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The biology and ecology of the pygmy sperm whale (*Kogia breviceps*) is poorly understood among odontocetes (McAlpine 2002). In Hawaiian waters, pygmy sperm whales are the second most frequently recorded stranded cetacean species, with 35 strandings documented between 1963 and 2008 (Shallenberger 1981, Nitta 1987,

Table 1. Pygmy sperm whales stranded in the Hawaiian Islands between 1986 and 2008 where stomach contents were examined.

Status at stranding	Date of stranding	Sex	Reproductive status	Body length (cm)	Location of stranding
Dead	8 January 1986[a]	M	Mature	301	Kalaupapa, Moloka‘i
Alive and died on site	3 June 2000	M	Immature	244	Na Pali coast, Kaua‘i
Alive and later euthanized	15 January 2005	F	Mature (with calf)	295	Kihei, Maui
Dead	20 May 2006	M	Mature	306	Kalaupapa, Moloka‘i
Dead	15 April 2007[a]	F	Mature (pregnant)	315	Lana‘i
Dead	25 April 2007	M	Mature	307	Kihei, Maui
Dead	1 January 2008	F	Immature	215	Midway atoll

[a]The 2007 Lana‘i and the 1986 Kalaupapa stranding date represent the dates of the initial observation. The individual from Lana‘i was found in a remote area of the island in a moderate state of decomposition and likely stranded at an earlier date.

Maldini *et al.* 2005, NMFS database[1]). Despite the high frequency of strandings, sightings of this species in Hawaiian waters are rare (Baird 2005). Given the low number of sightings, examination of stranded animals provides virtually the only means to study the biology and ecology of pygmy sperm whales in the area.

Pygmy sperm whales are recorded as feeding primarily on cephalopods from most locations where stomach contents have been examined (Wang *et al.* 2002, Bustamante *et al.* 2003, Santos *et al.* 2006, Beatson 2007). However, diet composition has not been previously examined for pygmy sperm whales from any location in the central Pacific Ocean. The primary objective of our study was to assess the diet of pygmy sperm whales in Hawai‘i through the examination of stomach contents of seven stranded specimens. In addition, we compare the diet composition of pygmy sperm whales in the Hawaiian Islands with that of whales from other geographic locations.

Stomach contents were collected from six of 16 pygmy sperm whales that stranded between 2000 and 2008 in the Hawaiian Islands and from one individual that stranded in 1986. Additional information on date of stranding, body length, and specific location is provided in Table 1. In all but one case, pygmy sperm whales were identified to species based on both the location of the dorsal fin and a height measurement that was less than 5% of the total body length (five of the seven were also longer than the known maximum body length for dwarf sperm whales). For the Midway individual, genetic analyses performed by the Southwest Fisheries Science Center was necessary to confirm the species identification.

Stomach contents were initially frozen for six of the pygmy sperm whales and fixed in formalin for one of the whales. Frozen contents were later thawed and each sample was then rinsed through a progression of sieves with decreasing mesh sizes of 1.4 mm, 0.94 mm, and 0.50 mm. After sorting, cephalopod beaks, fish bones and crustacean

[1]Available from Pacific Islands Regional Office, NOAA National Marine Fisheries Service, 1601 Kapiolani Boulevard, Suite 1110, Honolulu, HI 96814.

remains were preserved in 70% ethanol. Fish otoliths were stored dry in gelatin capsules. All remains were identified to the lowest possible taxon using the private reference collection of W. A. Walker and the fish bone, otolith and cephalopod beak reference collections housed at the National Marine Mammal Laboratory (NMML), Seattle, Washington. A voucher series of select beaks and otoliths representing each prey taxon were removed from the individual stomach samples and incorporated into the NMML reference collections. The remainder of the individual stomach samples were stored in alcohol at NMML.

A total number of each species of cephalopod was estimated as the number of lower beaks present. A total number of each fish species was estimated based on the greater number of left and right otoliths. In a few instances, the number of fish prey was estimated based on the greater number of left or right paired cranial bones. Crustacean abundance was estimated using the number of individual carapace remains in each stomach.

Dorsal mantle length and total weights were estimated by measuring lower beak rostral length for the cephalopod decapods and lower beak hood length for the cephalopod octopods and then applying the appropriate regression equations. Cephalopod beaks were measured to the nearest 0.1 mm with either an optical micrometer or, in the case of large beaks, Vernier calipers. With three exceptions, all regression equations came from Clarke (1986). There were no regression equations available for *Enoploteuthis* sp. *cf. E. reticulata, Japatella* sp., and *Ocythoe tuberculata*. Prey size for these species were estimated using data from individuals of near equivalent beak size housed in the NMML reference collection. Following Clarke (1986), pigmentation (darkening) of the wing portions of the lower beak were recorded for beaks of *Stigmatoteuthis hoylei*, *Taonius pavo, Liocranchia reinhardti*, and *Mastigoteuthis famelica*. Beaks were considered to be from adult squid when the wing pigmentation was complete. Fish otoliths and diagnostic bones were measured to the nearest 0.1 mm using an optical micrometer. In most cases, fish prey standard lengths and weights were estimated using regression equations from the literature (Smale *et al.* 1995, Ohizumi *et al.* 2001, Spear *et al.* 2007), or from regressions developed for similar, closely related species at NMML. In instances where appropriate weight regressions were unavailable, weight was estimated by comparison with other closely related species of similar size. Of the two crustaceans documented, carapace length and weight relationships had only been described for *Gnathophausia ingens.* As a result, weights were estimated for both species of shrimp by measuring carapace length and then applying the regression equation available for *G. ingens* (Childress and Price 1983).

Together the seven stomachs of pygmy sperm whales examined contained a total of 728 food items ranging from 12 to 300 prey items/stomach and six to 28 species/stomach. Predominant prey remains were cephalopod beaks. A total of 573 lower beaks were identified representing 17 families and 38 species (Table 2). Fish and crustaceans also contributed to the stomach contents. Five of the seven stomachs also contained fish remains representing 11 families, which comprised a total of 6.9% by number and 3.3% by mass. Two species of deep-water shrimp contributed 14.4% by number and 3.4% by mass to Hawaiian pygmy sperm whale diet.

Table 2. Pygmy sperm whale prey species identified from stomach contents among seven individuals stranded in Hawai'i.

	Minimum number of prey represented	Frequency by number	Occurrence	Estimated mean prey length[a] (mm)	Estimated mean prey weight (g)	Estimated contribution by mass (g)	Estimated % contribution by mass
Totals	728	100	7			71,495.5	100.0
Fish	50	6.9	5			2,327.1	3.3
Serrivomeridae							
Serrivomer beanii	15	2.1	2	715	24.0	360.0	0.5
Eurypharyngidae							
Eurypharynx pelicanoides	1	0.1	1	300	16.0	16.0	< 0.1
Opisthoproctidae							
Dolichopteryx sp.	1	0.1	1	81	14.6	14.6	< 0.1
Stomiidae	5	0.7	2			156.4	0.2
Astronesthes indicus	3	0.4	1	200	25.0	75.0	0.1
Chauliodus macouni	2	0.3	1	209	40.7	81.4	0.1
Synodontidae							
Bathysaurus sp. (juvenile)	1	0.1	1	38	0.4	0.4	< 0.1
Myctophidae	18	2.5	3			146.5	0.2
Lampadena urophaos	5	0.7	3	133	16.1	80.5	0.1
Lampadena sp. (juvenile)	1	0.1	1	12	1.2	1.3	< 0.1
Ceratoscopelus warmingi	1	0.1	1	76	24.1	24.1	< 0.1
Bolinichthys pyrsobolus	1	0.1	1	30	1.5	1.5	< 0.1
Nannobrachium sp.	2	0.3	2	121	16.7	33.4	< 0.1
Diaphus sp. *cf. D. perspicillatus*	5	0.7	2	39	1.0	5.0	< 0.1
Diaphus sp.	2	0.3	2	27	0.3	0.7	< 0.1
unidentified Myctophidae	1	0.1	1				< 0.1
Paralepididae	2	0.3	2			432.0	0.6
Magnisudis atlantica	1	0.1	1	300	377.0	377.0	0.5
Sudis atrox	1	0.1	1	100	55.0	55.0	0.1

Trachichthyidae							
Hoplostethus crassispinus	2	0.3	2	223	159.1	318.2	0.4
Diretmidae							
Diretmus argenteus	1	0.1	1	74	20.6	20.6	< 0.1
Gempylidae							
Gempylus serpens	1	0.1	1	368	349.0	349.0	0.5
Trichiuridae							
Lepidopus sp.	2	0.3	1	721	256.7	513.4	0.7
unidentified teleost	1	0.1	1				
Cephalopods	573	78.7	7			66,769.3	93.4
Enoploteuthidae	38	5.2	6			400.1	0.6
Abraliopsis sp.	12	1.6	2	54	5.6	67.2	0.1
Abralia trigonura	3	0.4	2	62	7.8	23.4	< 0.1
Enoploteuthis sp. *cf. E. reticulata*	4	0.5	1		23.0	92.0	< 0.1
Enoploteuthis sp.	2	0.3	1		17.0	34.0	< 0.1
Pyroteuthis addolux	10	1.4	4	68	9.6	96.0	< 0.1
Pterygioteuthis giardi	7	1.0	1	47	12.5	87.5	< 0.1
Ancistrocheiridae							
Ancistrocheirus lesueurii	1	0.1	1	407	2,073.1	2,073.1	2.9
Octopoteuthidae	3	0.4	2			295.8	0.4
Octopoteuthis nielseni	1	0.1	1	152	179.4	179.4	0.3
Octopoteuthis sp.	2	0.3	1	93	58.2	116.4	0.2
Onychoteuthidae	30	4.1	6			2,648.6	3.7
Onychoteuthis sp.	19	2.6	4	132	81.7	1,552.3	2.2
Moroteuthis sp. *cf. M. loennbergi*	7	1.0	2	216	116.5	815.5	1.1
Moroteuthis sp.	4	0.5	4	192	70.2	280.8	0.4
Chtenopterygidae							
Chtenopteryx sicula	2	0.3	1	91	66.7	133.4	0.2

(Continued)

Table 2 (Continued)

	Minimum number of prey represented	Frequency by number	Occurrence	Estimated mean prey length[a] (mm)	Estimated mean prey weight (g)	Estimated contribution by mass (g)	Estimated % contribution by mass
Gonatidae							
Gonatus californiensis	3	0.4	2	274	408.8	1,226.4	1.7
Histioteuthidae	177	24.3	7			27,305.5	38.2
Stigmatoteuthis hoylei	144	19.8	7	78	173.2	24,940.8	34.9
Histioteuthis sp. *cf. H. oceani*	20	2.7	3	68	91.0	1,820.0	2.5
Histioteuthis sp.	13	1.8	3	39	41.9	544.7	0.8
Pholidoteuthidae							
Pholidoteuthis boschmai	2	0.3	1	293	615.1	1,230.2	1.7
Brachioteuthidae							
Brachioteuthis riisei	2	0.3	1	75	7.8	15.6	0.0
Ommastrephidae	14	1.9	3			3,989.3	5.6
Sthenoteuthis oualaniensis	3	0.4	2	311	1,139.3	3,417.9	4.8
Nototodarus hawaiiensis	10	1.4	2	102	55.9	559.0	0.8
unid. Ommastrephidae (juvenile)	1	0.1	1	67	12.4	12.4	< 0.1
Cycloteuthidae	6	0.8	2			2,105.4	2.9
Cycloteuthis sirventi	2	0.3	1	369	843.9	1,687.8	2.4
Discoteuthis laciniosa	4	0.5	2	127	104.4	417.6	0.6
Chiroteuthidae							
Grimalditeuthis bonplandi	1	0.1	1	141	16.3	16.3	< 0.1
Mastigoteuthidae	47	6.5	5			5,274.9	7.4
Mastigoteuthis pyrodes	8	1.1	2	126	92.8	742.4	1.0
Mastigoteuthis famelica	20	2.7	4	137	113.1	2,262.0	3.2
Mastigoteuthis sp. A	19	2.6	5	141	119.5	2,270.5	3.2
Cranchiidae	218	29.9	7			14,172.4	19.8

Megalocranchia sp.	13	1.8	3	261	142.6	1,853.8	2.6
Taonius pavo	120	16.5	6	219	42.8	5,136.0	7.2
Taonius sp. *cf. T. borealis*	4	0.5	1	290	94.2	376.8	0.5
Galiteuthis phyllura	4	0.5	2	377	47.1	188.4	0.3
Galiteuthis sp. *cf. G. pacifica*	1	0.1	1	283	68.1	58.1	0.1
Liocranchia reinhardti	29	4.0	5	379	208.5	6,046.5	8.5
Leachia sp.	40	5.5	1	162	11.4	456.0	0.6
Helicocranchia sp.	1	0.1	2	148	17.8	17.8	< 0.1
unidentified Cranchiidae (juvenile)	6	0.8	1	86	6.5	39.0	0.1
Vampyroteuthidae							
Vampyroteuthis infernalis	21	2.9	3	75	276.3	5,802.3	8.1
Bolitaenidae							
Japatella diaphana	6	0.8	4		8.0	48.0	0.1
Ocythoidae							
Ocythoe tuberculata	2	0.3	2		16.0	32.0	< 0.1
Crustaceans	105	14.4	7			2,399.1	3.4
Pasiphaeidae							
Pasiphaea tarda	69	9.5	3	52	21.1	1,455.9	2.0
Lophogastridae							
Gnathophausia ingens	36	4.9	4	59	26.2	943.2	1.3

[a]Prey length measurements are standard length for fishes; dorsal mantle length for cephalopods; or carapace length for crustaceans.

The two most numerically abundant cephalopod families were Histioteuthidae (24.3%) and Cranchiidae (29.9%). These two families were found in all seven stomachs and collectively represented an estimated 58.0% of the total prey mass. The histioteuthid *Stigmatoteuthis hoylei* was found in all of the seven stomachs and represented 19.8% of the total abundance with estimated dorsal mantle lengths ranging from 38 mm to 149 mm (Fig. 1A). The total estimated weight contribution of *S. hoylei* was 34.9%. Representatives of the family Cranchiidae were dominated by *Taonius pavo*, found in six of the seven stomachs and constituting 16.5% of the total prey items. Estimated size for this prey species ranged from 98 mm to 326 mm and contributed 7.2% to the estimated total prey weight (Fig. 1B). Another cranchiid, *Liocranchia reinhardti* was found in five of the seven stomachs, represented 4.0% of the prey items, contributed 8.5% by weight and ranged in size from 281 mm to 462 mm (Fig. 1C). Remains of the vampyroteuthid, the vampire squid (*Vampyroteuthis infernalis)* were found in three of the seven stomachs examined and comprised 2.9% of the prey items with an estimated contribution by mass of 8.1%. Estimated mantle lengths for this species ranged from 43 mm to 118 mm (Fig. 1D).

Bean's sawtoothed eel (*Serrivomer beanii*) was the most common fish species ingested, representing 2.1% of the prey items identified and contributing 0.5% to the total prey weight. Members of the lanternfish family Myctophidae were not represented in high numbers, however, seven species of these fishes were identified (Table 2). The crustacean *Pasiphaea tarda* was found in three of the seven stomachs and contributed 9.5% to the total prey abundance and 2.0% by weight. Carapace length of this deepwater shrimp ranged between 40 mm and 65 mm (Fig. 2A). Another crustacean, *Gnathophausia ingens,* was found in four of the seven stomachs, contributed 4.9% to total prey abundance and 1.3% by weight. Carapace length ranged between 41 mm and 79 mm (Fig. 2B).

The primary prey of pygmy sperm whales in Hawaiian waters consists of a wide diversity of cephalopods. While it is often difficult to infer the foraging depth of predators from cephalopod prey remains (Roper and Young 1975), our results provide insight into the foraging depth and feeding preferences of pygmy sperm whales in Hawai'i as three of the 10 most abundant cephalopod prey species found in our stomachs (*Taonius pavo*, the vampire squid, and *Mastigoteuthis famelica*) do not undergo diel migrations.

Taonius pavo juveniles are found primarily between 600 m to 650 m and adults between 725 m and 970 m both day and night (Young 1975), the vampire squid is found between depths of 800 m and 1,200 m off O'ahu (Young 1978), and *Mastigoteuthis famelica* were taken off O'ahu between 675 m and 800 m during both day and night (Young 1978). The reported depths for these three important prey species suggest that in Hawai'i pygmy sperm whale dive behavior spans both the mesopelagic and bathypelagic zones and at least some foraging occurs between 600 m and 1,200 m.

Mesopelagic fish species were found to contribute to pygmy sperm whale diets in Hawai'i, comprising 6.9% of the total prey items, but only 3.3% by mass (Table 2). Although generally low in abundance, a wide diversity of fish species (19) from 11 different families was found among the seven stomachs. Bean's sawtoothed eel was

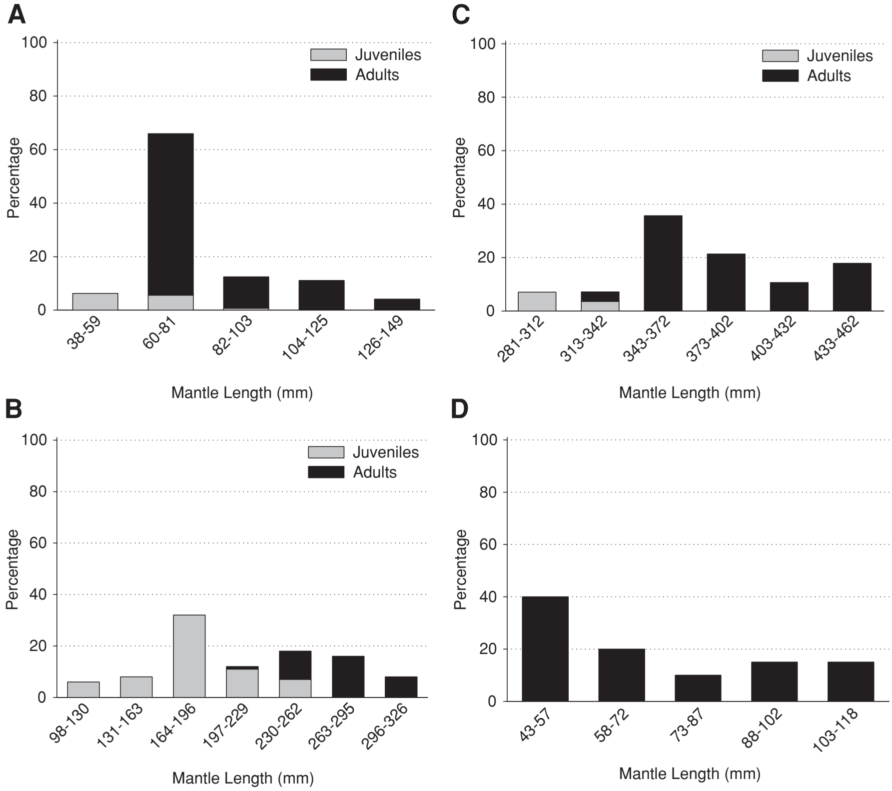

Figure 1. Frequency distribution of estimated mantle length and state of maturity of (A) *Stigmatoteuthis hoylei* (B) *Taonius pavo* (C) and *Liocranchia reinhardti.* Only estimated mantle length is provided for (D) *Vampryotheuthis infernalis.* Prey items were combined for the seven pygmy sperm whales.

the most abundant and contributed the highest proportion by mass of the deep-water fish species. Struhsaker (1973) collected specimens at depths of 640 m–869 m from the island of Hawai'i to Kaua'i and over 50 specimens of *Serrivomer sp*. were collected during day trawls between the depths of 735 m and 960 m off leeward O'ahu (Reid *et al.* 1991).

Two abundant species of mesopelagic crustaceans, *Pasiphaea tarda* and *Gnathophausia ingens*, found in this study have a wide distribution. *P. tarda* has been reported from both the Atlantic and Pacific oceans and *G. ingens* is common in tropical and subtropical regions worldwide (Hanamura and Evans 1994). *G. ingens* has been collected between 400 m and 1,200 m off O'ahu (Sanders and Childress 1990).

Cephalopods were the primary prey of pygmy sperm whales in Hawaiian waters making up 78.7% of prey abundance and 93.4% contribution by mass. Our stomach samples revealed an extreme diversity of cephalopod prey with 38 species from 17 different families. Especially given our sample size of only seven stomachs, this demonstrates a highly varied diet composition compared to almost all other regions

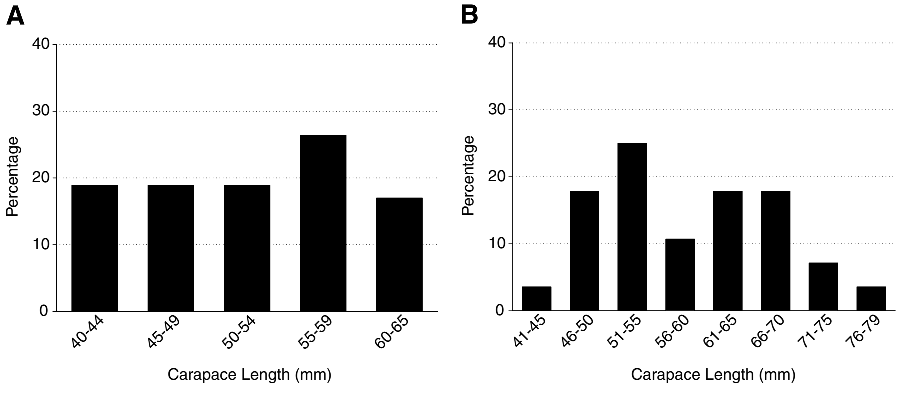

Figure 2. Frequency distribution of estimated size based on carapace length of (A) *Pasiphaea tarda* and (B) *Gnathophausia ingens* combined for the seven pygmy sperm whales.

where pygmy sperm whale stomach contents have been investigated. The only study in which more than 17 families of cephalopod prey were identified is that of Plön (2004), where 42 stomachs were examined in South Africa.

As already reported for the diet of this species cephalopods of the family Histioteuthidae are the most abundant prey ingested (Ross 1979, Klages *et al.* 1989, Sekiguchi *et al.* 1992, Plön 2004, Santos *et al.* 2006, Beatson 2007). Histioteuthids were also abundant in the stomachs from Hawai'i, where they were the second most abundant family and the greatest contributor by weight (Table 2). Taiwan is the only location where a study of pygmy sperm whale diet did not list histioteuthids as a dominant prey family. Wang *et al.* (2002) reported that this family contributed 8% to the diet by number and 10% by weight. The cephalopod family Cranchiidae has also been recognized as important to the diet of pygmy sperm whales from most geographic locations (Candela 1987, Wang *et al.* 2002, Beatson 2007). Cranchiids were the most abundant family (29.9%) of cephalopod prey represented in the Hawaiian pygmy sperm whale stomachs. However, they ranked second in terms of their contribution by mass (19.8%). Prey from this family have also been shown to be a major component of the diet of pygmy sperm whales in studies conducted off Taiwan (Wang *et al.* 2002), the southeastern United States (Candela 1987), in New Zealand (Beatson 2007), and as a dominant prey family in one of four studies conducted in South Africa (Ross 1979, Klages *et al.* 1989, Sekiguchi *et al.* 1992, Plön 2004).

The deep-water fish contribution to Hawaiian pygmy sperm whale diet was found to be similar to that of South Africa. Fish were present in 71% of the Hawaiian stomachs and in 75% of South African stomachs examined (Ross 1979). Mesopelagic fish contributed 6.9% to prey abundance in Hawai'i, whereas two studies from South Africa demonstrated a similar contribution of 9.1% and 10.3% (Klages *et al.* 1989, Plön 2004).

Crustaceans were found to be a significant component of the diet of pygmy sperm whales in Hawaiian waters when compared to reports from other regions.

Collectively, *Pasiphaea tarda* and *Gnathophausia ingens* accounted for almost 15% of the prey abundance and 3.4% by weight, a level not observed in other studies. No accounts of crustacean remains were reported in six stomachs from Taiwan (Wang *et al.* 2002). Beatson (2007) examined 27 stomachs from New Zealand waters where crustaceans were found to comprise <4% of the diet based on the abundance of prey. However, on a species level, the presence of *G. ingens* was similar between the Hawai'i (4.9% by prey abundance) and New Zealand stomachs (3.2% by prey abundance).

Most of what is known about pygmy sperm whales comes from waters off South Africa where a greater number of stomachs have been examined than for any other geographic location. Ross (1979) reported the presence of crustaceans in 75% of stomachs examined, represented by *Gnathophausia sp.* in more than half of the stomachs. In a more recent study in South Africa, crustaceans were found to contribute 2.5% to prey abundance and 1.1% for the species *G. ingens* (Plön 2004). In the northeastern Atlantic, crustacean prey appeared to play a minor role in the diet of the 14 whales examined (Santos *et al.* 2006), being found in only one individual where the stomach contents consisted entirely of 29 swimming crabs, *Polybius henslowii*.

Prior to this investigation of diet composition from seven stranded pygmy sperm whales in Hawai'i, little was known of the feeding ecology of *Kogia* in the central Pacific. Findings from this study suggest that pygmy sperm whales eat a wide diversity of prey and engage in foraging activity between 600 m and 1,200 m in Hawaiian waters, spanning both the mesopelagic and bathypelagic zones.

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