxon	Diagnostic Bones		Otoliths
	6.4mm	3.2mm	3.2mm*
Acanthuridae	0	2	0
Albulidae *Albula glossodonta*	0	0	2
Apongidae *Apogon* sp.	0	0	1
Balistidae	1	0	0
Elasmobranchii	1	0	0
Holocentridae	0	1	0
***Myripristis* sp.**	0	0	1
Labridae	6	3	0
***Thalassoma* sp.**	0	0	1
Mugilidae *Mugil cephalus*	0	0	1
Scaridae *Scarus* sp.	3	2	0
Otolith unidentified #1	0	0	2
NISP (Site = 27)	11	8	8
Number of Teleost Families	3	4	5+

*   No otoliths recovered from the 6.4 mm size class.
+   Unknown otoliths are not Acanthuridae, Albulidae, Holocentridae, Labridae, Mugilidae, or Scaridae and may represent an additional family-level identification. Taxa identified only with otoliths are highlighted.

Identifications of archaeological otoliths, reported here, were made with the aid of the reference collection (Appendix 1; Figs 3–6). In Figures 3c and d, 3e and f, 4c and d, and 4e and f, similarities can be seen between the reference and archaeological specimens in general outline and the nature of the cauda, sulcus, and ostium (see Fig. 1c for otolith landmarks).

It is significant to note that despite over three decades of systematic excavations in Hawai'i (Kirch 1985), and the presence throughout the major Hawaiian islands of over 200 prehistoric fishponds that were used for raising mullet and milkfish, it is only by the use of otoliths that I present the first identification of Mugilidae *Mugil cephalus* or mullet (cf. Fig. 4e, f). In addition, Albulidae, which one would expect to be present in archaeological sites adjacent to the south shore of Moloka'i, has been identified only by otoliths and is not accounted for by diagnostic bones. Genera-level identifications were also made for *Apogon*, *Myripristis*, and *Thalassoma*.

In sum, the use of otoliths has resulted in the identification of three families (and possibly a fourth, note unidentified otolith #1 in Table 3) and three genera that were not identified using 'diagnostic' bones.
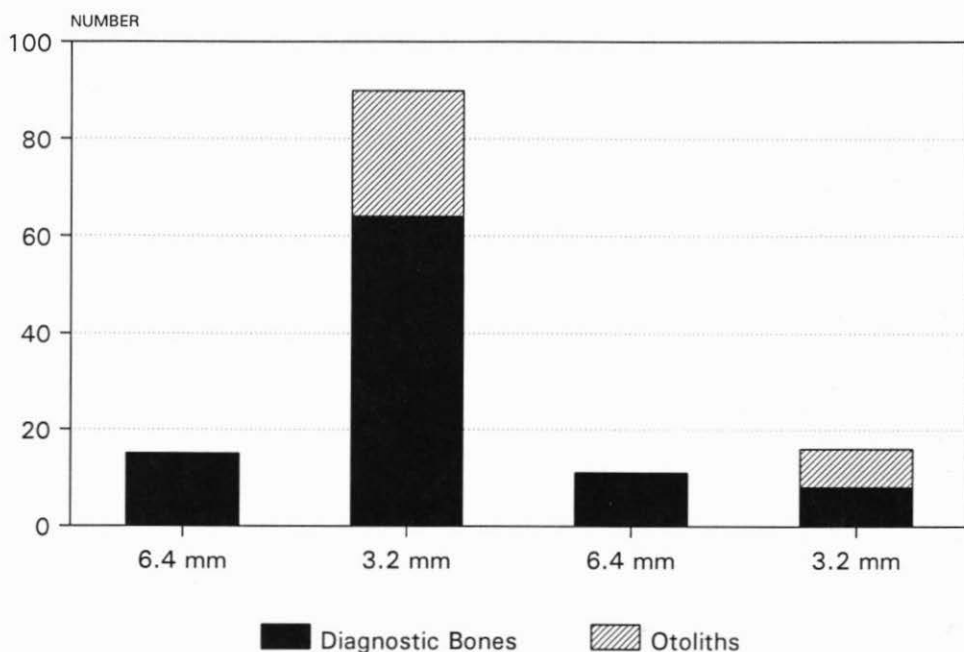
NISP FOR SITES B6-66 & T-62

Figure 7: Bar graph of NISP for archaeological sites B6-66 (left two bars) and T-62, island of Moloka'i, Hawaiian Islands. Note the contribution of otoliths to the overall site samples and the under-representation of NISP when only the 6.4 mm size class is considered.

CASE STUDY 2

Small sheltered embayments interrupt the rocky coastline of west Moloka'i and provided loci for habitation and exploitation of the adjacent marine environment. As the region is quite arid and not conducive to crop production, fishing the inshore waters was the dominant subsistence activity for the seasonal occupants.

Unlike the south shore (especially near site T-62), the marine physiography adjacent to site B6-66 consists of a small calcareous sand beach (*c.* 100 m across) enclosed by basalt boulder points. Abundant live coral fringes the seaward extension of the basalt cliffs and beaches. Coral-inhabiting inshore fish species, such as Holocentridae, Labridae and Scaridae are most abundant here.

Extending inland along a broad ridge are 98 late prehistoric habitation, religious, and gardening structures clustered in several groups. Near the seaward end of this sprawling complex is a large rectangular enclosure measuring 7.0 by 4.5 m overall with an interior area of 10.4 m square. The structure has a pavement or altar in the interior east side (Weisler 1984: Fig. 23), and has been interpreted as a fishing shrine (Stokes 1909; Summers 1971) where offerings such as branch coral, fish, and marine shells were made. Many branch coral heads, water-rounded stones, and whole marine shells were found on and

adjacent to the pavement (Weisler 1984). A 0.5 m square unit was excavated off the pavement and the sediment was dry-screened through 6.4 and 3.2 mm sieves and later water-screened in the lab and sorted.

TABLE 4
FISH BONE IDENTIFICATIONS FROM SITE B6-66

Taxon	Diagnostic Bones		Otoliths
	6.4mm	3.2mm	3.2mm*
Acanthuridae	1	4	0
Acanthurus xanophopterus	0	0	1
Naso sp.	1	3	0
Balistidae	0	2	0
Carangidae	1	2	0
Diodontidae *Diodon* sp.	1	2	0
Elasmobranchii	1	0	0
Holocentridae *Myripristis* sp.	0	0	1
Labridae	5	18	0
Calotomus sp.	0	6	0
Scaridae	0	1	0
Scarus sp.	5	23	1
Squamipinnes	0	0	1
Diagnostic unidentified #1	0	3	0
Otolith unidentified #1	0	0	21
Otolith unidentified #2	0	0	1
NISP (Site = 105)	15	64	26
Number of Teleost Families	5	6	3+

* No otoliths recovered from the 6.4mm size class.

\+ Unknown otoliths are not Acanthuridae, Carangidae, Holocentridae, Labridae, or Scaridae and may represent up to three additional family-level identifications. Taxa identified only with otoliths are highlighted.

Table 4 presents the fish identifications for site B6-66. Twenty-five percent of NISP are otoliths, including one family and one genus-level taxon. An expanded reference collection may permit the identification of up to three additional fish families from three unidentified otolith taxa. It is significant that 86% of NISP was recovered in the 3.2 mm size class suggesting that the analysis of fauna recovered only from 6.4 mm screens (the dominant size class analysed in Pacific island assemblages) may be biased.

SUMMARY

Sagittae have been recovered from a total of six archaeological sites on the island of Moloka'i, Hawai'i (Table 5) and from several sites recently excavated on Henderson island (Weisler in press); the details of two Moloka'i sites have been reported above. The Moloka'i sites include a coastal calcareous sand dune midden (Weisler and Kirch 1985: 150–151), residential structures situated on lateritic soil slopes (Weisler and Kirch 1985: 147), a totally enclosed religious feature (Weisler 1984), and a coastal rock shelter (Bonk 1954). Considering the range of formal site classes and sediment conditions where otoliths have been recovered, we could expect to find fish otoliths in any Pacific island midden.

TABLE 5
OTOLITHS IDENTIFIED FROM MOLOKAI'I ARCHAEOLOGICAL SITES

Lab. no.	Site	Taxon	Length	Width
A-1	62	*Myripristis* sp.	11.37	8.00
A-2	62	*Mugil cephalus*	6.16	3.38
A-5	62	Unknown #1	-	-
A-6	62	Unknown #1	-	-
A-7	62	*Apogon* sp.	-	4.03
A-17	62	*Thalassoma* sp.	-	3.36
A-18	62	*Albula* cf. *glossodonta*	-	-
A-21	62	*Albula* sp.	-	-
A-3	56E	*Apogon* sp.	6.15	4.79
A-8	178E	*Apogon* sp.	6.91	4.57
A-4	Mound	*Myripristis* sp.	14.15	7.45
A-9	Mound	Apogonidae	6.88	4.30
A-10	Mound	Unknown #2	10.06	6.03
A-11	Mound	Lutjanidae	13.29	7.83
A-12	Mound	Lutjanidae	-	8.06
A-13	Mound	*Albula* cf. *neoguinaica*	23.38	11.94
A-14	Mound	*Albula glossodonta*	16.91	8.38
A-15	Mound	*Albula* sp.	-	10.19
A-16	Mound	*Albula* sp.	13.41	6.63
A-19	Mound	*Albula neoguinaica*	18.48	-
A-20	Mound	*Albula glossodonta*	-	10.03
A-27	B6-66	*Myripristis* sp.	-	-
A-22	B6-66	*Acanthurus xanophopterus*	-	-
A-23	B6-66	*Scarus* sp.	-	-
A-24	B6-66	Squamipinnes	-	-
A-25	B6-66	Unknown #1, 21 pieces.	-	-
A-28	B6-66	cf. Holocentridae	-	-
A-26	Mo.2	*Albula* sp.	-	-

Note: measurements are in mm.

Seventy-seven percent of the archaeological otoliths from Moloka'i passed through the 6.4 mm sieves but were retained in the 3.2 mm size class. The use of 6.4 mm screens is probably why Masse (1986: 95) reported the absence of otoliths from assemblages in Palau despite recovering over 7,000 archaeological fish bones. We should not expect to find many otoliths if fine screens (3.2 mm and smaller) are not used or bulk sediment samples are not taken. (This latter sampling method was used by Mellars and Wilkinson [1980], and bulk samples collected from the famous site of Lapita, New Caledonia [Gifford and Shutler 1956] were recently found to contain otoliths.)

Figure 7 illustrates the effect of screen size on the number of identified specimens (NISP) of fish bone at sites B6-66 and T-62 from Moloka'i. Note that otoliths are totally absent in the 6.4 mm size class. Recently, Reitz and Quitmyer (1988) have demonstrated the recovery bias of using only large mesh screens (1/4 in. [6.4 mm] and 1/2 in. [12.8 mm]) and, at one coastal Georgia site, 96% of fish vertebrae passed through the 6.4 mm sieve but were retained in the 3.2 mm size class.

Examination of 45 archaeological otoliths from Moloka'i suggests that food preparation and hearth activity, consumption methods, as well as post-depositional alterations (see, for example, Wood and Johnson 1978) affect this faunal class in predictable ways. In general, thin areas along the margins are chipped and rounded, the latter of which could result from digestive acids (Jones 1986). Specimens also tend to break along deeply incised sulci (e.g., *Scarus* sp., Fig. 6a), along the cauda of *Albula glossodonta* (Fig. 3c), and at the ventral notch of *Mugil cephalus* (cf. Fig. 4e and f). Otoliths which are long, thin, and concave when viewed from the dorsal margin (such as the unidentified specimen seen in Fig. 6d), tend to break at the midsection (65% of specimens). Significantly, many fragmented otoliths are identifiable to genus and species. This is often not the case with the diagnostic elements of some fish taxa with fragile bones (especially *Albula* spp., *Chanos chanos*, and Mullidae).

CONCLUSIONS

Fish otoliths make an important addition to the elements routinely used for the identification of archaeological fish faunas from Pacific islands. Incorporating otoliths into faunal analyses has provided (1) identification of taxa never before documented from prehistoric middens in Hawai'i; (2) a broader range of family identifications; (3) more specific identifications to genus and species; and (4) an increase in the number of diagnostic elements used for identifications which more accurately reflect the species inventories represented in prehistoric middens. Fine sieving (3.2 mm and smaller) is necessary for recovering most otoliths from archaeological deposits, and expanded otolith reference collections will be necessary to increase the range of potentially identifiable taxa from Pacific island middens. This is especially true with fish species such as bonefish and mullets which have fragile bones that normally do not preserve in archaeological contexts. The development of a catalogue of SEMicrographs of otoliths representing different growth stages and from a broad range of fish taxa, including eels, should be a high priority; a similar call was made by Sutton more than a decade ago in reference to the Waihora, New Zealand assemblage where about 2500 otoliths have been recovered and await identification (1979: 345).

While we cannot control the biases introduced by indigenous food processing, consumption, and post-depositional alterations, we can use finer sieves to acquire more representative samples from archaeological deposits and, by using a greater number of elements, including otoliths, we can improve our analyses of fish archaeofaunas (Butler

1988: 109). If understanding subsistence practices, fishing strategies, and the nature and relationship of island adaptations is important to students of Pacific prehistory, then fish otoliths must be an integral part of this pursuit.

ACKNOWLEDGEMENTS

APPENDIX 1

DESCRIPTION OF OTOLITH REFERENCE SPECIMENS

Otolith terminology (see Casteel 1976: 21–22; Harkonen 1986: 16–18; Morrow 1979: 2, 22; Nolf 1985: 6–7) is described consistently for each taxon from a sample of one to eight specimens. Since all otoliths are subject to some ontological changes (Morrow 1979: 1; Nolf 1985: 8–11), and intra-species variability ranges from "almost nil to very great" (Blacker 1974: 84; Nolf 1985: 11), data described from subadults are noted and should be augmented in the future with samples from mature specimens. It is assumed that left and right otoliths are symmetrical and that gender has no detectable value within species. Otolith size relative to fish size is calculated by the ratio of otolith length to fish length (e.g., large = 1:17–1.39; medium = 1:40–1:59; small = 1:60–1:94). General shape has been calculated by the ratio of otolith width to length. For example: round = 1.00; oblong = 1.50; slightly elongate = 1.75; elongate = 2.00; and very elongate = 2.25+. Photographs have been included to reduce the chances of misidentifications as suggested by Blacker (1974: 86, 90) and to illustrate salient features (Stein and Fitch 1984: 81).

Acanthuridae *Acanthurus dussumieri*. Otolith of medium size (1:46) and slightly elongate (1.78). Dorsal margin is smooth and irregular with a central point. The ventral margin is smooth and slightly curved. Posterior margin is perpendicular to the long axis and jagged. The rostrum and antirostrum are easily defined, but not well developed. Medial is convex and concentric rings visible on the lateral concave surface. Cauda is strongly curved towards ventral. Ostium is open.

Acanthuridae *Acanthurus sandvicensis*. Medium size otolith (1:42) and slightly elongate (1.63). Dorsal margin is smooth and irregular with a central point. Ventral margin is smooth and slightly curved. Posterior margin is jagged and perpendicular to the long axis. The rostrum and antirostrum are easily defined, but not well developed. Medial is convex and concentric rings visible on the lateral concave surface. Cauda is strongly curved towards ventral. Ostium is open.

Acanthuridae *Naso annulatus*. A small otolith (1:94), subrounded in outline (1.00). All margins are jagged, but less so along the ventral perimeter. Both dorsal and ventral margins are slightly curved. Posterior is almost perpendicular to the long axis of the otolith. Rostrum protrudes and antirostrum is well developed. Medial is convex and lateral concave. Sulcus is relatively deep. Cauda is closed and slightly curved to ventral. Ostium is open.

Acanthuridae *Naso unicornis* (Fig. 3a). An otolith of medium size (1:50), relatively thick and oblong (1.54). Similar in outline to *Naso annulatus*. The difference in the relationship of otolith length to fish length (*N. unicornis* [1.54] fish length is 19.0 cm and *N. annulatus* [1.00] fish length is 45.5 cm) may be due to growth stage. All margins are jagged, but less so along the ventral perimeter. Both dorsal and ventral margins are slightly curved. Posterior is almost perpendicular to the long axis of the otolith. Rostrum protrudes and antirostrum is well developed. Medial is convex and lateral concave. Sulcus is relatively deep. Cauda is closed and slightly curved to ventral. Ostium is open. Not possible to distinguish taxa at species level, but differences noted between genera (e.g., *Acanthurus* sp. and *Naso* sp.).

Albulidae *Albula glossodonta* (Fig. 3d; see also photographs in Shaklee and Tamaru [1981: 139]). Large otolith (1:31) and elongate in shape (2.11). Dorsal margin somewhat linear, smooth and thick. Ventral margin is rounded, thick and smooth. Posterior is broadly pointed. Rostrum is rounded and antirostrum is absent. Medial is slightly convex. Lateral is slightly concave, smooth and concentric rings are not visible. Sulcus is broad, shallow and close to dorsal margin. Cauda is strongly curved to ventral margin and V-shaped in section. Ostium is open.

Apogonidae *Apogon menesemus* (Fig. 3f). Large, thick otolith (1:22) and oblong (1.50). Dorsal margin irregular, curved with a single deep cut at centre. Ventral margin slightly jagged and circular with a noticeable lip. Posterior irregular and perpendicular to long axis. Protruding rostrum, antirostrum weakly developed but distinct. Angle of rostrum and antirostrum is 90%. Medial is relatively flat. Lateral is slightly concave and smooth with no concentric rings visible. Sulcus is shallow (as well as cauda and ostium). Cauda is closed yet weakly defined. Ostium is open and broad. This genus has restricted morphological variation and examples of other species are illustrated in Nolf (1985: Fig. 12).

Carangidae *Caranx melampygus* (Fig. 4a). Small otolith (1:60) and very elongate (2.34). Dorsal margin is curved with a single protuberance at the centre. Ventral margin is slightly curved and somewhat jagged. Tapers to posterior with two points, the dorsal one longest. Very protruding rostrum, one-third of length, and well developed antirostrum. Angle of rostrum and antirostrum is acute. Medial flat and lateral concave with concentric rings visible. Cauda is closed near the posterior margin. Ostium is open. According to Nolf, the Carangidae family is characterised by small elongate otoliths with a deeply incised sulcus and a very prominent rostrum (Nolf 1985: 16, Fig. 17).

Carangidae *Trachurops crumenophthalmus* (Fig. 4b). Otolith of medium size (1:47) and slightly elongate (1.63). Dorsal margin is curved and irregular. Ventral margin is curved and slightly jagged near rounded posterior. Rostrum and antirostrum well developed and pointed. Medial of otolith is convex. Lateral is concave with concentric rings and grooves present. Sulcus is deeply incised. Cauda is closed and deep and ostium is open.

Holocentridae *Holocentrus lacteoguttatus*. Otolith of medium size (1:48), thin and slightly elongate (1.76). Dorsal margin is irregular and jagged. Ventral margin is smooth and slightly curved. Posterior is slightly rounded. Rostrum is rounded and antirostrum slightly developed. Medial is flat and lateral slightly concave. Cauda and ostium are open. Specimen is possibly from a subadult.

Holocentridae *Myripristis argyromus* (Fig. 4d). Large otolith (1:17), thick and triangular in shape (1.52). Dorsal margin is pointed (apex of triangle). Ventral margin is irregular, tapering to anterior. Posterior is pointed and smooth. Rostrum is wide and antirostrum absent. Medial is slightly convex and lateral slightly concave with concentric rings visible in one corner of triangle. Sulcus is situated at lower third of inside surface and is shallow. Cauda closed and ostium appears closed.

Kuhliidae *Kuhlia sandvicensis* (Fig. 3b). Large otolith (1:31), relatively thick and slightly elongate (1.74). Dorsal margin is slightly curved and smooth. Ventral margin is curved and jagged. Posterior is round and jagged. Rostrum is wide and short and antirostrum is distinct, small and pointed. Medial is strongly convex and lateral strongly concave. Cauda is closed and strongly curved to ventral. Ostium is broad at anterior margin.

Kyphosidae *Kyphosus cinerascens* (Fig. 5c). Large otolith (1:36), thin and very elongate (2.36). Dorsal, ventral, and posterior margins jagged. Dorsal margin is curved very slightly otherwise parallel to ventral margin. Posterior is rounded and extends longer towards the ventral. Rostrum is protruded and more than one-third of length. Antirostrum pointed and well developed. Medial is convex and lateral is concave with concentric rings visible. The cauda is closed and bends sharply to ventral. Ostium is open and wider at margin.

Labridae *Thalassoma ballieui*. Small otolith (1:66), thin and oblong (1.56). Dorsal and ventral margins are curved and smooth. Dorsal margin more irregular. Posterior rounded. Rostrum and antirostrum both well developed and pointed. Medial is convex and lateral strongly concave with concentric rings easily visible. Cauda and ostium both open.

Labridae *Thalassoma fuscum*. Small otolith, thin and slightly elongate (1.68). Dorsal margin curved and irregular. Ventral margin slightly linear and jagged. Posterior is bipointed. Rostrum and antirostrum well developed and pointed. Medial is convex and lateral smooth, concave with grooves radiating from the ventral margin. Cauda and ostium open and deep relative to inside of otolith surface.

Mugilidae *Mugil cephalus* (Fig. 4f). Medium size otolith (1:42), thin and very elongate (2.29). Dorsal and ventral margins are parallel. Dorsal margin has deep cuts near middle and anterior third tapers to ostium. Ventral margin has a single deep cut at the medial point. Posterior is rounded. Rostrum is pointed and antirostrum absent. Medial is convex and lateral concave and smooth with no concentric rings present. Cauda closed and posterior end slightly curved to ventral. Ostium is open.

Mullidae *Mulloidichthys auriflamma*. Otolith of medium size (1:54), thin and oblong (1.57). All margins jagged. Dorsal margin irregular and ventral margin curved with small holes near the ventro-anterior margin. Posterior rounded. Protruding rostrum with pointed antirostrum. Medial is slightly convex and lateral is concave, smooth with radiating grooves. The sulcus is shallow. Both cauda and ostium open and deep relative to outside surface area. Description from a subadult.

Mullidae *Parupeneus multifaciatus* (Fig. 5a). Medium size otolith (1:59), thin and subrounded (1.20). Dorsal margin with one deep notch at highest point. Ventral margin is curved and irregular. A single, slight point at the rounded posterior. Rostrum fairly wide and distinct from the antirostrum. Medial is convex. Radiating lines are present on the lateral surface and concentric rings are slightly visible. Sulcus is deep. Cauda is closed and curved to the ventral margin. Ostium open.

Mullidae *Upeneus arge* (Fig. 5b). Otolith of medium size (1:55), thin and slightly elongate (1.83). Dorsal margin curved with two deep cuts. Ventral margin linear and jagged. Posterior round and jagged. Rostrum well developed and pointed. Antirostrum slightly developed and pointed. Medial of otolith is convex and lateral concave, smooth and faint

concentric rings. Sulcus is shallow compared to cauda and ostium. Cauda is closed and curved to ventral. Ostium is open.

Polynemidae *Polydactylus sexfilis* (Fig. 5d). Otolith of medium size (1:40), somewhat thin and elongate (2.22). Margins are jagged, dorsal and posterior more so. Dorsal and ventral margins are parallel and posterior margin somewhat perpendicular to the long axis of otolith length. Rostrum and antirostrum both well defined; angle of two about 45 degrees. Medial of otolith is convex and lateral is smooth, concave with no visible concentric rings. Cauda is open and curved to ventral margin. Ostium is open and deep.

Pomacentridae *Abudefduf sordidus* (Fig. 5e). Otolith is relatively large (1:38). Elongate (1.88) with somewhat jagged margins. Dorsal margin is irregular with a single protrusion. Ventral margin is linear. Posterior is subrounded and pointed at the extreme end. Rostrum is pointed while the antirostrum is weakly developed. Medial is convex. In dorsal view the lateral is concave and exhibits strongly defined concentric rings and few radiating grooves. The sulcus is shallow. Cauda is open and deeply V-shaped in section. Ostium is open.

Priacanthidae *Priacanthus cruentatus* (Fig. 5f). Large otolith (1:34), thin and slightly elongate (1.69). Dorsal margin slightly curved and jagged. Ventral margin curved with deep cuts at the posterio-ventral area. Posterior is round and somewhat irregular. Rostrum is well defined and antirostrum present and rounded. Medial of otolith is strongly convex and lateral strongly concave with concentric rings and radiating grooves visible. Sulcus is deep and constricted. Cauda and ostium are open.

Scaridae *Calotomus sandvicensis*. Small, thin otolith (1:73) and slightly elongate (1.70). Dorsal margin slightly curved and somewhat jagged. Ventral margin more linear. Posterior is perpendicular to the long axis. Rostrum and antirostrum present but not well developed. Medial is slightly convex and lateral somewhat concave with radiating grooves but no concentric rings. Sulcus is constricted giving a 'barbell-like' appearance with the cauda and ostium which are both open. Specimen is probably a subadult.

Scaridae *Scarus perspicillatus* (Fig. 6a). Medium otolith, thick and somewhat oblong (1.35). Dorsal margin is curved and jagged with groove-like features perpendicular to the margin. Ventral margin is curved and smooth. Marked contrast between the opposing margins. Posterior margin is irregular and reflects characteristics of dorsal and ventral margins (Fig. 4c). Rostrum is rounded and antirostrum weakly developed. Medial of the otolith is convex and lateral is concave with radiating grooves. The sulcus is constricted and deep joined to the cauda and ostium to suggest a 'barbell-like' appearance. The cauda is closed and ostium open; both are deeply recessed from inside surface of the otolith.

Sphyraenidae *Sphyraena helleri* (Fig. 6b). Otolith of medium size (1:47) and very elongate (2.38). Smooth dorsal margin and somewhat jagged ventral margin are slightly curved and subparallel. The posterior is somewhat rounded, jagged and pointed. Rostrum is well developed and wide, while antirostrum is small and pointed. Medial is convex and lateral smooth and strongly concave. Cauda is closed and slightly curved to ventral. Ostium is open.

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