INCREASING TAXONOMIC RESOLUTION IN DIETARY ANALYSIS OF THE HAWAIIAN MONK SEAL

BY

KEN LONGENECKER[1], ROBERT A. DOLLAR[2], and MAIRE K. CAHOON[2]

ABSTRACT

We examined otoliths found in regurgitate samples (spews) of Hawaiian monk seals, *Monachus schauinslandi*, to identify fish prey, and report for the first time that these seals eat morid cods typically found at subphotic depths. Dietary information was used to build a comparative skeletal collection and create a digital image database to aid foraging ecologists in the efficient, species-level identification of fish remains. We suggest that high-resolution dietary analysis will significantly enhance understanding of monk seal foraging behavior and food requirements, and that previous assumptions that Hawaiian monk seals forage largely in shallow coral-reef habitats are in need of revision.

INTRODUCTION

The total population of the endangered Hawaiian monk seal, *Monachus schauinslandi*, is composed of approximately 1,300 individuals living mainly on six reef systems in the Northwestern Hawaiian Islands (Antonelis et al., 2006). The emaciated condition of some pups and adults suggests that starvation may be a threat to the species (Ragen and Lavigne, 1999; Parrish et al., 2000). Population biologists report declines in birth rates and survival rates of pups and juveniles, and increases in age of first reproduction of females (Stewart, 2004). A reduction in prey is most likely a significant factor influencing these trends (Parrish, 2004). Such a reduction could be caused by natural prey fluctuations or competition for prey resources (Goodman-Lowe, 1998). For these reasons, understanding the diet and foraging habits has been identified as a key component for successful conservation of the Hawaiian monk seal (Stewart, 2004). Such information can help resource managers evaluate concerns of user groups (lobster, finfish, and precious coral fisheries) and efforts to enhance juvenile survival (*e.g.*, translocation) when making management decisions for the conservation and recovery of monk seals. However, what and where monk seals eat must be fully understood (Ragen and Lavigne, 1999; Parrish, 2004) before assessments of prey availability and abundance can be made.

Early studies on the diving behavior of seals, combined with dietary analyses, led to the inference that seals forage mainly within the shallow coral-reef habitat. DeLong et al. (1984) used depth recorders to describe the diving behavior of six animals and

[1]Bishop Museum, 1525 Bernice Street, Honolulu, HI 96817 USA, E-mail: klongenecker@bishopmuseum.org
[2]NOAA Pacific Islands Fisheries Science Center, 2570 Dole Street, Honolulu, HI 96822 USA

reported that the majority (59%) of dives were shallower than 40 m. Kenyon and Rice (1959), DeLong et al. (1984), and Goodman-Lowe (1998) used a variety of techniques to describe the diet of seals at family-level taxonomy and reported that nearly all prey could be classified as reef-associated.

Since then, a variety of telemetry studies have provided cause to question whether seals feed primarily within the reef habitat. Seals routinely travel between the islands, banks, and seamounts of the Northwestern Hawaiian Islands (Parrish, 2004) and may travel up to 160 km from their haul-out location (Abernathy, 1999). More recent depth recorder data shows seals spend a large portion of their dive time between 50 and 300 m (Stewart, 1998). Furthermore, some seals routinely dive to subphotic depths. Parrish (2004) summarized telemetry data and found that, of 37 adults tagged (Abernathy, 1999; Stewart 2004; Stewart & Yochem, 2004 a and b), 47% dove to at least 300 m. Combined, these telemetry data suggest seals forage at the edges of atolls and banks, in the slope habitat (Parrish, 2004).

Seal-mounted video cameras further show that most time in shallow water (>50%) is spent sleeping and socializing (Parrish et al., 2000). Other shallow dives (<20 m) are prolonged midwater swims as seals travel to foraging grounds at remote locations (Parrish et al., 2002). Thus, shallow-water activity does not coincide with prey capture. In fact, seal-mounted video cameras show that, although most time is spent in the shallow waters of the atoll, most prey are captured at depths of 50-100 m (Parrish et al., 2000). Seals ignored shallow-water reef fishes and fed on fishes from low-relief habitats in deeper water (Parrish et al., 2000).

By increasing taxonomic resolution in dietary studies, we will obtain a more detailed picture of food resource use by monk seals and an increased probability of detecting relationships between prey resources and monk seal demography. Although nearly all fishes eaten by monk seals belong to a reef-fish family (Kenyon and Rice, 1959; DeLong et al., 1984; Goodman-Lowe, 1998), most reef-fish families have deep-water members. For instance, all dietary analyses indicate that conger eels are an important part of seal diets. Kenyon and Rice (1959) noted that these eels are abundant within the atolls, and DeLong et al. (1984) state that the family prefers shallow, benthic habitats. A plot of the depths where the 10 Hawaiian congrids occur (Fig. 1) shows that the distribution of these eels is more complicated. A similar pattern can be found for nearly all fish families important (prevalent) in the monk seal diet. Species-level dietary analysis can be combined with known patterns of habitat use (depth and bottom type) by prey species to infer where seals successfully capture food.

We performed preliminary dietary analysis on Hawaiian monk seals, and used the information to describe seal prey use, to infer foraging behavior, and to guide the expansion of a comparative collection of fish skeletons. With access to the information housed in such a comparative collection, most foraging ecologists can conduct species-level dietary analysis and contribute to a better understanding of seal food resource use. We describe a prototype photographic database (virtual collection) designed to give researchers remote access to the collection and to identify fish remains to species more efficiently.

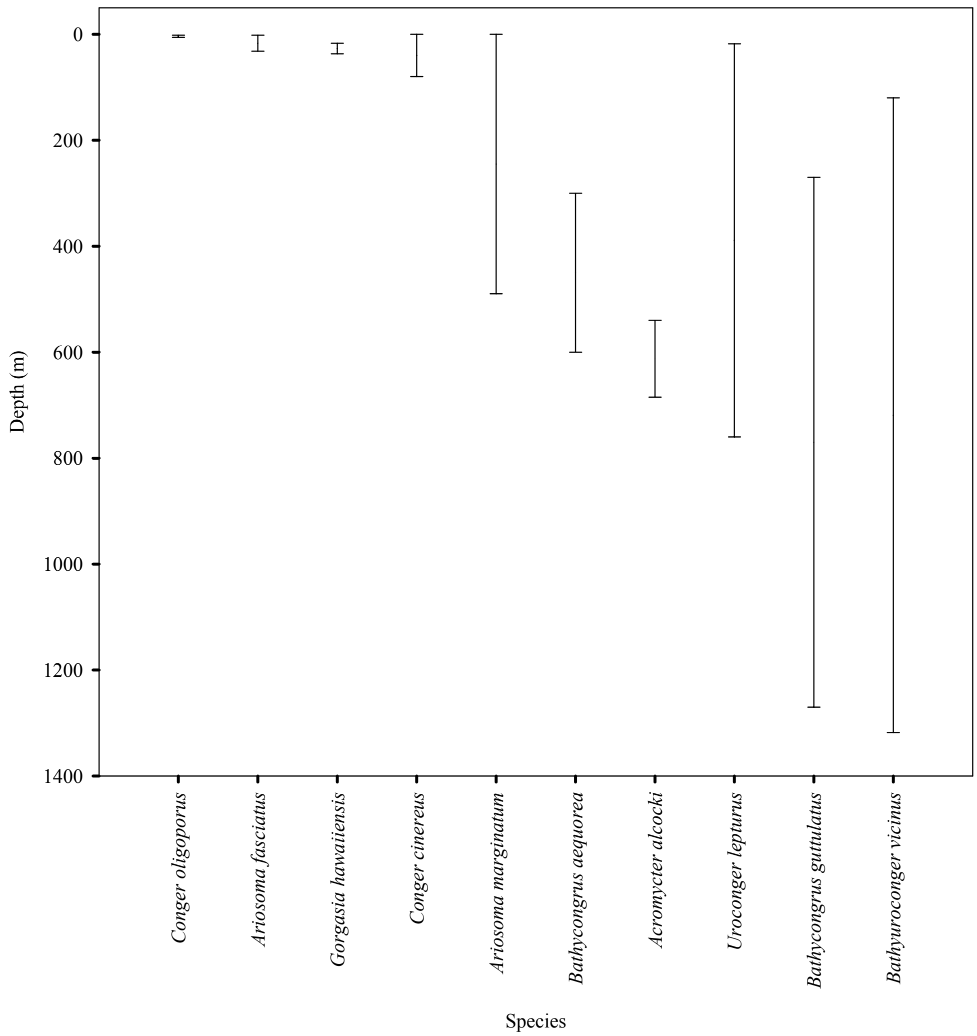

Figure 1. Depth distribution of 10 Hawaiian congrid species.

METHODS AND MATERIALS

Overview

Our methods were an iterative process. Preliminary dietary analyses were performed on seal regurgitate samples (spews), and this information, combined with results from past dietary studies (DeLong et al., 1984; Goodman-Lowe, 1998), was used to compile a list of fish families important in seal diets. These families were then targeted for collection, with the intention of building a comparative skeletal collection of all Hawaiian species in those families. Diagnostic bones were photographed and incorporated into an image management program to aid rapid identification of fish remains. These physical and virtual comparative collections were then used to re-examine samples, to examine other spew samples, and eventually to examine fecal samples (scats). More prey species or families will be added to the collection as necessary.

Dietary Analysis

Spews were used for the preliminary analysis because fish prey tends to be less digested than in feces; thus the likelihood of identifying prey was increased. Spews were collected from the Northwestern Hawaiian Islands (NWHI), during the 1996-2001 National Marine Fisheries Service (NMFS) summer field camps. Samples were sent to the lab, washed with fresh water, dried, and stored in plastic bags for processing. Otoliths were the primary structures used to identify fish prey because the otolith literature most fully represents Hawaiian fish families. We used the otolith atlases of Smale et al. (1995), Rivaton and Bourret (1999), and Dye and Longenecker (2004) as identification guides. We also used, when appropriate, a comparative collection of fish skeletons housed at the Bishop Museum to identify bones.

Physical Comparative Collection

Species from fish families important in the diet of monk seals were collected during NMFS cruises, and frozen until processing. Fishes were identified to species, measured, and photographed. A disarticulated skeleton does not possess the features typically used for taxonomic work; therefore, any deviations from the species description were noted.

Scales were sampled from six locations (Casteel, 1974) on each specimen: the nape, dorsally on the flank, ventrally on the flank, posterior to the dorsal fin, dorsally on the caudal peduncle, and ventrally on the caudal peduncle. These were mounted in a standardized order between glass slides. Skeletons were prepared by eviscerating, skinning, and removing most muscle from the specimen; drying the carcass; and cleaning it with dermestid beetles (see Sommer and Anderson, 1974 and Bemis et al., 2004 for details and variations of techniques). Skeletons were further cleaned and partially disarticulated by cold-water maceration (Hildebrand, 1968).

Virtual Comparative Collection

Structures incorporated into the virtual collection (i.e., photographic database) are those commonly found in seal spews (personal observation) and described as useful taxonomic indicators by Wheeler & Jones (1989). These structures are [following the terminology of Rojo (1991)]: saggitae (saccular otoliths), premaxilla, maxilla, dentary, angular, quadrate, hyomandibular, prevomer, parasphenoid, basioccipital, supraoccipital, pterotic, frontal, opercle, preopercle, three precaudal vertebrae, three caudal vertebrae, and the six scales collected as described above. The three vertebrae selected for the precaudal and caudal series represent the range of conditions for each vertebral type. Because the neurocranium of fishes is often found relatively intact in seal spews, images were included for each species.

Structures were photographed from several aspects (typically lateral and medial, or dorsal and ventral) on a dissecting microscope at the highest magnification that included the whole structure in the field of view. Images were incorporated into the photo management program, SuperJPG. This program allows images to be linked to keywords (e.g., family name, genus name, species name, bone name, and features found on each bone). An extensive review of phylogenetic literature provided the terminology used to describe bone features. An illustrated glossary of these terms (Longenecker, 2004) was produced to accompany the virtual collection.

RESULTS

Dietary Analysis

Thirty-one spews from the 1996-2001 field collections were examined for preliminary dietary analysis. The majority of spews (22) were collected at Laysan, six were from Lisianski, one from Seal-Kittery Island at Pearl and Hermes Reef, and one each from Disappearing Island and Little Gin Island at French Frigate Shoals. In Table 1, we present fishes eaten, by family. Not all prey items were identified. However, the percent number (number of prey from a given taxon divided by the total number of identified prey, expressed as a percentage) and percent frequency of occurrence data do give an estimate of which families are most important in the monk seal diet. Moridae and a tentatively identified Cynoglossidae are reported as monk seal prey for the first time.

Some fishes were identified beyond family level. Thirty-five of the 47 congrids were *Ariosoma marginatum*. One of the labrids was a razor wrasse (*Iniistius*). Both holocentrids were *Myripristis* species (soldierfish).

Parts of crustaceans and molluscs were also found. Of the crustacea, one was a stomatopod and another was a lobster.

Table 1. Family-level identification of fishes from 33 spews of Hawaiian monk seals collected 1996 – 2001 from Laysan Island, French Frigate Shoals, Lisianski Island, and Pearl and Hermes Reef. Eighty-eight individuals were identified.

Family	% Number	% Frequency of Occurrence
Congridae	53.4	25.8
Tetraodontidae	22.7	6.5
Labridae	6.8	9.7
Scaridae	4.6	3.2
Holocentridae	2.3	6.5
Priacanthidae	2.3	3.2
Moridae	1.1	3.2
Ophidiidae	1.1	3.2
Scorpaenidae	1.1	3.2
Acanthuridae	1.1	3.2
Monacanthidae	1.1	3.2
Balistidae	1.1	3.2
Cynoglossidae (tentative)	1.1	3.2

Table 2. Fish families important in the monk seal diet (≥3% Frequency of Occurrence as reported in Goodman-Lowe, 1998), the approximate number of Hawaiian species, and the number of species in the comparative skeletal collection.

Family	# Hawaiian species	# species in collection
Congridae	10	3
Tetraodontidae	14	4
Labridae	41	13
Scaridae	7	5
Holocentridae	18	5
Priacanthidae	4	2
Ophidiidae	4	0
Acanthuridae	23	15
Monacanthidae	9	4
Balistidae	10	5
Muraenidae	40	4
Synodontidae	15	2
Mullidae	11	10
Kyphosidae	5	1

Physical Comparative Collection

The comparative skeletal collection currently houses 515 specimens representing 177 species. Our collection is far from complete; approximately 1,000 fish species are known from the Hawaiian Islands. Even when considering only the subset of families documented from monk seal diets (DeLong et al., 1984; Goodman-Lowe, 1998; Parrish et al., 2000; present study), we have only 34.5% of the species, and no family is complete. Table 2 is a list of fish families important in the monk seal diet, the approximate number of species in Hawaii, and the number of species in the collection.

Virtual Comparative Collection

The digital image database currently contains 414 images representing 21 species from 7 families. These are linked to descriptors (key words) which can be used to sort images and display only those structures with specific character(s). Each image is linked to the family, genus, species, and structure (bone name or otolith) it represents. Structures are being linked to character states used in phylogenetic analyses. For example, the dentaries are linked to 24 character states that can be selected singly or in combination. The sorting power of the database is illustrated in Figure 2; an investigator attempting to identify a bone can display all images of bones from one or more taxa, all images of a single bone type with one or more characters, or all images of a single bone type from a given taxon.

DISCUSSION

Dietary analysis using spews and scats is inherently biased. Because seals may travel up to 160 km from their haul-out location (Abernathy, 1999), prey eaten at distant locations may be voided before the seal returns to a beach. Thus, spews and scats may mostly represent prey taken in nearby locations (Parrish, 2004). Variation in digestion rates of prey parts may lead to over- or under-representation of prey. Spew analysis may present unique problems. Goodman-Lowe (1998) suggests eels are more likely to be regurgitated than other prey. Similarly, fishes likely to be ciguatoxic may be over-represented in spews. Despite these potential drawbacks, scat and spew analysis remains the most direct way to determine what seals eat. This low-technology, low-cost method can potentially generate large amounts of information from the abundant deposits (thousands have been collected) left by seals on beaches.

Our work represents the first report of morid cods (Moridae) in the diet of Hawaiian monk seals. Nine morid species occur in Hawaii, and all are found in depths greater than 95 m. The family is characteristic of the subphotic fish community (Parrish, 2004). The morid was found in a spew collected on Laysan. This finding is consistent with recent telemetry studies showing most seals at Laysan (80%) dove at least to depths of 100 m, and all adult females dove beyond 300 m (Stewart and Yochem, 2004b).

We found at least four congrid eel species in seal spews. As these are identified to less-inclusive taxonomic groups (genus and species), we will gain increasingly

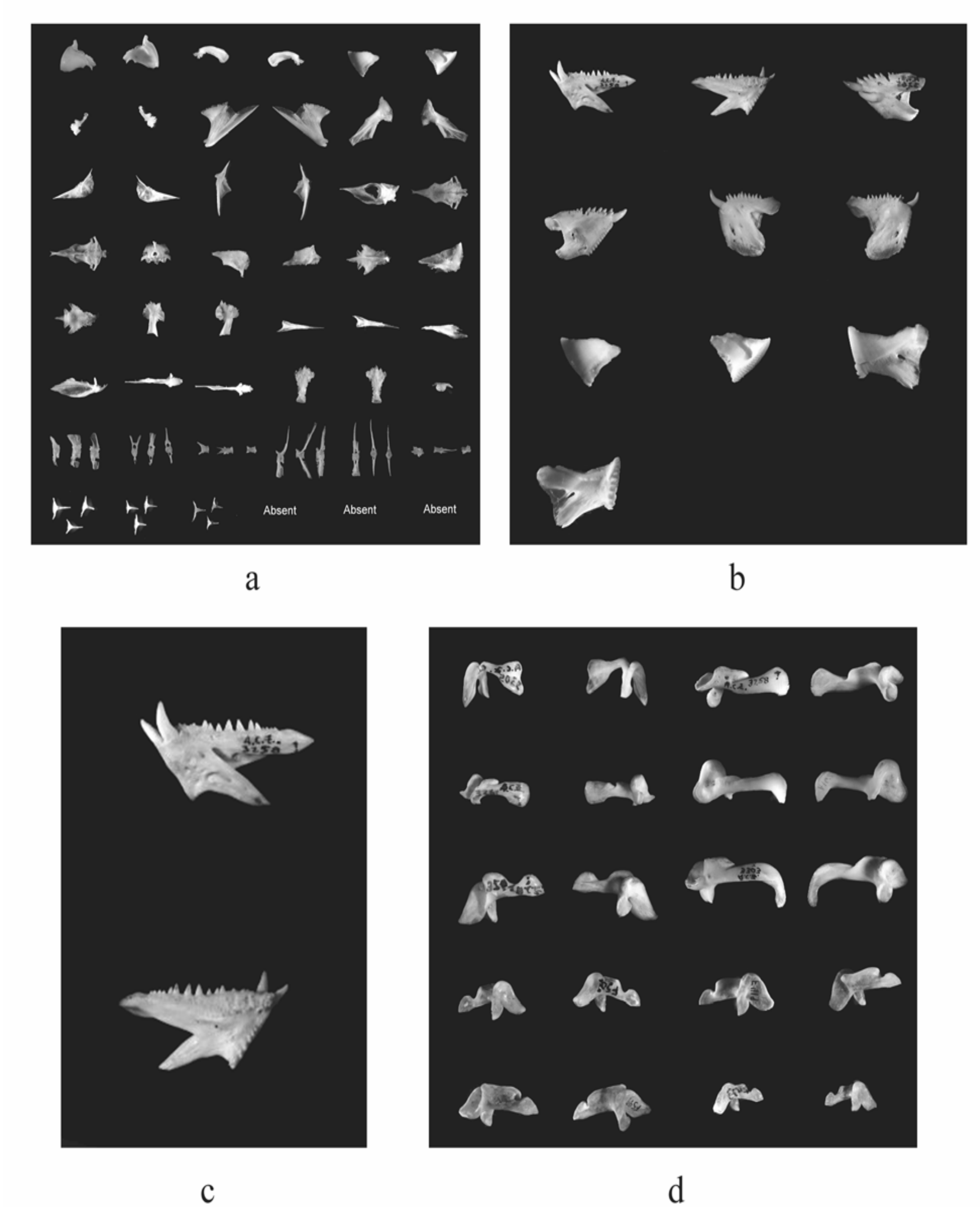

Figure. 2. Examples of the sorting power of the virtual comparative collection. (a) all structures from *Canthigaster jactator* (“absent” represents scale-less locations), (b) all dentaries with an interdigitate mandibular symphysis, (c) all dentaries with an interdigitate mandibular symphysis and a pointed ventral process, (d) all labrid maxillae.

detailed knowledge about the foraging habits of monk seals. For instance, the majority of congrids consumed were *Ariosoma marginatum*. This is a sand-dwelling species (Randall, 1996). Of the labrids eaten, one belonged to the genus *Iniistius*. These razorfishes also live over open sand bottom (Randall, 1996). The presence of these prey in spews corresponds with evidence from seal-mounted video cameras that sand bottoms are the second most frequent habitat searched by foraging seals (Parrish et al., 2000).

A current drawback of using fecal and regurgitate samples to describe monk seal foraging behavior is an inability to match a scat or spew found on the beach to a single animal. Thus, it is possible that some animals will be sampled repeatedly, and others not at all. Efforts are now underway to match scats and spews to individuals so that bias can be reduced, and sex- and age-based dietary analyses can be performed.

Species-level identification of prey fish previously required access to a large comparative collection of fish bones and an intimate knowledge of its contents. Unfortunately, there are few of these comparative collections, their creation and maintenance is time-consuming and costly, they require a significant amount of space, and accessing them can be difficult. Further, few foraging ecologists have the necessary familiarity with comparative fish osteology to realize the full potential of a comparative osteological collection. The imaging technology we describe will give many researchers unlimited virtual access to a comparative collection and will efficiently guide foraging ecologists toward high-resolution identification of fish remains.

We are currently working to incorporate cephalopod beaks into the image database. These are abundant in scats and spews (Kenyon and Rice, 1959; DeLong et al., 1984; Goodman-Lowe, 1998; present study). Goodman-Lowe (1998) was particularly successful at high-resolution identification of cephalopod beaks. We anticipate that our virtual reference collection will help others perform the same quality of work.

The digital image database described here was designed specifically to aid studies of Hawaiian monk seal foraging ecology. The disarticulated skeletons prepared in this study will be added to a comparative collection begun by archaeologists at Bishop Museum. We anticipate the virtual collection will be useful to a broad range of foraging ecologists, archaeologists, and paleontologists.

ACKNOWLEDGEMENTS

The Marine Mammal Commission provided partial funding for this work. The project is built upon the work and vision of Leslie Hartzell. Albert Harting and Brenda Becker gave invaluable advice on creating the photographic database. Arnold Suzumoto, Carla Kishinami, and Holly Bolick directed the organization and management of the comparative collection. Kristine Nakamoto, Alexia Pihier, Carmen Surface, and Melissa Vaught of Bishop Museum's internship program assisted in the building, organizing, databasing, and photographing of the comparative collection. This internship program is funded by the U.S. Department of Education. The program is an initiative under the Office of Innovation and Improvement of the U.S. Department of Education. Education through Cultural & Historical Organizations, also known as ECHO, provides educational enrichment to native and non-native children and lifelong learners. We thank Bud Antonelis and Charles Littnan for comments on the manuscript. This is contribution #2005-004 to the Hawaii Biological Survey.

LITERATURE CITED

Abernathy, K.J.
1999. *Foraging ecology of Hawaiian monk seals at French Frigate Shoals, Hawaii*. MS Thesis. University of Minnesota. 65 pp.

Antonelis, G.A., J. Baker, T.C. Johanos, R.C. Braun, and A.L. Harting
2006. Hawaiian monk seal (*Monachus schauinslandi*): status and conservation issues. *Atoll Research Bulletin* (this issue) 543:75-100.

Bemis, W.E., E.J. Hilton, B. Brown, R. Arrindell, A.M. Richmond, C.D. Little, L. Grande, P.L. Forey, and G.J. Nelson
2004. Methods for preparing dry, partially articulated skeletons of osteichthyans, with notes on making Ridgewood dissections of the cranial skeleton. *Copeia* 2004:603-609.

Casteel, R.W.
1974. On the remains of fish scales from archaeological sites. *American Antiquity* 39:557-581.

Delong, R.L., G.L. Kooyman, W.G. Gilmartin, and T.R. Loughlin
1984. Hawaiian monk seal diving behavior. *Acta Zoologica Fennica* 172:129-131.

Dye, T.S., and K. Longenecker
2004. Manual of Hawaiian fish remains identification based on the skeletal reference collection of Alan C. Ziegler and including otoliths. *Society for Hawaiian Archaeology Special Publication* No. 1. 134 pp.

Goodman-Lowe, G.
1998. Diet of Hawaiian monk seal (*Monachus schauinslandi*) from the Northwestern Hawaiian Islands during 1991-1994. Marine Biology 132:535-546.

Hildebrand, M.
1968. *Anatomical Preparations*. University of California Press, Berkeley. 100 pp.

Kenyon, K.W., and D.W. Rice
1959. Life history of the Hawaiian monk seal. *Pacific Science* 13:215-252.

Longenecker, K.R.
2004. Virtual comparative collection of diagnostic fish structures. *Hawai'i Biological Survey* No. 2004-006. 16 pp.

Parrish, F.A.
2004. *Foraging landscape of the Hawaiian monk seal*. PhD Dissertation. University of Hawaii. 146 pp.

Parrish, F.A., M.P. Craig, T.J. Ragen, G.J. Marshall, and B.M. Buhleier
2000. Identifying diurnal foraging habitat of endangered Hawaiian monk seals using a seal-mounted video camera. *Marine Mammal Science* 16:392-412.

Parrish F.A., K. Abernathy, G.J. Marshall, and B.M. Buhleier
2002. Hawaiian monk seals (*Monachus schauinslandi*) foraging in deepwater coral beds. Marine Mammal Science 18:244-258.

Ragen, T.J., and D.M. Lavigne
1999. The Hawaiian monk seal: biology of an endangered species. Pp. 224-245. In: J.R. Twiss and R.R. Reeves (eds.), *Conservation and Management of Marine Mammals*. Smithsonian Institution Press. Washington, D.C.

Randall, J.E.
1996. *Shore Fishes of Hawaii*. Natural World Press, Vida. 216 pp.

Rivaton, J., and P. Bourret
1999. Les otolithes des poisons de l'Indo-Pacifique. *Documents Scientifiques et Techniques* II 2. 378 pp.

Rojo, A.L.
1991. *Dictionary of Evolutionary Fish Osteology*. CRC Press. Boca Raton. 273 pp

Smale, M.J., G. Watson, and T. Hecht
1995. Otolith atlas of Southern African marine fishes. *Ichthyological Monographs of the J.L.B. Smith Institute of Ichthyology* No. 1, xiv, 253 pp., 149 plates.

Sommer, H.G., and S. Anderson
1974. Cleaning skeletons with dermestid beetles – two refinements in the method. *Curator* 17:361-372.

Stewart, B.S.
1998. Foraging ecology of Hawaiian monk seals (Monachus schauinslandi) at Pearl and Hermes Reef, Northwestern Hawaiian Islands: 1997-1998. *HSWRI Technical Report* No. 98-281:1-83.
2004. Geographic patterns of foraging dispersion of Hawaiian monk seals (*Monachus schauinslandi*) at the Northwestern Hawaiian Islands. *NOAA Pacific Islands Fisheries Science Center Administrative Report*. H-04-05C. 25 pp.

Stewart, B.S., and P.K. Yochem
2004a. Use of marine habitats by Hawaiian monk seals (*Monachus schauinslandi*) from Kure Atoll: Satellite-linked monitoring in 2001-2002. *NOAA Pacific Islands Fisheries Science Center Administrative Report*. H-04-01C. 113 pp.
2004b. Use of marine habitats by Hawaiian monk seals (*Monachus schauinslandi*) from Laysan Island: Satellite-linked monitoring in 2001-2002. *NOAA Pacific Islands Fisheries Science Center Administrative Report*. H-04-02C. 131 pp.

Wheeler, A., and K.G. Jones
1989. *Fishes*. Cambridge University Press. New York. 210 pp