PLASTIC INGESTION BY BLACK-FOOTED ALBATROSS *PHOEBASTRIA NIGRIPES* FROM KURE ATOLL, HAWAI'I: LINKING CHICK DIET REMAINS AND PARENTAL AT-SEA FORAGING DISTRIBUTIONS

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ABSTRACT

HYRENBACH, K.D., HESTER, M.M., ADAMS, J., TITMUS, A.J., MICHAEL, P., WAHL, T., CHANG, C.-W., MARIE, A. & VANDERLIP, C. 2017. Plastic ingestion by Black-footed Albatross *Phoebastria nigripes* from Kure Atoll, Hawai'i: Linking chick diet remains and parental at-sea foraging distributions. *Marine Ornithology* 45: 225–236.

We quantified the incidence (percentage of samples with plastic) and loads (mass, volume) of four plastic types (fragments, line, sheet, foam) ingested by Black-footed Albatross *Phoebastria nigripes* chicks raised on Kure Atoll, the westernmost Hawaiian colony. All 25 samples contained plastic, mostly in the form of foam and line. On average (± SD), boluses and stomachs contained 28.2 ± 14.3 g and 40.3 ± 29.0 g of plastic, respectively. Plastic was the dominant indigestible material in the boluses and the stomach samples, accounting for 48.8%–89.7% of the bolus mass (mean 67.4 ± 12.1%, median 67.5%, $n = 20$), and for 18.2%–94.1% of the stomach content mass (mean 70.0 ± 30.3%, median 75.6%, $n = 5$). Although the ingested plastic fragments ranged widely in size, most (92% in boluses, 91% in stomachs) were mesoplastics (5–25 mm), followed by macroplastics (>25 mm; 7% in boluses, 6% in stomachs), and microplastics (1–5 mm; 1% in boluses, 4% in stomachs). Yet the two fragment size distributions were significantly different, with more small-sized items (3–8 mm) in stomachs and with more large-sized items (46–72 mm) in boluses. To investigate where albatross parents collect this material, we tracked seven provisioning adults during 14 foraging trips using satellite-linked transmitters. The tracked birds foraged west of Kure Atoll (180–150°E, 30–40°N) and spent most of their time over pelagic waters (>2 000 m deep; averaging 89 ± 9%), with substantial time over seamounts (averaging 11 ± 7%). Together, these results indicate that Black-footed Albatross chicks at Kure Atoll ingest plastics sourced by their parents foraging in waters of the western North Pacific. Provisioning adults forage within an area of surface convergence, downstream from the Kuroshio Current, and frequently visit seamounts northwest of the Hawaiian archipelago.

Key words: Black-footed Albatross, *Phoebastria nigripes*, boluses, Kure Atoll, marine debris, plastic ingestion, seamounts, tracking

INTRODUCTION

Black-footed Albatross *Phoebastria nigripes* (hereafter, BFAL) are far-ranging, surface-foraging seabirds with a diverse diet, including flyingfish (Exocoetidae), squid, crustaceans, neustonic invertebrates, carrion, and fishery discards (Harrison *et al*. 1983, Gould *et al*. 1997, Awkerman *et al*. 2008). The BFAL's tendency to ingest floating flyingfish egg masses and to aggregate at vessels are likely partly responsible for the high prevalence of plastic ingestion in this species, with published incidence rates from necropsies of by-caught adults ranging from 45.0% to 100.0% (Lavers & Bond 2015). Recent (2006–2013) necropsies of BFALs that died of natural causes from French Frigate Shoals (Northwestern Hawaiian Islands) documented high plastic ingestion rates (mean ± SD, unless otherwise specified) of 96.4 ± 3.6% and 58.8 ± 12.3%, in chicks ($n = 28$) and adults ($n = 17$), respectively. Moreover, despite their smaller body masses, chicks contained significantly larger plastic loads (6.8 ± 14.7 g, $n = 16$) than adults (0.6 ± 1.0 g, $n = 9$; Rapp *et al*. 2017). These results illustrate the transfer of ingested plastics from adults to chicks, and the accumulation of this material in the chicks' stomachs over time. During the breeding season (January–June), BFAL parents ingest floating plastic during their far-ranging foraging trips and deliver this material to their chicks at the nest. Before fledging at the end of the chick-rearing season (May–June), chicks regurgitate a bolus of indigestible material, containing a record of the prey items and the marine debris ingested during their 5–6 month development.

BFAL boluses collected in 1999 from Kure Atoll, located at the westernmost end of the Hawaiian Island Archipelago, contained natural food remains (squid beaks and eye lenses), natural non-food items (pumice stones and seeds), and plastic (Kinan & Cousins 2000). In fact, all analyzed boluses contained large loads of plastic, averaging 78 ± 38 g ($n = 17$). Ingested plastic items ranged from a few millimeters to 15 cm in length, and involved fragments, nurdles (preproduction microplastic pellets), bottle caps, tubing, pieces of shopping bags, rubber, sponges, toys, disposable cigarette lighters, toothbrushes, fishing floats, styrofoam, neoprene material, and monofilament line (Kinan & Cousins 2000). Altogether, these results documented the large loads of plastic ingestion by BFAL chicks from Kure Atoll.

Yet it is unknown whether adults collect this plastic from the western garbage patch, the continental shelf off Japan, the Subtropical

Convergence, or oceanic waters around their colony because foraging movements of BFALs from Kure Atoll have not been described (Titmus & Hyrenbach 2011, Howell *et al.* 2012). BFAL tracking studies during the incubation (late November to mid-January) and the chick-rearing (mid-January to late June) periods have documented long-distance foraging trips, from colonies in the central North Pacific Ocean to productive continental shelves in the Gulf of Alaska and the California Current (Fernández *et al.* 2001, Hyrenbach *et al.* 2002, Kappes *et al.* 2010). For instance, BFALs from Tern Island (23.87°N, 166.28°W), French Frigate Shoals (~15 degrees east of Kure), commuted eastward up to 9 000 km from their colony to the California Current during the chick-rearing period (Fernández *et al.* 2001). Because Kure Atoll is much closer to the western boundary (Oyashio Current) than to the eastern boundary (California Current) of the North Pacific, we hypothesized that BFAL foraging distributions from Kure would differ from those of birds tracked from colonies farther to the east.

Researchers' ability to study the plastics ingested during their long-distance foraging trips and delivered back to their chicks on the nesting colonies make far-ranging albatrosses ideal bio-indicators for monitoring pollutant distributions across the North Pacific Ocean (Pitman *et al.* 2004, Finkelstein *et al.* 2006, Young *et al.* 2009). Nevertheless, to effectively use marine birds as biological indicators of oceanic plastic pollution requires an inter-disciplinary analysis of the ingested debris in relation to the at-sea distribution (aggregations) and provenance (sources) of this material (e.g., Yamashita & Tanimura 2007, Titmus & Hyrenbach 2011, Ito *et al.* 2013). To this end, we concurrently collected data on the foraging trips of breeding adults equipped with satellite-linked transmitters and on the amounts and types of plastics provisioned to nestlings using 20 regurgitated boluses and five stomachs of naturally deceased chicks. Our underlying assumption was that the tracked parents foraged and sampled plastics similarly to the non-tracked parents whose chicks we analyzed. By integrating movement data from chick-provisioning adults with information on the plastic ingested by chicks from the same colony during the same study year, we provide a spatially explicit snapshot of plastic ingestion by BFAL breeding in the westernmost Hawaiian colony and foraging in the western North Pacific.

STUDY AREA AND METHODS

All field work took place at Kure Atoll (28°25′N, 178°20′W), a State of Hawai'i Wildlife Sanctuary located within the Papahānaumokuākea Marine National Monument (Northwestern Hawaiian Islands), where an estimated 2 020 BFAL pairs nested (Naughton *et al.* 2007).

Sample collection

Boluses: Two of us (CV and MH) collected 20 boluses during the end of the chick-rearing season of 2008. Between 26 June and 2 July, we collected every fresh intact BFAL bolus from two shoreline sub-colonies (Pier and Dump) where only BFALs nest. If a Laysan Albatross *Phoebastria immutabilis* chick wandered into the area, fresh wet boluses on Kure Atoll were distinguishable between species by the composition and color of the organic material. Because crabs disintegrated BFAL boluses overnight by consuming the organic material, we sampled recently regurgitated fresh boluses in the morning. Although we sampled the boluses from the same sub-colonies where the tracking took place, it was

not possible to ascertain whether boluses belonged to the chicks of the tagged parents because chicks abandon their nest sites and become mobile towards the end of the breeding season.

We processed the boluses at the Kure Atoll field station to remove the organic digestible detritus, by soaking the samples in detergent and water for 24 h, spraying the samples over a 1-mm sieve, dipping the remaining indigestible parts in 20% bleach to discourage mold, and air-drying them on screens protected from scavenging crabs for 48 h. We stored the clean boluses in insect-proof buckets and transported them to O'ahu for laboratory analysis.

Although BFAL chicks on Kure Atoll generally regurgitated boluses in a single compact pellet, we did not assume that a sample bolus represented all of the material consumed by an individual chick during the entire breeding season. Rather, we defined a bolus as a regurgitation event, which is representative of the material fed to the chick during the rearing period.

Stomachs: To place these bolus samples in a broader context, we collected dead BFAL chicks, found opportunistically throughout Kure Atoll between 19 June and 1 July. Two of us (CV and MH) collected five recently dead chicks from the same sub-colonies where the satellite tracking took place, including two from nests where one parent was tracked (Appendix 1, available on the website). We necropsied these specimens in the field, removed and preserved the contents of the proventriculus and the ventriculus in 5% formaldehyde, and shipped them to O'ahu for laboratory analysis.

Because BFAL chicks regurgitate indigestible material at the end of the breeding season, before their initial flights, we could not assume that the stomach contents of chicks close to fledging contained all the ingested plastic. Rather, we treated the stomach contents as a sub-sample of the indigestible material fed to the chick by its parents during the breeding season.

Sample processing

One of us (TW) sorted the stomach and bolus contents at Hawai'i Pacific University, following a standardized protocol. First, we rinsed the samples in fresh water over a 1-mm sieve and separated them by density. We excluded the sinking material (e.g., sand grains and coral fragments) from subsequent analyses and quantified all floating material. Following standardized protocols, we sorted the contents into 11 distinct categories within four broader classes: plastic, natural food, natural non-food, and other. We considered five plastic types defined by the flexibility and dimensionality of the items: sheets, line, foam, fragments, and nurdles (van Franeker *et al.* 2011, Donnelly-Greenan *et al.* 2014). Natural food included two categories: squid beaks and other food (e.g., eye lenses and fish bones). Natural non-food involved items of non-human origin (e.g., pumice, twigs, feathers, leaves, worms). The "other" class included two categories: sinking material and unclassified floating material that was not retained by the 1-mm mesh sieve.

Sample quantification and analysis

We followed a hierarchical approach to characterize the incidence and loads of the different plastic types. First, we scored each stomach / bolus sample for the presence or absence of plastic, regardless of its specific type, and calculated plastic incidence as the proportion of samples containing any of this material. Next, we compared the

relative make-up (by mass) of three broad classes within a given sample: all plastics, all natural food items, and all natural non-food items. Finally, we calculated the proportional abundance (by mass) of the distinct categories within these three classes.

The same people made all the size measurements of the stomach contents (KDH) and of the boluses (AJT). We air-dried all the sorted material for one week under a fume hood before quantifying the mass and volume. For each category, we quantified the mass ($\pm$ 0.1 g) using an electronic scale (Acculab model EC211), and quantified the displacement volume ($\pm$ 1 mL) using a cylindrical beaker with 300 mL capacity, 7.6 cm diameter, with a mesh-screen cap that kept the floating material below the fill line. After placing the dry material from each category inside the cylinder and attaching the screen cap, we filled the cylinder with water from another beaker. When the fill line was reached, the remaining water yielded the displacement volume. Certain items prone to capturing air bubbles (i.e., squid beaks and line) required agitation and stirring while submerged within the cylinder to yield accurate results, ascertained using the mass to volume relationships via linear regression (mass [g] = intercept + slope × volume [mL]). Overall, all three classes (plastics, natural food, natural non-food) showed highly linear fits, which explained 85%–97% of the variance, as evidenced by $r^2 > 0.85$ (Table 1).

Moreover, to assess the reproducibility of these measurements, we quantified the mass and volume of each bolus twice: by measuring clean boluses before they were sorted and by measuring their constituents separately, after sorting. The highly significant correlations of the bolus mass measurements (Pearson correlation, $r = 0.99$, $n = 20$, $P < 0.01$), and of the bolus volume measurements (Pearson correlation, $r = 0.96$, $n = 20$, $P < 0.01$) before and after sorting, indicated negligible amounts of material were lost during sample sorting.

Although we measured both the mass and the volume of all the samples, we focused subsequent analyses exclusively on the mass, because the overall mass and volume of the five stomach contents (Pearson correlation, $r = 0.960$, $n = 5$, $P < 0.01$) and of the 20

boluses (Pearson correlation, $r = 0.939$, $n = 20$, $P < 0.01$) were highly correlated. Thus, we would expect the volumetric and mass results to mirror each other.

Quantification of plastic fragments

We enumerated the fragments found within the stomach contents and the boluses, and quantified their size and color. One of us (CC) measured the longest dimension of every item using a handheld ruler (resolution 1 mm) and categorized each fragment's color using a palette (Mallory 2008, Donnelly-Greenan *et al*. 2014). We also enumerated nurdles because this categorization has been important in some regions (e.g., North Sea and US Great Lakes; van Franeker 2004, Zbyszewski *et al*. 2014) to track waste originating from industrial sources. Post-consumer items (i.e., upholstery, insulation, toys) also contain nurdles; thus, herein we do not define nurdles as strictly from industrial sources in the North Pacific. We also noted the presence of tar in each sample (van Franeker 2004).

Satellite tracking

From 27 May to 15 June 2008, three of us (MH, CV, AM) captured seven adult BFALs that were rearing chicks within two sub-colonies at Kure Atoll and outfitted them with satellite-linked platform terminal transmitters (PTTs; Sirtrack Kiwisat 202; 54 g, $50 \times 26 \times 11$ mm). We attached the PTTs to the dorsal body feathers between the wings with waterproof tape and small amounts of epoxy. The 54 g package amounted to 1.5%–1.9% of the average body mass of adult BFAL (Harrison *et al*. 1983), within the recommended weight (<3% body weight; Phillips *et al*. 2003). The PTTs were programmed to operate continuously, or to follow a duty cycle (10 hours on and 14 hours off) designed to prolong battery life. Although this study was designed to quantify post-breeding dispersal of breeding birds from the colonies, we opportunistically sampled provisioning trips during the last quarter of the chick-rearing period. The sex of the tagged birds was determined using genetic methods, with a sex ratio of five males and two females (Young *et al*. 2008).

Filtering and processing of location data

We obtained individual bird locations using the ARGOS system and archived the data via the Satellite Tracking and Analysis Tool (STAT; Coyne & Godley 2005). Two of us (JA and PM) performed the ARGOS data analysis. We used STAT to flag and manually correct "mirror" locations and to remove duplicate records (i.e., when ARGOS returned two records with the same time), and retained those records with location class (LC) quality of higher accuracy or the greater number of satellite messages. We filtered the remaining ARGOS data (LC-3 through LC-B) using a speed–distance–angle (SDA) filter (modified sdafilter function in the argosfilter package in R; Freitas *et al*. 2008) using a 70 km h^{-1} (or 19.4 m s^{-1}) speed threshold and the default settings for distances and angles. Our speed threshold is slightly greater than the mean $\pm$ 1 SE allometric prediction for flight speed over ground (15.9 m s^{-1}) among albatrosses flying with a 5 m s^{-1} tailwind (see Table 2 in Spear & Ainley 1997).

Identifying chick-provisioning trips

We determined adult track types (provisioning or post-breeding migration) based on chick status: those trips initiated with a live

TABLE 1
Results of the mass–volume regression analyses
for 20 boluses and five stomachs from 25 BFAL chicks
obtained in 2008 on Kure Atoll, Hawai'i

Class / Category	Intercept (± SD)	Slope (± SD)	r^2	*P* value
All plastic	0.728 ± 2.721	1.503 ± 0.093	0.918	< 0.001
Sheet	-0.240 ± 0.148	1.286 ± 0.112	0.852	< 0.001
Line	-0.340 ± 0.765	1.249 ± 0.059	0.951	< 0.001
Foam	1.928 ± 1.462	2.136 ± 0.153	0.895	< 0.001
Fragment	0.426 ± 0.339	1.039 ± 0.046	0.958	< 0.001
All natural food	-0.253 ± 0.806	1.146 ± 0.092	0.871	< 0.001
Squid beaks	-0.456 ± 0.525	1.183 ± 0.084	0.897	< 0.001
Other food	0.101 ± 0.282	1.094 ± 0.094	0.854	< 0.001
All natural non-food	0.087 ± 0.407	1.601 ± 0.062	0.967	< 0.001

chick on the nest were considered provisioning birds. Furthermore, we analyzed only complete loops; that is, when adults completed a provisioning trip by departing from and returning to the nest site. Because adults usually spend only a short time (<30 min) at the nest site after feeding their chicks during the late chick-rearing period, some tags did not transmit from the colony during the provisioning visit. Thus, to standardize the identification of colony visits, given the inherent positional errors of the satellite locations and the short colony visits, we defined departure (and arrival) locations as the first interpolated position outside (or inside) a 3.12-km buffer around the nesting colony that was followed (or preceded) by at least three positions of equal or greater distance moving away (or toward) the colony. This buffer was based on the circular error probability (CEP), which is related to the root mean square (RMS) of the kernel smoothing parameter (RMS = CEP /(sqrt[pi/2]) = CEP / 1.25 = 3.12). The CEP of a normal bivariate distribution, centered about the mean, is defined to include 50% of the sample. We selected a 3.12 buffer, comparable to the methods of Kappes *et al.* (2010). To estimate the time spent at sea, we used the SDA-filtered data and generated hourly locations for consecutive locations separated by <8 h, according to the linear method in Tremblay *et al.* (2006).

Habitat utilization

Using post-filtered data, we separately calculated 95% Brownian bridge utilization distributions (95% UDs; Horne *et al.* 2007; function *kernelbb*, in the *adehabitat* package in R; Calenge 2006) for individual foraging trips. To create 95% UDs, we specified the first (19.44 m) and second (2 490 m) smoothing parameters, which relate to nominal albatross speed and ARGOS location estimate inaccuracy, respectively. Because the Brownian bridge movement model assumes a circular normal error distribution, the second smoothing parameter (2 490 m) approximates the circular standard deviation estimated from the median circular error probability (defined here as the individually averaged, 68th percentile ARGOS location-class–specific errors from SDA-filtered data; see Costa *et al.* 2010). These parameters yielded appropriate estimates of space-use at the scale of the ARGOS data. To represent the utilization distributions graphically, we mapped the summed 95% UD raster layers in ArcMap 9.3.1 (ESRI, Redlands, CA) using the World Mollweide equal area projection and displayed them with a color gradient (blue to red = low to high use).

TABLE 2
Summary of plastic contents of BFAL chick boluses and stomachs from Kure Atoll, Hawai'i

Characteristic	Measurement	Boluses $n = 20$[a]	Stomachs $n = 5$[b]
Total mass (g)	Mean ± SD	36.18 ± 15.44	74.70 ± 8.70
	Median	47.9	80.5
Total volume (mL)	Mean ± SD	52.68 ± 23.70	49.24 ± 34.49
	Median	49.0	31.0
Correlation	Mass and volume	$r = 0.950$	$r = 0.960$
	P value	< 0.01	< 0.01
Plastic incidence	% samples	100.00	100.00
Plastic mass (g)	Mean ± SD	28.2 ± 14.3	40.3 ± 29.0
	Median	24.3	45.1
	Range	66.7–11.9	85.3–3.3
Plastic type	Mass, %, mean ± SD (median)		
Foam		29.1 ± 13.8 (25.3)	42.9 ± 22.5 (53.5)
Line		46.0 ± 12.8 (46.0)	34.1 ± 20.3 (30.1)
Fragment		20.6 ± 13.8 (25.3)	17.6 ± 18.5 (10.9)
Sheet		4.3 ± 1.4 (4.4)	5.4 ± 6.5 (2.5)
Fragment length (mm)	Sample size	1 040	160
	Mean ± SD	14.3 ± 7.7	12.5 ± 8.8
	Median	13	11
	Range	3–72	3–73
Fragment color	Dominant color, %	White, 53.6%	White, 75.0%
Nurdles	Samples, %	10.0	40.0
	Fragments, %	0.2	1.9
Tar	Incidence, % of samples	5.0	0.0

[a] Fresh wet boluses regurgitated by chicks collected from 26 June to 2 July 2008.
[b] Stomach contents obtained from necropsies of dead chick collected from 19 June to 1 July 2008.

Association of tracked albatross with bathymetry

In addition to mapping BFAL movements, we identified the bathymetric domains and habitats where the tracked birds spent their time at sea. We matched each of the interpolated locations with depth values from the ETOPO 1-minute global relief grid (http://www.ngdc.noaa.gov/mgg/global/global.html) within a 2.3 km radius, determined by the 95% confidence interval of the post-filtered ARGOS error (Witt *et al.* 2010). To avoid problems of statistical pseudo-replication, we performed these calculations proportionally for each individual total tracking time, and averaged the individual results.

We defined three bathymetric domains as follows: (1) continental shelf (0–200 m isobath surrounding an emergent land mass), (2) continental slope (200–2 000 m isobath surrounding an emergent land mass), and (3) pelagic waters (>2 000 m depth) (Briggs *et al.* 1987). We defined shallow seamounts as closed 200–400 m isobaths disconnected from an emergent landmass (Morato *et al.* 2008).

RESULTS

Boluses

The mass and volume of the indigestible contents of boluses were highly correlated, both before ($r = 0.95$, $n = 20$, $P < 0.01$) and after ($r = 0.94$, $n = 20$, $P < 0.01$) sorting. Overall, the unclassified floating material accounted for a negligible amount of the total mass, averaging $0.6 \pm 1.0\%$, and of the total volume, averaging $0.7 \pm 1.1\%$ of the boluses. Once we excluded the sinking material and the unclassified floating material, the sorted boluses averaged 36.2 ± 15.5 g and 52.7 ± 23.7 mL.

All 20 sorted boluses contained plastic (incidence 100%), with a mass averaging 28.2 ± 14.3 g and a volume of 43.7 ± 22.2 mL (Table 2). Every bolus also contained indigestible food remains (e.g., squid beaks and lenses), averaging 7.7 ± 3.1 g and 8.61 ± 3.9 mL, and other natural non-food items (e.g., twigs, feathers, pumice), averaging 4.5 ± 5.2 g and 7.3 ± 8.2 mL. Plastic was the dominant

bolus constituent, accounting for 48.8%–89.7% of the total bolus mass (mean $67.4 \pm 12.1\%$, median 67.5%, Fig. 1).

Whereas all four plastic categories were found in every bolus (Table 2), category masses varied significantly (ANOVA, $F_{3,76} = 51.086$, $P < 0.001$), with normally distributed residuals (one-sample Kolmogorov–Smirnov test, $n = 80$, maximum difference 0.118, $P = 0.221$). All six pairwise comparisons between any two plastic categories were significantly different (post-hoc Tukey tests, mean differences <9.952, $P < 0.029$). Line was the dominant plastic type, followed by foam and fragments. Sheets were rare, making up <5% of plastic mass (Fig. 2). Only one bolus contained traces of tar (Table 2).

The 20 sorted boluses contained a total of 1 040 plastic fragments, including several nurdles, with each bolus containing 15–119 fragments (average 52 ± 28 fragments, median 53). The fragments in the boluses ranged widely in size, 3–72 mm (average 14.3 ± 7.7 mm, median 13.0 mm), and the size distribution was positively skewed (mean $\pm$ SE $= 2.3 \pm 0.1$) and kurtosis (mean $\pm$ SE $= 9.0 \pm 0.2$), indicating that smaller fragments (<13.0 mm) were numerically dominant, despite infrequent large items. Whereas we documented fragments of nine different colors, the majority (53.6%) were white, followed by yellow (9.9%), black (9.8%), blue (7.3%), grey (5.2%), green (4.7%), brown (3.9%), orange (2.8%), red (1.7%), and transparent (i.e., colorless; 1%).

Stomach contents

The indigestible stomach contents of the five necropsied chicks varied substantially in volume and ranged 6.9–127.8 mL (mean 74.7 ± 50.8 mL, median 80.5 mL). Similarly, the mass of the stomach contents varied 3.3–85.3 g (mean 49.2 ± 34.5 g, median 47.9 g). While all necropsied chicks contained plastic, indigestible food remains, and natural non-food remains (incidence 100%), plastic was the dominant material by mass in every stomach (average $70.0 \pm 30.3\%$, median 75.6%)
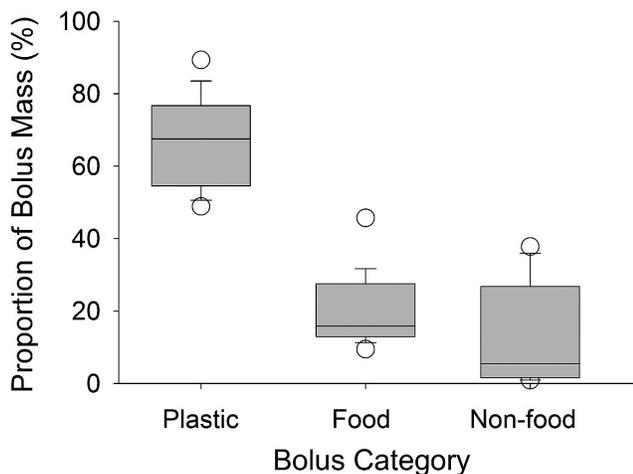

Fig. 1. Bolus composition of indigestible contents (by mass) from three broad classes. Box plots indicate the range (95%, 5%) of the distribution (circles) and the distribution (75%, 50%, 25%) (lines) of the mass of plastic, food, and non-food items in 20 sorted boluses.
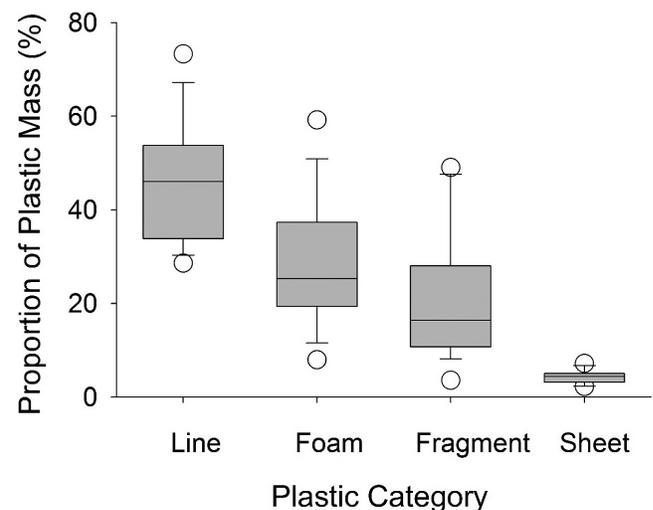

Fig. 2. Bolus plastic composition (by mass) from four plastic categories. Box plots indicate the range (95%, 5%) (circles) and the distribution (75%, 50%, 25%) (lines) of the proportional mass of four different plastic categories (line, foam, fragments, sheet) in 20 sorted boluses.

(Table 2), despite accounting for a wide range of the relative mass (18.2%–94.1%). Indigestible food (e.g., squid beaks and lenses and crustacean carapaces) was the next most numerous material by mass (range in relative mass 1.7%–33.3%, average 16.1 ± 11.8%, median 18.0%). Natural non-food items were less dominant by mass (range in relative mass 0.4%–6.3%, average 2.4 ± 2.4%, median 1.0%). The remaining stomach contents, involving unidentifiable and small (<1 mm in length) floating material (range in relative mass 0.7%–3.0%, mean 1.5 ± 0.9%, median 1.5%) and unclassified sinking material (range in relative mass 0.7%–42.4%, mean 10.0 ± 18.1%, median = 1.7%) were the least abundant by mass. Notably, one chick (of tracked parent PTT 84321) appeared to have regurgitated its bolus before dying and had a largely empty stomach containing three coral fragments, which accounted for 42.4% of the mass of the stomach contents (Appendix 1, available on the website).

Although all four plastic categories were found in every stomach (Table 2), their masses varied significantly (ANOVA, $F_{3,16} = 4.190$, $P = 0.023$), with normally distributed residuals (one-sample Kolmogorov–Smirnov test, $n = 20$, maximum difference 0.187, $P = 0.435$). Only one of the six pairwise comparisons between any two plastic categories (foam versus sheet) yielded significantly different masses (post-hoc Tukey test, mean difference 20.860, $P = 0.026$). On average, the plastic mass was made up of the following: foam (43%), line (34%), fragments (18%), and sheets (5%) (Table 2).

The five chick stomachs contained on average 32 ± 21 fragments (median 35, range 8–63). The 160 fragments recovered from the stomach contents ranged in size 3.0-73.0 mm (mean 12.5 ± 8.8 mm, median 11.0 mm), and the size frequency distribution was positively skewed (mean ± SE = 3.1 ± 0.2) and kurtotic (mean ± SE = 14.8 ± 0.4), indicating a large proportion of small fragments (<11.0 mm) and few large items. Although we documented 10 fragment colors (including transparent), the majority were white (75%), followed by green (7%), blue (6%), black (6%), yellow (3%), grey (1%), red (1%), transparent (colorless; 1.3%), beige (0.6%), and orange (0.5%). We found three nurdles, ingested by two different birds, and many post-consumer plastic items, but no traces of tar (Appendix 1, available on the website).

Stomach and bolus comparisons

The 20 boluses averaged 44.8 ± 16.4 g (median 42.0 g, range 23.7–77.6 g), with plastic contributing on average 62 ± 12% (median 64%, range 44%–87%). The five stomach samples averaged 49.2 ± 34.5 g (median 47.9 g, range 3.3–85.3 g), with plastic contributing 70 ± 30% (median 76%, range 18%–94%).

To investigate differences in the plastic loads from the boluses and stomachs, we related the plastic mass to the type (bolus versus stomach) and overall mass of the sample, using a general linear model (GLM). There was a significant relationship between plastic mass and sample mass, with larger samples containing more plastic ($F_{1,22} = 218.843$, $P < 0.001$); however, this relationship differed by sample type ($F_{1,22} = 8.654$, $P = 0.008$), indicating that, after accounting for the overall mass of their contents, stomachs contained disproportionally more plastic than boluses. The best-fit model accounted for 92% of the observed variance in the plastic mass of the samples, and the model residuals were normally distributed (one-sample Kolmogorov–Smirnov test; maximum difference 0.077, $n = 25$, $P = 0.996$) (Fig. 3).

Furthermore, we used simple linear regressions to examine the relationship between the plastic mass and the sample mass for the bolus ($n = 20$) and stomach ($n = 5$) samples, separately. Both regressions were significant, indicating that larger boluses ($F_{1,18} = 113.212$, $P < 0.001$) and larger stomach samples ($F_{1,3} = 75.220$, $P = 0.003$) contained more plastic, with both regressions having normally distributed residuals (Table 3). Although the slope coefficients of the two best-fit lines were not
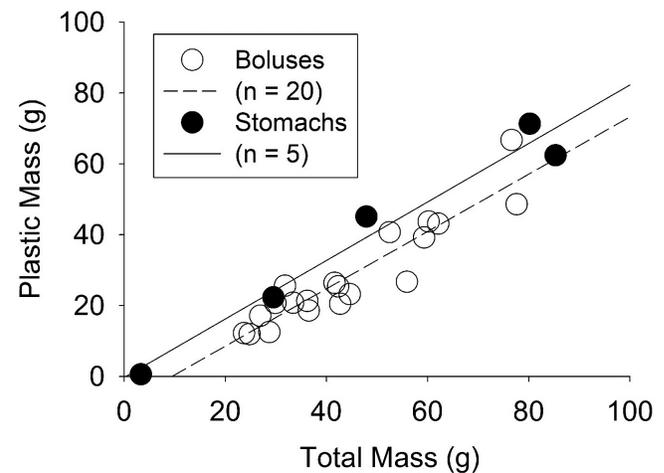

Fig. 3. Linear relationship between the plastic mass and the total mass of a sample, showing the data and the best-fit lines for stomachs and boluses separately.

TABLE 3
Linear regression analysis results relating the plastic mass to the sample mass
for BFAL chick boluses and stomach contents from Kure Atoll, Hawai'i

Simple linear regression[a]						Kolmogorov–Smirnov test[b]	
Sample (*n*)	Intercept ± SE	*t* (*P* value)	Coefficient ± SE	*t* (*P* value)	r^2	Maximum difference	*P* value
Boluses (20)	-7.642 ± 3.586	-2.131 (0.047)	0.809 ± 0.076	10.64 (<0.001)	0.863	0.112	0.939
Stomachs (5)	-0.301 ± 5.530	-0.054 (0.960)	0.825 ± 0.095	8.673 (0.003)	0.962	0.229	0.903

[a] Plastic mass = intercept + (coefficient × sample mass).
[b] The regression residuals were normally distributed, as determined by a one sample Kolmogorov–Smirnov test.

different, the intercepts differed. While the bolus line intercept (-7.6) was significantly less than 0, the stomach line intercept (-0.3) was not different from 0 (Table 3). Therefore, we used two different lines to graphically represent these linear relationships (Fig. 3).

Foam was the most abundant plastic type in the stomach samples, followed by line and fragments. Conversely, line was the most abundant plastic type in the boluses, followed by foam and fragments. Yet, despite the difference in the predominant plastic type, the relative composition of the plastic mass did not differ significantly when we compared the boluses and the stomachs (*G* test, $G = 4.819$, df = 3, $0.30 < P < 0.40$). Sheets were the least abundant plastic type in all samples (Table 2).

The size distributions of the fragments in the bolus and stomach samples were significantly different (two-sample Kolmogorov–Smirnov test, $n = 1200$, maximum difference = 0.184, $P < 0.001$). Notably, there were proportionally more small-sized (3–8 mm) fragments in the stomach contents and proportionally more large-sized (46–72 mm) fragments in the boluses (Fig. 4). Finally, white was the dominant color of the fragments retrieved from the boluses (53.6%) and the stomach samples (75.0%). As would be expected, the relative composition of the different color fragments in the bolus and the stomach samples was significantly correlated (Spearman rank correlation, $r_s = 0.703$, $n = 11$, $0.01 < P < 0.05$) (Fig. 5).

Satellite tracking

We tracked 14 complete foraging trips made by seven individual parents provisioning chicks between 27 May and 15 June 2008 (85.9 bird-tracking days). Individual tracking periods spanned on average $12.3 ± 8.6$ d (median = 9.0 d, range = 2.5–8.6 d, n = 7) (Table 4). The 14 individual foraging trips ranged in duration from 1.1 d (maximum distance 77 km) to 18.3 d (maximum distance 3201 km). The distributions of trip durations and foraging ranges were asymmetrical (skewness >1) and had large outliers (mean > median) caused by a single long-range (3201 km) and long-duration (18.3 d) foraging trip. Otherwise, the ranges and durations of the individual foraging trips were positively correlated (Pearson
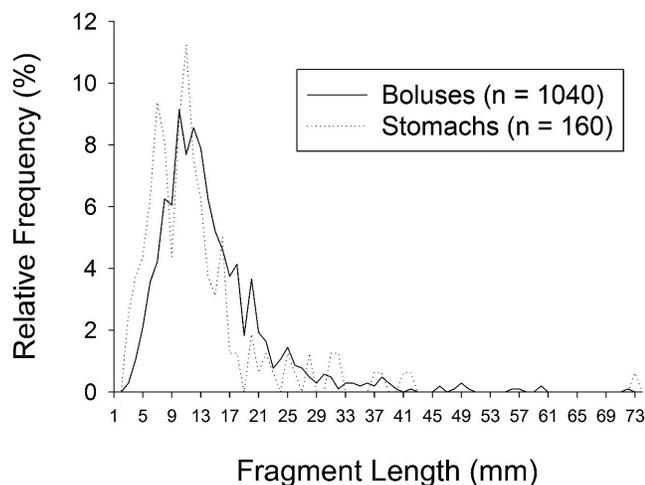
correlation, $r = 0.901$, $n = 14$, $P < 0.001$), indicating that birds venturing farther from the colony spent more time at sea.

Association of tracked albatross with bathymetric habitats

Breeding adult BFAL from Kure foraged in the western Pacific, throughout a large oceanic region spanning 180°–150°E and 30°–40°N. The overall utilization distribution (UD) of the satellite-tracked BFAL, calculated using the summed set of individual trip 95% UD kernels, was characterized by a disjunct pattern, with high-use areas (depicted by the red shading in Fig. 6) scattered in the vicinity of the colony and seamounts to the northwest of Kure Atoll. None of the tracked BFALs commuted to a continental shelf. Instead, the seven tracked BFAL spent the majority of their time (mean 89 ± 9%) at sea over deep (>2000 m) oceanic waters, and the rest of the time (mean 11 ± 7%) over shallow (200–400 m) waters within 2.3 km of seamount summits. Nevertheless, we observed individual variability, with most trips (85%, 12 of 14) and birds (85%, 6 of 7) approaching seamounts (Table 4).

DISCUSSION

Plastic ingestion is pervasive among BFAL chicks from Kure Atoll, with every sample (20 regurgitated boluses and five stomachs) containing plastic. Furthermore, we documented large loads of plastic (by mass), up to 66.7 g in boluses and 85.3 g in stomachs. Although larger samples (with greater mass) had more plastic, chick stomachs contained disproportionally more plastic than boluses, after accounting for the overall mass of these samples. Furthermore, stomach contents and boluses were characterized by different best-fit regression lines, with indistinguishable slopes but with different intercepts. Notably, whereas the stomach regression had an intercept no different than 0, the bolus regression had a significantly negative intercept (Fig. 3). We attribute this disparity to the chicks' inability to cast the plastics accumulated in the ventriculus, which were then retained after discarding the material from the proventriculus via the bolus. Because the stomach contents include material from both
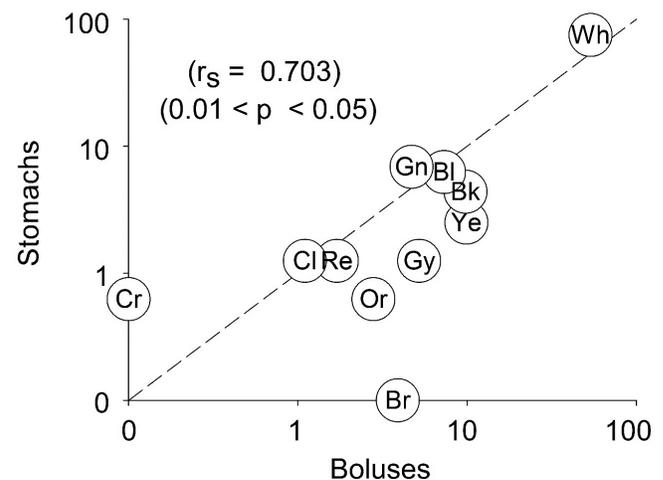

Fig. 4. Frequency distribution of ingested plastic fragment sizes, for stomachs and boluses separately. For each fragment, the length (largest dimension) was measured to the closest millimeter.

Fig. 5. The relative abundance of different color fragments in BFAL boluses ($n = 1040$) and stomachs ($n = 160$) were significantly correlated. Ten colors (Bl: Blue, Bk: Black, Br: Brown, Cr: Cream, Gn: Green, Gy: Grey, Or: Orange, Re: Red, Wh: White, Ye: Yellow) and colorless (Cl: Clear) fragments were considered.

chambers (proventriculus and ventriculus), even a chick that likely had already regurgitated a bolus and whose stomach only contained 3.3 g of material, contained 0.6 g of plastic (Appendix 1, available on the website). Conversely, because boluses include only the contents of the proventriculus, they do not reflect the entire plastic load in the birds' stomach.

Despite these potential biases, the composition of the two sample types was not different, when we compared the relative mass of the different plastic types. Whereas all samples (five stomachs and 20 boluses) contained all four plastic types, foam and line were the most abundant types in the stomachs and the boluses, respectively. Yet the overall relative composition of the ingested plastic in the boluses and the stomachs did not differ significantly. In contrast with observations from many other North Pacific seabird species (e.g., Robards *et al.* 1995, Rapp *et al.* 2017), fragments were not the predominant plastic type ingested by BFALs. Finally, sheets were the least abundant plastic type, on average accounting for 4% and 5% of the plastic mass in boluses and stomachs, respectively (Table 2).

The predominance of foam and line in BFAL boluses and stomach contents is consistent with previous qualitative analyses of albatross boluses from Kure, based on the presence / absence of specific recognizable items (Kinan & Cousins 2000). In 1999–2000, line was the most ubiquitous plastic type in BFAL boluses (100%

incidence), while large fragments were absent (*n* = 56). Conversely, 20% of Laysan Albatross boluses (*n* = 88) contained lighters or lightsticks, but were devoid of line (Kinan & Cousins 2000). Together, these results indicate that these two sympatrically breeding albatrosses ingest different types of plastic, likely due to distinct foraging distributions, different foraging behaviors at sea, and dietary differences (Harrison *et al.* 1983, Hyrenbach *et al.* 2002, Conners *et al.* 2014, Kappes *et al.* 2015). In particular, BFAL ingestion of line and foam is likely related to the presence of flyingfish eggs masses attached to floating plastic, as previously noted (Fry *et al.* 1987, Kinan & Cousins 2000).

Ingested plastic fragments spanned three size classes: microplastics (<5 mm), mesoplastics (5–25 mm), and macroplastics (>25 mm). Overall, the size distributions of the fragments in the boluses and the stomachs were significantly different, with more small-sized items (3–8 mm) in the stomachs and more large-sized items (46–72 mm) in the boluses. Yet, most fragments were mesoplastics (92% in boluses, 91% in stomachs), followed by macroplastics (7% in boluses, 6% in stomachs), and microplastics (1% in boluses, 4% in stomachs). The disproportional representation of microplastics in stomach samples is indicative of the influence of the ventriculus, where only small fragments enter and are mechanically broken down. Yet, because the ventriculus contents are not regurgitated in a bolus, they can only be analyzed via necropsy. Conversely, bolus samples only contain the plastics that

TABLE 4
Summary of satellite-derived locations of seven chick-provisioning adult BFALs breeding at Kure Atoll, Hawai'i, tagged 27–31 May 2008 and with transmissions ending by 15 June 2008

Bird and trip			Ranging behavior			% time at sea	
PTT ID	Sex	Program[a]	Trip	Duration (days)	Range (km)	Pelagic	Seamounts[b]
84320	♂	C	1	7.3	966.6	73.0	27.0
			2	1.8	178.9		
84321	♀	C	1	2.8	151.9	95.1	4.9
			2	1.7	265.2		
			3	1.5	307.7		
84318	♂	C	1	9.4	1 067.7	87.8	12.2
			2	3.0	435.2		
84316	♀	C	1	7.0	899.6	94.3	5.7
			2	1.1	252.3		
66529	♂	DC	1	18.3	3 200.7	93.0	7.0
			2	3.9	736.6		
66534	♂	DC	1	12.1	993.5	80.9	19.1
			2	13.5	1 207.5		
77030	♂	DC	1	2.5	77.1	100.0	0.0
Mean				6.13	767.18	89.17	10.83
± SD				± 5.38	± 801.68	± 9.37	± 9.37
Median				3.45	585.94	93.01	6.99
Min–Max				1.1–18.3	77.1–3200.7	73.0–100.0	0.0–27.0

a Transmitters operated following two programs: continuously (C) or on a 10 h ON:14 h OFF duty cycle (DC).
b In the vicinity (within 2.3 km) of a shallow seamount summit (200–400 m depth).

accumulate in the proventriculus and can be regurgitated by the chicks. Nevertheless, it is possible that not all the contents of the proventriculus are cast in the bolus, and that small food and plastic items remain in the stomach. These processes likely influence the incidence and loads of nurdles, which were much more common in stomachs (incidence 40 ± 25%, relative abundance 2% of all fragments) than in boluses (incidence 10 ± 7%, relative abundance 0.2% of all fragments).

Altogether, these results highlight the value of BFAL boluses and chick stomachs in sampling the wide-range of floating plastic types and sizes collected by their parents. Furthermore, satellite tracking of foraging parents revealed that BFAL parents collected this material from the western North Pacific (Fig. 6). Moreover, the tracked birds did not commute to shallow continental shelves, as previously documented for BFALs breeding at Tern Island, French Frigate Shoals (Hyrenbach *et al*. 2002). Rather, parents from Kure Atoll spent most of their time at sea over deep (>2 000 m) oceanic waters and frequently visited shallow seamounts (peaks 200–400 m beneath the sea surface) along the Emperor Chain (Table 4). Yet these results need to be interpreted with caution because the foraging trips analyzed only represent the last month of chick rearing, and parents likely delivered plastic to chicks throughout the five-month provisioning season. BFALs increase the duration of their foraging trips after the brooding period (first 18 d post-hatching), and this expansion likely influences their foraging

locations and how much plastic they encounter at-sea (Fernández *et al*. 2000, Hyrenbach *et al*. 2002).

The foraging area of the Kure BFALs (180°–150°E, 30°–40°N) lies within the latitudinal band influenced by the subtropical convergence, a region characterized by wind convergence, surface downwelling, and the aggregation of floating material, including marine debris (Niiler & Reynolds 1984, Pichel *et al*. 2007, Howell *et al*. 2012). In particular, the North Pacific Transition Zone Chlorophyll Front (TZCF) shifts northward between February (30°–35°N) and August (35°–40°N), as evidenced by the latitudinal migration of the 0.2 mg m^{-3} chlorophyll-*a* isopleth (Howell *et al*. 2012). Therefore, the BFAL foraging area crosses the surface convergence zone associated with the TZCF, from south to north, during the breeding season. In contrast, satellite-tracked BFALs from Tern Island foraged to the south of this feature, in warm (sea surface temperature >18 °C) and clear (chl <0.2 mg m^{-3} chlorophyll-*a*) waters south of the TZCF, shifting their foraging range northwards between the chick brooding (February–March) and the chick-rearing (April–May) periods (Hyrenbach *et al*. 2002). Thus, we expect that Kure BFALs also shift their foraging range northwards, following the latitudinal migration of the TZCF.

Furthermore, the BFAL foraging grounds are located downstream from the Kuroshio Extension, a dynamic oceanographic region where the Kuroshio flows east, after flowing northeast past Japan
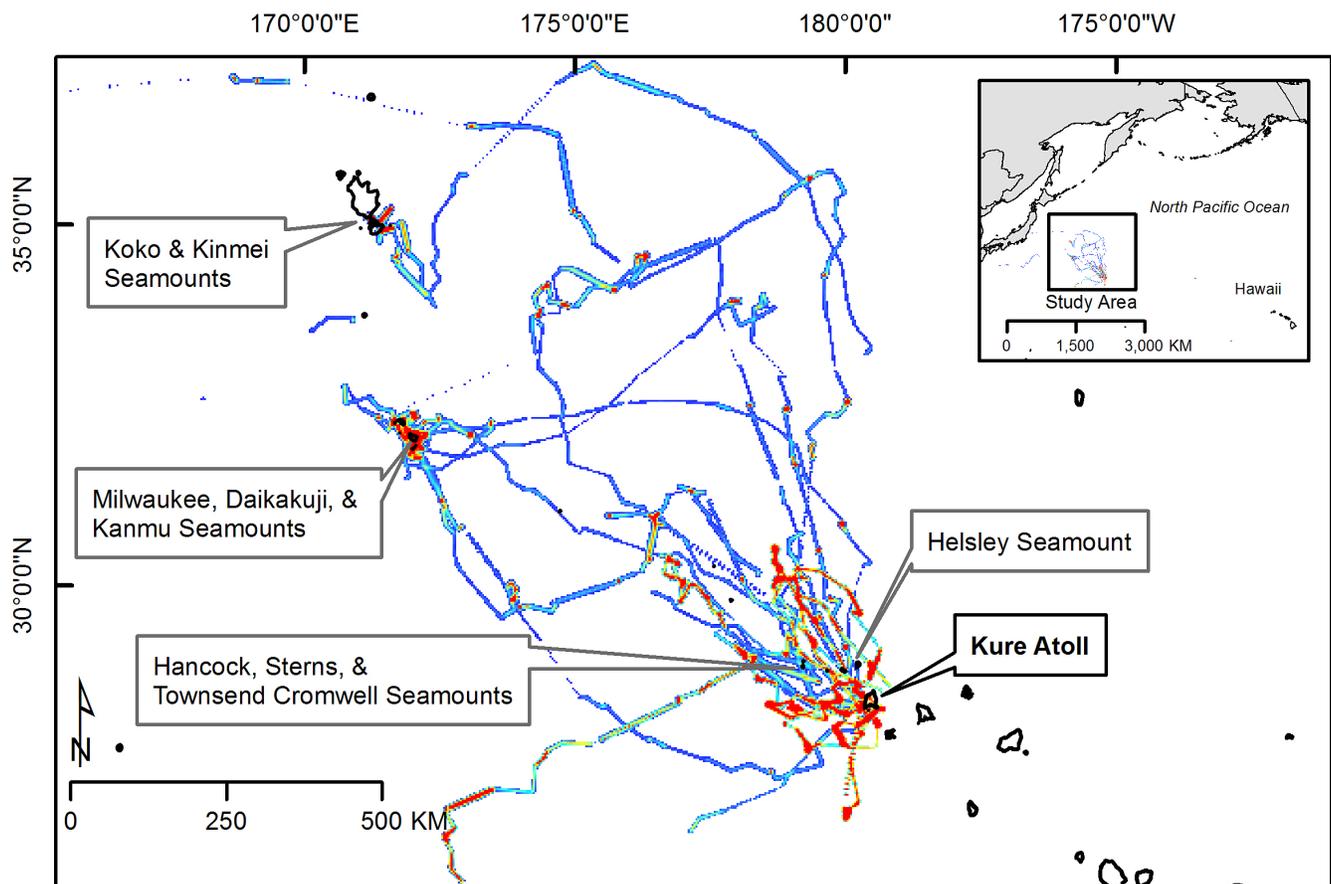

Fig. 6. Habitat utilization by seven BFALs tagged at Kure Atoll during the chick-rearing period (May–June 2008). The utilization function kernels are depicted by a color gradient spanning from blue (low use) to red (high use). Map shows shallow seamounts (200–400 m summit depth) north of the breeding colony.

and meeting the southward Oyashio at the Kuroshio-Oyashio Front. As the Kuroshio passes 170°E, it forms the weaker eastward North Pacific Current (NPC), delineating the northern end of the subtropical gyre (Pickard & Emery 1990). Thus, we would expect floating marine debris originating in Asia to be transported northeastward by the Kuroshio Current and to become concentrated within the BFAL foraging grounds.

The transport of marine debris by the Kuroshio Current was first hypothesized in the early 1980s (Day & Shaw 1987) and later verified through at-sea surveys in the late 1980s and early 2000s using neuston net tows (Day *et al*. 1990, Yamashita & Tanimura 2007). A large-scale survey of the North Pacific, conducted in 1985–1988, revealed the highest density of floating plastic (316 800 pieces km^{-2}) in Transitional Water east of Japan (35°59′N, 152°00′E) (Day *et al*. 1990). A study of the Kuroshio Current (31°–34°N, 135°–139°E) in 2000 and 2001 revealed an average of 174 000 plastic pieces km^{-1}. Plastics were especially abundant between 32°N and 33°N, suggesting that the Kuroshio Current plays a major role in transporting and distributing plastics across the North Pacific (Yamashita & Tanimura 2007).

Additionally, these at-sea surveys revealed that the proportion of styrofoam was greater in the Kuroshio Current area (21% of all plastic items; Yamashita & Tanimura, 2007) than in the North Pacific Central Gyre (1% of all plastic items; Moore *et al*. 2001). This difference was ascribed to the short residence time of styrofoam at the sea surface, due to its tendency to absorb water and sink (Yamashita & Tanimura 2007). Interestingly, foam was a major plastic type ingested by BFALs from Kure, making up 29% and 43% of the plastic mass in the boluses and the stomach contents, respectively. These results indicate that BFALs either targeted foam or were foraging in areas where this short-lived material accumulated or entered the marine environment.

In summary, BFAL chicks from Kure Atoll were exposed to high levels of ingested plastics, which their parents collected from the Northwest Pacific Ocean. Our satellite tracking revealed that provisioning birds were commuting to seamounts to the northwest of the Hawaiian Archipelago. BFALs are known to aggregate at shallow seamounts (e.g., Haney *et al*. 1995), and longline vessels are known to target seamounts (e.g., Gilman *et al*. 2012). More specifically, vessel-based surveys in the North Pacific Transition Zone, (30°–40°N, 180°–140°E) during the BFAL post-breeding period (July–October), revealed that BFALs were widely distributed across sea surface temperature regimes (17.7–27.4 °C.), but aggregated around the Emperor Seamount Chain. Moreover, BFALs were observed attending longline and pole-and-line vessels around these seamounts (Nishizawa *et al*. 2015). These findings suggest that the aggregation of BFAL and fishing vessels around productive seamounts may lead to higher localized fisheries interactions, including the potential ingestion of fishing related debris at these sites.

Because tracking based on satellite telemetry limited the accuracy of the estimated locations (a few to tens of kilometers obtained during this study, fine-scale tracking using archival geographic positioning system (GPS) tags (tens of meters) would better elucidate how much breeding BFALs make use of seamounts and other small-scale oceanographic features within their large foraging range. This information will allow for more accurate maps depicting areas where Kure BFALs collect floating marine debris at sea.

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