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SHORT RESEARCH AND DISCUSSION ARTICLE

Assessments of metallic contents in rare cephalopods from the Canary Islands: relationships with depth habitat and body size

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Abstract

This study investigated 20 elements in the muscle of 11 cephalopod species caught in the Canary Islands inhabiting from coastal to meso-bathypelagic habitats. Among them, trace element contents from large and elusive cephalopods such as *Architeuthis dux*, *Taningia danae*, *Lepidoteuthis grimaldii*, and *Haliphron atlanticus* were determined. Statistically significant differences in element concentration were found among class sizes and habitat. Large species that are inhabiting in deepest waters such as *Loligo forbesii*, *A. dux*, *T. danae*, *H. atlanticus*, and *L. grimaldii* showed a high load and variability in Fe and Al, while coastal species were characterized by a homogeneous element composition, being the Zn loads highest than other elements. Metal contents in large and elusive cephalopod species were dominated by Fe, Ni, Al, Zn, and Sr, with these species being able to carry important amounts of these elements to predators such as deep-diving odontocetes that reside around the Canary waters.

Keywords Giant squid · *Architeuthis* · *Taningia* · *Haliphron* · Deep sea · Trace element

Introduction

Cephalopods (squid, cuttlefish, octopuses, and nautilus) with approximately 845 species described to date (Hoving et al. 2014) are distributed in all marine habitats from coastal waters to very deep-sea environments (Delgado-Suárez et al. 2021; Jamieson and Vecchione 2020). Here, they play a major role in marine ecosystems as predators and simultaneously as prey for a wide variety of marine species such as seabirds, fish, and marine mammals (Boyle and Rodhouse 2005; Villanueva et al. 2017). Cephalopods also are a valuable fisheries resource for humans, increasing its catches during the last decades up to four million tons (FAO 2020). As a consequence, trace element and organic and inorganic pollutant concentrations in cephalopods have received increasing interest in the last decade due to the discovery of species being able to accumulate high levels of them in its tissues, being a significant vectors of contaminants to the consumers (reviewed in Penicaud et al. 2017). In this manner, cephalopods have been proposed as useful bioindicator species to follow the metallic pollutants in the marine environment over time due their short life cycles, typically from 1 to 2 years in most of the species, and their capacity to bioaccumulate metals and radionuclides in their tissues, specially Ag, Cd, Cu, Hg, Zn, and ^{210}Po (Miramand and Bentley 1992; Bustamante et al. 2002, 2006; Penicaud et al. 2017). However, most of the studies concerning metal bioaccumulation have focused on fishery interest species, primarily in shallow water species easy to sample such as cuttlefishes (e.g., *Sepia* spp.), octopuses (e.g. *Octopus* spp.), and squids (e.g. *Loligo* spp., *Alloteuthis* spp.) (Miramand and Bentley 1992; Seixas et al. 2005; Pierce et al. 2008). On the contrary, the metal and trace element contents on the vast majority of deep-sea species are practically

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unknown, despite its critically importance in marine food webs. In this way, data on metal contents are constrained to commercially targeted oceanic squids, such as ommastrephids (e.g. *Todarodes filippovae*, *Illex argentinus*, *Sthenoteuthis oualaniensis*, *Dosidicus gigas*) (Falandysz 1988; Gerpe et al. 2000; Pierce et al. 2008; Raimundo et al. 2014; Wu et al. 2017). In the same manner, data of only 12 mesopelagic squid species from the North Atlantic and Southeastern Pacific are limited to mercury contents (Bustamante et al. 2006; Pethybridge et al. 2010).

Among deep-sea species, the lack of data is particularly accentuated in uncommon species, which are rarely caught by fishing operations, for example, the charismatic giant squid (*Architeuthis dux*) which, as far as we are aware, the metal content has been described from only six specimens stranded in Spain (Bustamante et al. 2008). Other elusive cephalopod species are also considered large with more of 1 m of mantle length, such as the colossal squid (*Mesonychoteuthis hamiltoni*), deep sea hooked squid (*Taningia danae*), the scaled squid (*Lepidoteuthis grimaldii*), or the seven-arm giant octopus (*Haliphron atlanticus*) species that reach up to 4 m of total length, of which no information about its elemental composition is available.

The Canary Islands with 85 species registered have one of the largest cephalopod diversities of the European waters (Escánez et al. 2020). Also in this archipelago has been identified a hot spot of large cephalopods (*A. dux*, *T. danae*, and *H. atlanticus*), situated in the channel between Tenerife and La Gomera islands (Escánez and Perales-Raya 2017; Escánez 2019). This hot spot constitutes a valuable source of samples for the study of these elusive and very unknown species. Despite this, in the Canary Islands, few studies have been carried out regarding the concentration of metals and trace elements in cephalopods; only the studies by Lozano-Bilbao et al. (2018, 2020a) studied the concentration of metals and trace elements in two mesopelagic squids *Abraliopsis morisii* and *Pyroteuthis margaritifera* and the cephalopod class as a whole, without distinguishing among species.

The main aim of this work is to describe the metal and trace element concentrations of poorly studied deep-sea cephalopod species including three of the largest known species, such as *A. dux*, *T. danae*, and *H. atlanticus* among others, and investigate its relationships with depth habitats and body size, comparing them with coastal species.

Material and methods

Sample collection

A total of 67 specimens of eleven cephalopod species were selected to cover a wide range of vertical distributions, from epipelagic (<200 m) to bathypelagic (>2000 m) and from coastal to pelagic environments in the sub-tropical Eastern Atlantic. All samples were collected in the Canary Islands. Samples from species of commercial interest such as *Loligo forbesii* (*n*=3), *Loligo vulgaris* (*n*=14), *Octopus vulgaris* (*n*=16), and *Sepia officinalis* (n=20) were obtained from local fish markets, while no commercial interest and therefore difficult to sample species such as *L. grimaldii* (*n*=2), *H. atlanticus* (*n*=4), *A. dux* (*n*=3), *T. danae* (*n*=2), *Histioteuthis* spp. (*n*=1), *Thysanoteuthis rhombus* (*n*=1), *Chiroteuthis* spp. (*n*=1) were obtained from fresh individuals found floating and picked up by whale watching boats, between years 2012 and 2017. Among them, large and uncommon cephalopod species with 1 m or more of mantle length *A. dux*, *T. danae*, and the giant seven-arm octopus *H. atlanticus* were collected from fresh animal remains found floating in the southeastern coast of Tenerife. Only fresh individuals that show postmortem movements as suckers' suction, muscle contraction reflex, or chromatophore contractions at the time of pick-up were sampled (Fig. S3). The specimens were transported to the laboratories of Universidad de La Laguna, where they were examined and classified at species level using taxonomic keys for cephalopods of Guerra (1992) and Jereb and Roper (2010) (see Escánez 2019, for more information).

Sample preparation

Once captured, all samples were frozen at −20 °C, and the analytical sample consisted of a portion of arm muscular tissue of around 10–15 g. The samples were placed in porcelain crucibles and dried in an oven at a temperature of 70°C for 24 h. They were then incinerated in a muffle furnace for 48 h at 450°C ± 25°C, until obtaining white ashes. If after this time, the total mineralization of the samples had not been achieved (white or gray-white ash), a few drops of 65% HNO_3 were added to the samples under the gas hood, and they were later evaporated on a heating plate at 70–90°C. Once treated, they were re-incinerated in a muffle furnace at 450°C ± 25°C until white ashes were obtained.

Once the white ashes were obtained, they were filtered with a 1.5% HNO_3 solution, made up to 25 ml for the subsequent determination of the concentration of 20 trace elements (Al, B, Ba, Ca, Cd, Co, Cr, Cu, Fe, K, Na, Ni, Mg, Mn, Mo, Li, Pb, Sr, V, Zn) and one metalloid (B) by means of inductively coupled plasma optical emission spectrometry (ICP-OES), for each cephalopod sample. A quality control solution was used to assess the determinations accuracy and read every 10 samples. Moreover, certified reference materials (DORM-1 and DOLT 2) were used to ensure the precision and accuracy of the results. All data is presented as milligrams per kilogram, wet weight (mg/kg w.w.). Blanks and standard reference materials were run together with samples.

Statistical analyses

Multivariate analyses were used to examine the main patterns of the element composition in the sampled cephalopod muscle tissues. A principal coordinate analysis (PCoA) was performed to visualize the multivariate patterns of the element composition among species, on Euclidean distance matrix, after the standardization and square root transformation of all element concentration. Elemental composition was compared among previously defined groups among two factors: the "body size" factor, with two levels of variation (large *vs*. medium), and "depth habitat" factor, with four levels of variation (coastal-benthic, shelf-slope, mesopelagic, meso-bathypelagic cephalopods); both analyses were tested using the permutational analysis of variance (PERMANOVA) (Anderson 2017). In all analyses, 4999 interchangeable unit permutations and a posteriori comparison were used to determine the differences between the levels of significant factors (p value <0.01). For all multivariate analyses, used were PRIMER 7 and PERMANOVA + v.1.0.1 softwares (PRIMER-E, Plymouth, UK) (Clarke and Gorley 2015).

Results

Data relative to 20 elements concentration in eleven cephalopod species are presented in Table 1. The most abundant elements in all species analyzed were macroelements in order of concentration K > Na > Ca and Mg. Mean concentration of trace elements in muscle tissue was in the following order Fe > Ni > Al > Zn > Sr > Mn > Cu > B > Cr > Ba > Li > Co > Pb > Cd > V and Mo.

Trace element concentration measured in muscle tissue showed clear size and habitat differences when PCoA was applied (Fig. 1). According to the eigenvalues, the first and second principal components (PCs) explained 97.4% of the total variance. All the elements were consequently well represented by these two PCs. The first component (PC1), which accounted for 93.6% of variance, was mainly driven by increasing Fe (0.986) and Al (0.146), respectively. Along PC1 axis, large cephalopod species that are inhabiting in deepest waters (island slope and mesopelagic to bathypelagic) such as *L. forbesii*, *A. dux*, *T. danae*, *H. atlanticus*, and *L. grimaldii* showed a high load and variability in these trace elements. The second component (PC2), which accounted only 3.8% of the total variance, was negatively related with loads of Al (−0.912) and positively with Li (0.172) loads.

Coastal species represented by medium body size cephalopods (*O. vulgaris*, *S. officinalis*, and *L. vulgaris*) were grouped in PCoA; these species were characterized by a homogeneous element composition, being the Zn loads highest than other metals and metalloids, with values between 5.670 and 7.061 mg/kg in wet weight.

The permutational analysis of variance (PERMANOVA) was appointed to significant differences (p value <0.01) of elemental composition between the two body size classes (large and medium) (Table S1) and between the four depth habitats analyzed (coastal-benthic, island slope, mesopelagic, and bathypelagic) (Table S2). Significant differences in individual metal concentrations among factors are showed in Table 2. Most marked different metal contents among sizes and habitat classes are shown in Figs. S1 and 3.

Metalloid contents in giant squids (*A. dux*) were dominated by Fe, Ni, and Al concentrations with mean values of 84.716 ± 62.268, 27.301±21.135, and 13.962 ± 19.182 mg/kg wet weight, respectively (Table 1) (Fig. S2). In the same manner, the other four species considered as large or giant such as the deep sea hooked squid (*T. danae*), the scaled squid (*L. grimaldii*), diamondback squid (*T. rhombus*), and the seven-arm giant octopus (*H. atlanticus*) showed the same pattern in the dominant elements, with *T. danae* presenting the highest mean values of Fe 360.43 ± 157.87 mg/kg and Al of 31.630 ± 24.586 mg/kg, among them (Table 1). In contrast, the seven-arm giant octopus showed the lower values for all elements analyzed. The diamondback squid highlighted its Zn contents 30.819 ± 4.887 mg/kg, exceeding the values of all species analyzed. Sr values were higher in *A. dux* and *T. danae* ranging from 5.587 to 8.799 mg/kg, respectively (Table 1). However, these results should be interpreted carefully in some species, due to the low number of individuals analyzed (n>3).

Discussion and conclusion

Several cephalopod species of oceanic and deep-sea habitats such as the enigmatic giant squid (*A. dux*) or the colossal squid (*Mesonychoteuthis hamiltoni*) among others are considered rare and elusive, due its fast swimming and capacity to avoid from scientific sampling methods (Wormuth and Roper 1983; Pereira et al. 2017). Hence, very little data are available in the literature due to the limited opportunities to sampling entire well-conserved specimens. The find of several freshly dead specimens floating near shore of the Tenerife Island during the last years allowed the opportunistic sampling of valuable tissues to study different topics. Despite it is well known that the digestive gland of cephalopods is the main organ in which many trace elements accumulate particularly for metals, whichever of the exposure pathway (absorption, ingestion) (Raimundo et al. 2005; Penicaud et al. 2017), our analysis was limited to muscle tissue samples. This was due to the characteristic of the findings of these rare large species. In this manner, the three *A. dux* samples araised from incomplete specimens, where only remains of mantle, head, and arm crown were found. In the same way, samples of *T. danae* were obtained from two specimen remains, an arm crown and rest of mantle and head of another individual. These findings have

Table 1 Macro and trace element concentrations (mean ± SD, mg/kg wet weight) in the muscle tissue of different cephalopod species from the Canary Islands analyzed in this study and the number of samples of each species

	Large-sized species					**Medium-sized species**					
N°	*A. dux* (3)	*T. danae* (2)	*T. rhombus* (1)	*L. grimaldii* (2)	*H. atlanticus* (4)	*Chiroteuthis* spp. (1)	*Histioteuthis* spp. (1)	*L. forbesii* (3)	*L. vulgaris* (14)	*O. vulgaris* (16)	*S. officinalis* (20)
Ty	*c*	*d*	*c*	*d*	*d*	*c*	*c*	*b*	*b*	*a*	*a*
Li	1.014±0.623	0.752±0.8	1.868	0.004±0.001	0.074±0.108	0.11	0.501	1.950±1.335	0.82±0.212	0.609±0.372	0.403±0.246
B	2.061±1.34	3.806±1.567	2.059	1.542±0.757	0.553±0.285	1.458	1.679	7.722±2.346	0.047±0.03	0.154±0.122	0.332±0.605
Na	4506.2±5123.9	4255.2 ±514.22	1843.4	832.44 ±131.08	1133.1±828.22	2675.4	2713.1	5931.3 ±3658.8	1717.8 ±76.618	2210.1±221.07	2498.5±99.043
Mg	1678.1±1289.3	640.99 ±141.91	978.56	59.189±8.138	186.64±152.6	524.12	645.36	3097.1 ±1986.3	191.14 ±46.316	259.69±88.981	175.60±44.68
Al	13.962 ±19.182	31.630 ±24.586	17.379	23.725 ±13.236	8.627±4.271	20.636	8.271	47.114 ±24.586	1.893±0.552	1.953±0.786	3.042±1.48
K	3891.1±2774.1	2525.6 ±1011.5	8973.5	193.94 ±10.355	339.093 ±466.89	1800.4	4899.7	7585.8 ±6356.6	1228.9±123.2	1159.6±191.04	1158.9±178.44
Ca	2649.02 ±1364.6	2910.9 ±411.56	5562.7	626.07 ±579.22	203.981 ±212.48	1092.1	520.05	8093.1 ±3534.3	78.226±7.168	154.93±51.925	232.81±89.451
V	0.057±0.044	0.107±0.058	0.004	0.051±0.002	0.010±0.010	0.053	0.138	0.146±0.074	0.045±0.044	0.040±0.041	0.067±0.048
Cr	2.424±2.322	1.466±0.662	0.987	0.236±0.186	0.143±0.127	1.127	1.842	6.767±2.725	0.041±0.011	0.036±0.012	0.042±0.014
Mn	1.470±0.906	2.805±1.815	6.740	0.606±0.114	0.349±0.245	1.031	1.523	18.09±13.14	0.129±0.028	0.130±0.159	0.225±0.322
Fe	84.71±62.26	360.4±157.8	283.417	54.589 ±24.607	47.054±38.631	101.09	97.744	641.1±524.6	1.245±0.199	0.956±0.3	1.317±0.569
Co	0.105±0.079	0.196±0.123	0.430	0.025±0.012	0.025±0.022	0.046	0.125	1.519±1.622	0.455±0.0	0.035±0.112	0.007±0.0
Ni	27.30±21.13	81.92±68.75	95.014	3.780±1.586	7.883±6.975	14.167	14.286	117.8±28.4	0.027±0.015	0.016±0.006	0.021±0.009
Cu	1.439±0.861	1.519±0.864	3.439	2.409±0.653	0.616±0.443	1.386	1.134	7.658±3.987	1.388±0.296	1.157±0.422	1.1±0.446
Zn	7.276±4.887	5.858±0.499	30.819	3.751±0.501	0.875±0.442	7.127	6.454	29.57±19.94	7.061±0.650	6.711±1.370	5.670±0.575
Sr	5.587±7.799	8.779±12.141	2.030	0.002±0.001	0.575±0.631	1.096	0.313	28.24±28.67	0.904±0.101	1.568±0.260	3.028±1.437
Mo	0.047±0.057	0.038±0.016	0.057	0.039±0.010	0.005±0.001	0.029	0.063	0.127±0.104	0.006±0.002	0.010±0.003	0.008±0.002
Cd	0.073±0.065	0.056±0.008	0.085	0.099±0.028	0.007±0.005	0.114	0.031	0.140±0.114	0.049±0.037	0.034±0.022	0.175±0.106
Ba	0.996±0.398	1.5±1.397	3.179	1.127±0.659	0.515±0.48	0.675	1.203	3.487±2.403	0.315±0.095	0.334±0.117	0.488±0.154
Pb	0.530±0.621	0.327±0.182	0.207	0.400±0.284	0.110±0.065	0.285	0.138	0.726±0.576	0.030±0.014	0.028±0.005	0.033±0.006

a, coastal-benthic

b, shelf-slope

c, mesopelagic

d, meso-bathypelagic

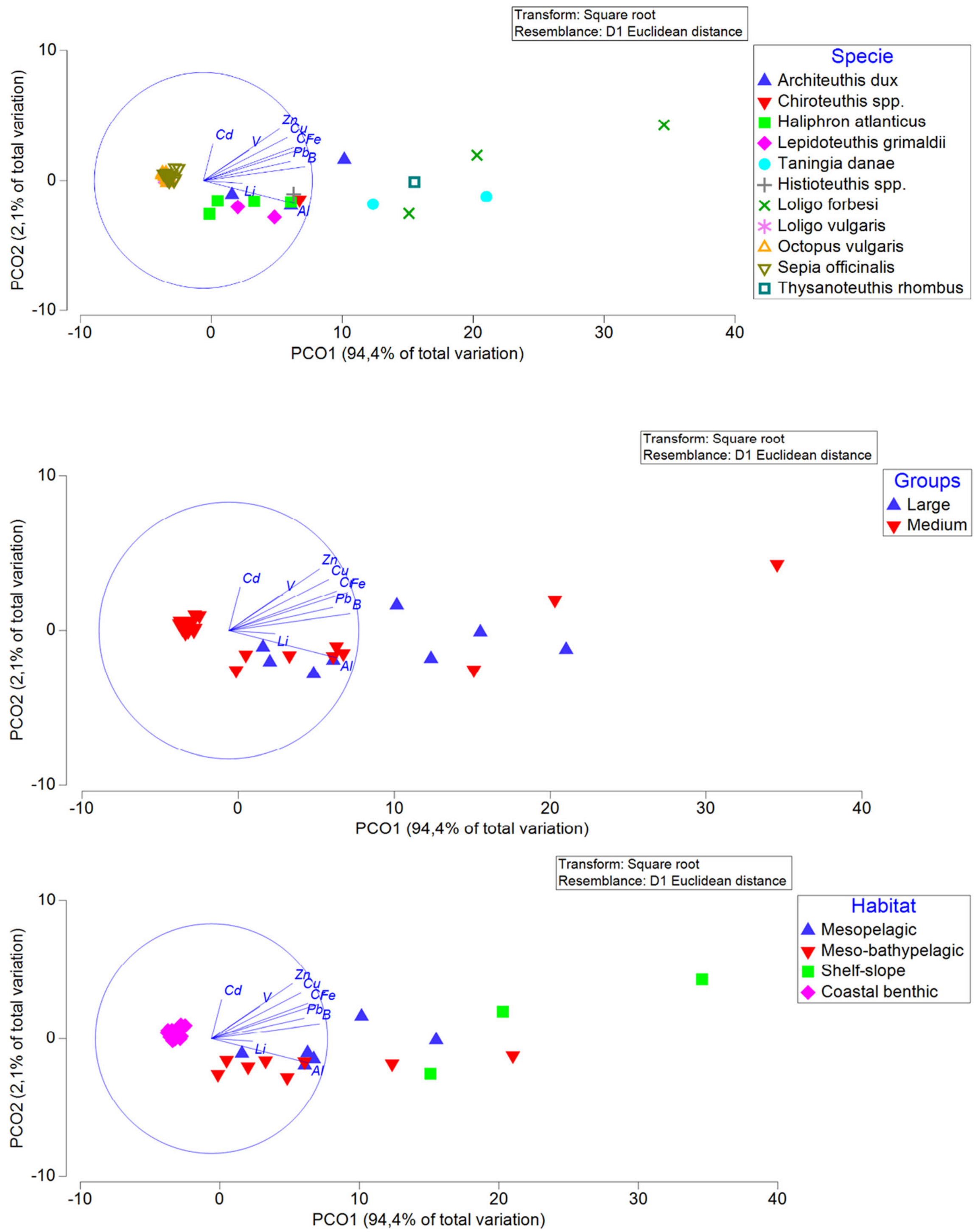

Fig. 1 Principal coordinate analysis (PCoA) showing the first two axes (97.4% of variability), based on Euclidean distances of square root transformed data of trace element contents in cephalopods with contrasting species, body sizes, and deep habitats

been related with the presence of a resident population of short-finned pilot whales (*Globicephala macrorhynchus*) in the SW of Tenerife that seems depredate upon these large squid species (Escánez and Raya 2017; Escánez 2019). Despite the inaccessibility to digestive gland samples, any data on trace elements in these elusive species are a unique and valuable information.

As far we can know, only six *A. dux* specimens from North Spain (Asturias) have been analyzed for its trace element contents (Bustamante et al. 2008). In this case, the mantle tissue in contrast to digestive gland showed lowest loads of trace elements, except to Hg and Cr follow by Fe, Cu, and Zn. In our specimens, Fe, Al, and Zn prevailed over other metals or metalloids in muscle tissue. Al contents in muscle were high in

Table 2 Results of pairwise tests examining the significant factor of "size" and "habitat" obtained in one-way ANOVAs analyzing the variation in the content of the main trace elements in the groups of cephalopods

Metal	Mesopelagic, meso-bathypelagic	Mesopelagic, shelf-slope	Mesopelagic, coastal benthic	Meso-bathypelagic, shelf-slope	Meso-bathypelagic, coastal benthic	Shelf-slope, coastal benthic	Large vs medium
Al	0.007*	0.322	0.026*	0.00001*	0.00001*	0.221	0.0001*
B	0.013*	0.011*	0.008*	0.001*	0.001*	0.557	0.0001*
Ba	0.09	0.261	0.347	0.004*	0.002*	0.842	0.002*
Ca	0.735	0.007*	0.001*	0.006*	0.001*	0.762	0.001*
Cd	0.464	0.347	0.028*	0.875	0.176	0.022*	0.215
Co	0.456	0.001*	0.043*	0.001*	0.005*	0.001*	0.475
Cr	0.243	0.001*	0.001*	0.041*	0.001*	0.002*	0.001*
Cu	0.067	0.001*	0.004*	0.52	0.021*	0.001*	0.508
Fe	0.019*	0.007*	0.001*	0.001*	0.001*	0.001*	0.001*
K	0.003*	0.713	0.005*	0.001*	0.001*	0.001*	0.001*
Li	0.377	0.011*	0.368	0.001*	0.012*	0.003*	0.003*
Mg	0.354	0.297	0.007*	0.929	0.056	0.052	0.025*
Mn	0.232	0.352	0.001*	0.038*	0.001*	0.023*	0.002*
Mo	0.45	0.041*	0.001*	0.008*	0.002*	0.894	0.001*
Na	0.033*	0.002*	0.001*	0.731	0.006*	0.001*	0.024*
Ni	0.419	0.009*	0.001*	0.003*	0.001*	0.001*	0.001*
Pb	0.093	0.011*	0.001*	0.001*	0.001*	0.004*	0.001*
Sr	0.738	0.181	0.002*	0.564	0.017*	0.005*	0.037*
V	0.197	0.358	0.323	0.638	0.696	0.832	0.968
Zn	0.871	0.001*	0.002*	0.006*	0.006*	0.005*	0.001*

*p value<0.05

A. dux with mean values of 13.962 ± 19.182 mg/kg; unfortunately, no data on Al contents were described in Bustamante et al. (2008), hindering its comparison. However, high concentration in mantle muscle of Al has been reported in several cephalopod species; in this manner, Nho et al. (2016) found concentration between 10.6 and 40.4 mg/kg. The Canary archipelago has a volcanic origin and can affect the concentration of elements such as Fe and Al. Lozano-Bilbao et al. (2018) found that the concentration of Al and Cd in squid that had survived an underwater eruption was much higher than the concentrations of the same species in areas where the eruption did not influence; that is why in areas of volcanic origin such as our study, the concentrations of Fe and Al compared to other studies are higher. These metals are sedimented on the bottom of the ocean, so the species that live in great depth will have higher concentrations (Kucuksezgin et al. 2006).

Zn values in muscle tissues of *A. dux* were 7.276 ± 4.887 mg/kg; this value was not elevated in comparison with the other species analyzed here. Cd also is accumulated primarily in the digestive gland of several mollusks including cephalopods, where it is efficiently absorbed and retained (Bustamante et al. 1998; Bustamante et al. 2002); however, minor amounts of this toxic metal are found in the muscle tissues of mantle and arms in cephalopods (Miramand and Bentley 1992). In the case of *A. dux* specimens analyzed here, Cd loads were low (0.073 ± 0.065 mg/kg) and were exceeded by coastal species such as *L. forbesii* (0.140 ± 0.114 mg/kg) and *S. officinalis* (0.175 ± 0.106 mg/kg); these species of coastal habitat have a higher concentration of Cd because this metal has a great anthropic character, and therefore the species linked to the coast have a higher concentration. High concentrations of Cd can be found in the polar regions regardless of present contamination, because Cd naturally concentrates in polar waters (Bustamante et al. 1998; Lischka et al. 2021; Lozano-Bilbao et al. 2020b; Vallius 2014).

Regarding to the other large/giant species, no data in the literature has been found, being the present work the first data on trace element loads for *T. danae*, *T. rhombus*, *L. grimaldii*, and *H. atlanticus*. Among them, *H. atlanticus* showed the lowest values of trace elements, which can be partly explained by its lifestyle that differs from the other cephalopods analyzed here. This gelatinous octopod uses both continental slope benthic habitats and open-ocean mesopelagic and bathypelagic habitats, feeding on gelatinous zooplankton such as cnidarians (e.g., *Atolla* sp., *Phacellophora* sp.), tunicates, and shrimps (O'Shea 2004; Hoving and Haddock 2017; Xavier et al. 2018).

The metabolism and bioaccumulation of trace elements are similar in the same groups of cephalopods but may vary between them due to ecological and physiological differences (Bustamante et al. 2008). However, these concentrations may vary with many factors, such as size, age, sex, and geographical origin. In this way, ages of *A. dux* from Canary Islands with 823 and 1418 mm of mantle length have been estimated between 13 and 22 months (Perales-Raya et al. 2020). For *T. danae* specimens of 1050 and 1320 mm of mantle length, González et al. (2003) estimated its age between 23 and 30 months. These long life cycles differ from medium-sized species with typically annual life cycles. In addition, large squid species occupy higher levels in the marine trophic chains, feeding on large fishes and squids varying between species the life cycle (González et al. 2003; Cherel and Hobson 2005; Deagle et al. 2005; Regueira et al. 2014). Hence, all these features may contribute on its major loads of trace elements.

Despite the low contents in Pb, Zn, and Cd, total body burden could be significant in large species because the muscle tissue represents the main proportion of the squid mass. These make that large cephalopod species could be carriers of an important metal content to its predators (Lischka et al. 2018). In this manner, Bustamante et al. (1998) correlate the high concentrations of Cd in cephalopods with high concentrations in many oceanic top predators in the North Atlantic area. In the case of large cephalopods from the Canary Islands, they may be carriers of large amounts of Fe, Al, Zn, and Sr, and by extension, the rich community of deep-diving odontocetes that are inhabiting in the region, such as short-finned pilot whales, sperm whales (*Physeter macrocephalus*), Blainville's beaked whales (*Mesoplodon densirostris*), and Cuvier's beaked whales (*Ziphius cavirostris*), would be exposed to high levels of these elements. Future research is needed to evaluate the biomagnification of toxic trace elements through the food chain, from deep sea squids to apex predators in the Canary Islands marine ecosystem. Moreover, the availability in the future of more whole individuals of large cephalopod species will allow analysis of the body distribution of trace elements.

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Results and discussion: AE, ELB, GL, DGW, AJG, CR, SP, AH
Conclusions: AE, ELB, AJG

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Declarations

Ethics approval All authors declare that the use of animals for this research complies with the requirements of the European legislation on the use of animals for experimentation. All the f samples collected were provided by the fishermen in the fish markets, so these organisms were not slaughtered by the authors of this manuscript; therefore we faithfully comply with the Code of Practice for Housing and Care of Animals Used in Scientific Procedures.

Consent to participate For the study, no animals had to be killed, so it is not applicable.

Consent for publication The authors consent the publication of this study.

Competing interests The authors declare no competing interests.

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