Interspecific and geographical variations of trace element concentrations in Pectinidae from European waters

Paco Bustamante, Pierre Miramand

► To cite this version:

Paco Bustamante, Pierre Miramand. Interspecific and geographical variations of trace element concentrations in Pectinidae from European waters. *Chemosphere*, 2004, 57 (10), pp.1355-1362. 10.1016/j.chemosphere.2004.08.077 . hal-00186644

HAL Id: hal-00186644

<https://hal.science/hal-00186644>

Submitted on 10 Nov 2007

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

1 Interspecific and geographical variations of trace
2 element concentrations in Pectinidae from European
3 waters

4
5 Paco Bustamante*, Pierre Miramand

6
7 Laboratoire de Biologie et Environnement Marins, FRE 2727 du CNRS, Université de La
8 Rochelle, 22, Avenue Michel Crépeau, F-17042 La Rochelle, France

9
10 *Corresponding author: Dr. Paco Bustamante
11 Laboratoire de Biologie et Environnement Marins,
12 FRE 2727 du CNRS
13 Université de La Rochelle
14 22, Avenue Michel Crépeau
15 F-17042 La Rochelle (France)
16
17 Tel.: (+33) 546 500 294
18 Fax: (+33) 546 500 294
19 e-mail: pbustama@univ-lr.fr

20
21 * Corresponding author. Tel.: +33 546 500 294; e-mail: pbustama@univ-lr.fr
22
23

ABSTRACT : Cd, Cu and Zn were analysed in the organs and tissues of the three scallop species from the Bay of Biscay, the variegated *Chlamys varia* L., the queen scallop *Aequipecten opercularis* L. and the common scallop *Pecten maximus* L. for interspecific comparisons. In *P. maximus* the greatest concentrations of Cd and Cu were found in the digestive gland, whereas the two other species showed similar levels of Cd between digestive gland and kidneys and higher renal Cu concentrations. However, the digestive gland of all Pectinidae species contained from 75 to 93 % and 52 to 74 % of the total body burdens of Cd and Cu, respectively. Whatever the species and the origin, kidneys displayed the highest Zn concentrations, which therefore contained from 53 to 97 % of the total body burden of this metal. Also using reported results, ratios between the concentrations in the digestive gland and that in the kidneys discriminated two groups of Pectinidae : 1) the *Pecten* group (*P. maximus*, *P. jacobus* and *Adamussium colbecki*) with a Cd ratio ≥ 4 , a Cu ratio ≥ 1 and a Zn ratio $> 20 \cdot 10^{-3}$ 2) the *Chlamys* group with a Cd ratio ≤ 1 , a Cu ratio ≤ 1 and a Zn ratio $\leq 6 \cdot 10^{-3}$. However, no differences in the detoxification processes in the digestive gland were found between groups in this study. 72 to 80 % of the total Cd was found to be soluble, probably bound to metalloproteins such as metallothioneins, while Cu and Zn were mainly found associated to the insoluble fraction of the digestive gland cells whatever the species. Queen scallops from the Faroe Islands were also considered to examine variations of the metal concentrations due to the geographical origin. In this northern area, queen scallops displayed Cd concentrations 2, 4 and 6 times higher in kidneys, muscle and digestive gland, respectively, compared to those from the Bay of Biscay. Consequently, the Cd concentrations in the whole soft parts of the queen scallops were more than 6 times higher in the Faroe Islands than in the

Bay of Biscay. In contrast to Cd, both Cu and Zn concentrations in the whole soft parts were 2 times lower in the Faroe Islands, suggesting lower bioavailability of these essential elements.

Key words : Heavy metals ; Bioaccumulation ; Body distribution ; Subcellular distribution ; Scallop

INTRODUCTION

Among seashells, numerous scallop species represent an important target to commercial fisheries. Many of them are actually cultured for direct commercial production or to provide juveniles for reintroduction programs in areas over-exploited. On the French Atlantic coasts and in the English Channel, scallops are relatively common, largely distributed and belong to three species: the variegated scallop *Chlamys varia* on rocky substrata, the queen scallop *Aequipecten opercularis* and the common scallop *Pecten maximus* on sandy bottoms. In France, these three species are captured during winter time and mobilises around one thousand fishing boats with various duration. The total of the catch varies greatly from one year to another, ranging from 6 000 tons to 25 000 tons per year (Quéro and Vayne, 1998). The three species are also captured for leisure activities, directly on the shore or by snorkelling. Scallops represent therefore an elevated economic values in fishing areas.

Bivalves are classically chosen for studies on trace element bioaccumulation (Bryan 1976). They are poorly capable to regulate ion concentrations in internal fluids and they are highly tolerant, metal ions being sequestered in excess of metabolic requirement (George, 1980). Therefore, bivalves often display high accumulation levels without apparent toxic effect. Among bivalves, scallops have shown a particular ability to concentrate high levels of pollutants such as trace elements, even in areas remote from direct anthropogenic contamination like the Antarctic (Mauri et al., 1990, Berkman and Nigro, 1992, Viarengo et al., 1993) or the Arctic Oceans (Stepnowski and Skwarzec, 2000). Therefore, scallops are generally considered as valuable bioindicators to monitor marine pollution (Bryan, 1973, Bustamante et al., 2002a). However, large interspecific variations seem to occur when compared trace element concentrations between different scallop species (Mauri et al., 1990, Viarengo et al., 1993). Such variations are not well characterized since only a single species is usually studied at the same place. Furthermore, geographical variations for a single scallop species have been rarely considered, different species from various latitudes being generally compared.

In this study, Cd, Cu and Zn, were analyzed in the organs and tissues of the three common scallop species living along the Atlantic coast of France. Those metals were determined by flame and graphite atomic absorption spectrophotometry in the variegated scallop *C. varia*, in the queen scallop *A. opercularis* and in the common scallop *P. maximus*, from the Charente-Maritime coasts, Bay of Biscay, France, in an attempt to determine the interspecific variations in the metal bioaccumulation. Furthermore, specimens of *A. opercularis*, a widely distributed species in the Northeastern Atlantic

from Morocco to the north of Norway, were collected off the Faroe Islands for comparison. Elemental concentrations, tissular and subcellular distributions, and interspecific and geographical differences were therefore examined.

MATERIAL AND METHODS

Sampling and sample preparation

In February 1996, 41 variegated scallops (*Chlamys varia*, Linné, 1758) were collected by hand in the infralittoral zone in the coast of Charente-Maritime (Bay of Biscay, France). After 48 hours depuration in clean sea water to eliminate faecal and pseudo-faecal material, scallops were pooled by size classes.

The queen and common scallops (*Aequipecten opercularis*, Linné, 1758 and *Pecten maximus*, Linné, 1758, respectively) have been opportunistically collected by bottom trawl along the Charente-Maritime coasts between February and May 1997. Individuals (n=11 for each species) were separated in individual plastic bags and frozen on board.

Queen scallops *A. opercularis* from the Faroe Islands have also been collected opportunistically by bottom trawl in August 1996 and frozen on board as described above (n=31).

For each scallop, adductor muscle, gonad, gills, kidneys, and digestive gland were separated from the rest of the soft part. The remaining tissues including the mantle, the foot, the intestine and the heart, were also analysed in order to calculate the whole trace element contained of the soft parts.

Subcellular fractionation

The partitioning of trace elements between soluble and insoluble subcellular fractions of the digestive gland was investigated in the three scallop species. Thus, 40 *Chlamys varia*, 23 *Pecten maximus*, and 10 *Aequipecten opercularis* were devoted to subcellular investigations. Four pools were made with the digestive glands removed from the soft parts of *C. varia* and *P. Maximus* freshly dissected. In the case of *A. opercularis*, digestive glands were removed on board to be deep frozen in liquid nitrogen and consequently were treated individually.

Both pooled and individual digestive glands were subsequently homogenised in a Dounce potter on ice with 10 volumes of a 0.02 M TRIS-HCl buffer in 0.25 M sucrose with 1 mM PMSF (phenylmethylsulfonylfluoride, as protease inhibitor) and 5 mM DTT (dithiothreitol, as reducing agent), at pH 8.6 (Bustamante et al. 2002b). The homogenates were centrifuged at 100 000 G for 1 h at 4°C in a Beckman LE-70 ultracentrifuge. Particle-free supernatants (cytosols) were separated from the pellet. Aliquots of the homogenates, cytosols and pellets were analysed for trace elements.

Trace element analyses

Tissue samples were dried for several days at 80°C to constant weight. Whenever possible, two aliquots of approx. 300 mg of each homogenised dry sample were digested with 4 ml of 65% ultrapure HNO₃ and 0.3 ml of ultrapure 70 % HClO₄ at 80°C until the solution was clear. Then acids were evaporated and residues were dissolved in 0.3N ultrapure nitric acid.

Cadmium, copper and zinc were determined by flame and graphite furnace atomic absorption spectrophotometry with a Varian spectrophotometer Vectra 250 Plus, with Deuterium background correction. Certified reference materials, dogfish liver DOLT-2 (NRCC) and dogfish muscle DORM-2 (NRCC), were treated and analysed in the same way as the samples. The results for standard reference materials were in good agreement with certified values (Table 1). The detection limits calculated for 0.3 g of dry tissue were ($\mu\text{g.g}^{-1}$ dwt): 0.005 (Cd), 0.5 (Cu), and 3 (Zn). Metal concentrations in tissues are given relatively to the dry weight ($\mu\text{g.g}^{-1}$ dry wt) while the distribution percentages were calculated for wet weight.

Data analyses

Comparison of metal concentrations between species were tested by one-way ANOVA (after log transformation of data when necessary) followed by the Tukey's multiple comparison test in the MINITAB 13.1 software. Changes in metal distribution among scallop tissues were tested for significance by the G procedure (adapted from the log-likelihood ratio test) for 2 x k contingency tables (Zar, 1996). The significance level for statistical analyses was always set at $\alpha = 0.05$.

RESULTS

Concentrations of Cd, Cu and Zn in the tissues of 3 scallop species from the Bay of Biscay and 1 species from the Faroe Islands are presented in Table 2. Concentrations in the whole soft parts were calculated using the concentrations determined in each

compartments. The body distribution of the trace elements of the scallops is presented in Table 3.

Cadmium

Among tissues, the digestive gland and the kidneys displayed the highest Cd concentrations for all species and in both areas. Interestingly, the Cd values measured in the different species were in the same range of concentrations in both organs with the exception of *P. maximus*. In this species, Cd concentrations in this species were around 4 times higher in the digestive gland than in the kidneys, i.e. $264 \pm 33 \mu\text{g.g}^{-1}$ dwt vs $70.6 \pm 12.6 \mu\text{g.g}^{-1}$ dwt, respectively (Table 2). The digestive gland contained most of the total body burden of Cd in all species, probably because of the significance in weight of this organ (Table 3). For Cd, a G-test did not indicate any significant ($p>0.05$) difference among metal body distribution between species and areas.

Among the scallops from the Bay of Biscay, *P. maximus* showed a strong accumulation of Cd in its tissues, especially in kidneys, muscle and digestive gland compared to the other species. Thus, these tissues displayed Cd concentrations 2, 4, and 6 times higher, respectively, than those measured in *C. varia* and in *A. opercularis* (Table 2). Consequently, the whole soft parts of *P. maximus* contained Cd concentrations more than 4 times higher than in the other two scallop species (Table 2).

When compared Faroe Islands and Bay of Biscay, Cd concentrations in *A. opercularis* were in the same range in the gonad, gills, and muscles for both geographic areas ($F=2.31$ $p=0.140$). Nevertheless, *A. opercularis* from the Faroe Islands displayed more than 4 times Cd concentrations in the digestive gland and 7 times higher in the kidneys than in

queen scallops from the Bay of Biscay (Table 2). Consequently, the digestive gland of *A. opercularis* from the Faroe Island contained even higher percentage to the total body burdens of Cd, i.e. 90% vs 75% (Table 3). Whichever the origin was, in the digestive gland of the three species more than 70 % of the total Cd was found in the particle free supernatants (Table 4).

Copper

Similarly to Cd, the digestive gland and the kidneys displayed the highest Cu concentrations for all species and in both areas. However, this metal displayed large variations according to the species and to the origin of the scallop.

In the scallops from the Bay of Biscay, Cu clearly showed the highest concentrations in kidneys except for *P. maximus*, whose concentrations were 3 times higher in the digestive gland (Table 2). Specifically in this species, the gonad exhibited relatively elevated Cu concentrations ($19.7 \pm 16.1 \mu\text{g.g}^{-1}$ dwt), which were in the same order of magnitude than in kidneys ($13.5 \pm 2.0 \mu\text{g.g}^{-1}$ dwt). Despite such variations in the Cu concentrations, the digestive gland of the different scallop species contained most of the whole body burden of Cu (Table 3). Therefore, tissue distribution of Cu did not varied significantly (G-test, $p>0.05$) between all the different scallop species.

Considering the whole soft parts, scallops from the Faroe Islands showed Cu concentrations 2 times lower than those from the Bay of Biscay (Table 2). Globally, the concentrations of Cu in the gonad, gills, muscle and remaining tissues were slightly lower in scallop from the Faroe Islands. This difference was even more important for the digestive gland and kidneys (Table 2). However, the digestive gland of the scallops from

the Faroe Islands also contained most of the whole body burden of Cu, i.e. $61 \pm 4\%$ (Table 3).

Whichever the origin was, in the digestive gland most of the Cu was found associated to the pellet of centrifugation, only 25 to 43% of the total Cu being soluble (Table 4).

Zinc

In scallops, kidneys displayed the highest Zn concentrations for all species and in both areas (Table 2). These concentrations were several thousand of μg (i.e. exceeding 30,000 $\mu\text{g Zn.g}^{-1}$ in *A. opercularis* from the Bay of Biscay).

In the Bay of Biscay, the concentrations of Zn were 7 times higher in *A. opercularis* than in *P. maximus* but not significantly different from *C. varia*. In contrast, *P. maximus* exhibited Zn concentrations in the digestive gland which were 4 times higher than in *C. varia* and *A. opercularis*. Despite such differences in the tissue concentrations, kidneys of the different scallop species contained from 72 to 91 % of the whole body burden of Zn (Table 3). Moreover, a G-test did not indicate any significant ($p > 0.05$) difference among metal body distribution between these species.

In the Faroe Islands, *A. opercularis* exhibited lower Zn concentrations in all their tissues than in the Bay of Biscay (Table 2). This was particularly obvious for the kidneys which concentrations were 7 times lower compared to *A. opercularis* from the Bay of Biscay while such a difference was only a 2 or 3 fold for the other tissues. Consequently, *A. opercularis* from the Faroe Islands only exhibited 53 % of the whole body burden of Zn in their kidneys (Table 3).

Despite interspecific and geographical differences in the concentrations, the proportion of soluble Zn within the digestive gland cells poorly varied, i.e. from 38 to 50% in the different scallop species (Table 4).

DISCUSSION

Interspecific comparisons

Among bivalves, scallops accumulate trace elements at often high concentrations, depending on the metal and the tissue. The kidney and the digestive gland have a major importance in the bioaccumulation of Cd, Cu and Zn in Pectinidae. These organs exhibited high metal concentrations and contained most of the total body burden of these trace elements (Tables 1 & 2). The other tissues seems to have a minor importance in the storage of Cd, Cu and Zn although they might have a major role in uptake and transfer of trace elements. However, one of the goals of the present study was to provide background levels against which to perform interspecific comparison within the Pectinidae family. Results from this study allowed to discriminate two groups of scallops : on the one hand *Chlamys varia* and *Aequipecten opercularis* (formerly called *Chlamys opercularis*) and on the other side *Pecten maximus*. These two groups are revealed by the ratio between the concentrations of trace elements in the digestive gland and that in kidneys : 1) the *Pecten* group (*P. maximus*) with a Cd ratio ≥ 4 , a Cu ratio ≥ 1 and a Zn ratio $> 20 \cdot 10^{-3}$ and, 2) the *Chlamys* group (*C. varia* and *A. opercularis*) with a Cd ratio ≤ 1 , a Cu ratio ≤ 1 and a Zn ratio $\leq 6 \cdot 10^{-3}$. Even though metal concentrations have been studied in various scallop species, little data from the current literature allowed to make such calculations, mainly

because of the lack of values in kidneys. Table 5 reports Cd, Cu and Zn concentrations in the digestive gland and kidneys of different scallops species from various locations. Even though the variation of the concentrations of Cd, Cu and Zn in both tissues is very large, the ratio of the concentrations between the digestive gland and the kidneys were consistent with our results. Thus, *P. maximus* from the English Channel and *P. jacobus* from the Mediterranean showed ratios around 4 for Cd, $> 20 \cdot 10^{-3}$ for Zn, and respectively 3 and 1 for Cu. These calculated ratio were even higher for the Antarctic scallop *Adamussium colbecki* (i.e. 12 for Cd, 3 for Cu and $377 \cdot 10^{-3}$ for Zn) suggesting a metabolism of metals close to the one of the *Pecten* group. In contrast, taking into account the moisture of the tissues, a ratio around 1 for Cd suggests that *Placopecten magellanicus* is closer to the *Chlamys* group.

The bioaccumulation of trace elements in the digestive gland and kidneys might be related to the detoxification processes of metals. The reasons of high concentrations of trace elements in the tissues of Pectinidae are typically attributed to the binding to cytosolic proteins in the digestive gland and to precipitation on granules in kidneys (George et al., 1980, Ballan-Dufrançais et al., 1985, Stone et al., 1986, Fowler and Gould, 1988, Mauri et al., 1990, Viarengo et al., 1993). Globally, information on the subcellular distribution of metals in Pectinidae is scarce. The cytosolic proteins of the digestive gland cells of the three scallop species seem to have a minor importance in the binding of Cu and Zn. These two metals were generally found in large proportions into the insoluble fraction, which represent the metals trapped within the organites, associated to membranes or to granules. This might be due to their numerous biochemical functions that imply they are involved in the structure of several proteins. In contrast to Cu and Zn,

from 72 to 80 % of the total Cd was found in the cytosolic fraction of the digestive gland cells of the three scallop species. With the exception of the Antarctic scallop *Adamussium colbecki*, for which only 30 % of the total Cd was soluble (Viarengo et al., 1993), 60 to 99 % of the Cd was found in the soluble fraction of the digestive gland of Pectinidae from field or after experimental exposure to this metal (Evtushenko et al., 1986, 1990, Stone et al., 1986, Lukyanova and Evtushenko, 1989). This strongly suggests the occurrence of mechanisms of accumulation and detoxification of Cd involving proteins such as metallothioneins (Evtushenko et al., 1986, 1990, Stone et al., 1986, Viarengo et al., 1993, Bustamante, 1998). Similar detoxification strategies for Cd, Cu and Zn in the digestive gland of the *Chlamys* and the *Pecten* groups suggest that differences between the two groups are related to detoxification and excretion processes in the kidneys. Indeed, metal-rich granules from the kidney of *P. maximus* are considered as excretory concretions which can be eliminated in urine (George et al., 1980). Higher excretion rates in the *Pecten* group compared to the *Chlamys* one might lead to overall lower Cd, Cu and Zn concentrations in this organ. However, further studies in the *Chlamys* group are needed to support this hypothesis.

Geographical comparisons

Scallops of different species within the same area and scallops of the same species from different latitudes showed elevated variations in their ability to concentrate trace elements (Table 5). Such variations are due to interspecific diversity but also to geographic conditions. Accumulation of high metal concentrations, particularly Cd, even in unpolluted areas might be related to different bioavailability of the elements, to different

297 feeding habits, as well as to physiological features. As regards to the concentrations
298 found in the gills, seawater appears to be an important source of metals for scallops.
299 However, trace element concentrations in the soft tissues and primarily in the digestive
300 gland might substantially be influenced by the metal content of their food. Indeed,
301 scallops are filter feeders using different types of food such as phytoplankton, detritus
302 and resuspended matter which are major components of the variation in food quality in
303 the field through variation in their carbon and nitrogen contents (Grant and Cranford,
304 1991, Alber and Valiela, 1996). It would therefore be of particular interest to characterise
305 the food composition and its metal concentrations of the different scallops.

306 As reported for other marine invertebrates (Cubadda et al., 2001), the use of scallops as
307 biomonitors on large geographical scales, i.e. between 44 to 46° N for the Bay of Biscay
308 and 61 to 63 ° N for the Faroe Islands, might be envisaged with caution. In this
309 investigation, the higher Cd concentrations found in *A. opercularis* from the Faroe
310 Islands compared to those from the Bay of Biscay highlighted that the contents of one or
311 more metals in marine organisms can be increased by specific geochemical or
312 hydrodynamic conditions. In the Faroe Islands, enrichment of metals due to industrial
313 contamination does not exist. Consequently, the high Cd concentrations in the tissues of
314 *A. opercularis* might be considered as natural in this sub-polar area. Reported Cd
315 enrichment throughout the Arctic remained globally unclear. Several authors have
316 proposed that a phenomenon of Cd abnormality occurs in polar and subpolar areas,
317 leading to very high Cd concentrations in marine biota (Petri and Zauke, 1993, Bargagli
318 et al., 1996, Bustamante et al., 1998a, Zauke et al., 1999). Several results suggest that
319 such an abnormality has also to be considered in the Faroe Islands (Caurant et al., 1994,

320 Bustamante et al., 1998b, 2004). Indeed, similarly to polar regions, soluble trace element
321 concentrations in seawater appear to be relatively low around this area (Mart and
322 Nürnberg, 1984). Despite that, very high Cd concentrations have also been found in
323 several cephalopod species caught around the archipelago, i.e. from $2.1 \mu\text{g.g}^{-1}$ dwt in the
324 Loliginid squid *Loligo forbesi*, to $46.8 \mu\text{g.g}^{-1}$ dwt in the octopus *Eledone cirrhosa*
325 (Bustamante, 1998, Bustamante et al., 1998b). Moreover, coastal invertebrates such as
326 dog-whelks and limpets also displayed elevated Cd concentrations, i.e. $140 \mu\text{g.g}^{-1}$ dwt
327 and $50 \mu\text{g.g}^{-1}$ dwt, respectively (Dam, 2000). Therefore, the high Cd concentrations in the
328 tissues of *A. opercularis* might reflect a global enrichment by this metal in the Faroe
329 Islands biota. Nevertheless, the reasons of such an enrichment remain to be determined.

330 In contrast, Cu and Zn appeared to be concentrated in much lower extent in the scallops
331 from the Faroe Islands compared to those from the Bay of Biscay and from the English
332 Channel (Bryan, 1973). Lower concentrations of these essential elements could be due to
333 low bioavailability of these two metal in the Faroe Island waters. High Cd concentrations
334 associated with low Cu and Zn values are typically attributed to the substitution of Cd
335 ions for essential metals under deficient conditions (Zauke and Petri, 1993, Bustamante et
336 al., 1998a). This possibly occurred in *A. opercularis* from the Faroe Islands. Indeed, the
337 digestive gland showed a high Cd / Cu ratio (i.e. 8.8) compared to the Bay of Biscay (i.e.
338 0.6). In the Faroe scallops, this high ratio was due to both elevated Cd concentrations and
339 to low Cu concentrations. Cu concentrations in the digestive gland were lower than
340 concentrations found in the temperate scallop species but in the same range than the
341 concentrations reported for the Antarctic scallop *A. colbecki* (Table 5). Large amounts of
342 Cu are essential to marine mollusks, for which Cd and Cu are known to interfere on the

343 same type of metalloproteins (i.e. metallothioneins) in the digestive gland. A competition
344 or a substitution between the two elements may have occurred in the Faroe scallops.

346 **CONCLUSION**

347
348 The three different species examined in this study accumulated high trace element
349 concentrations in their tissues, particularly in the digestive gland and in the kidney. The
350 accumulation of Cd was even higher for Cd in the subpolar Faroe area. In contrast to Cd,
351 lower Cu and Zn concentrations suggests a poor bioavailability of these essential
352 elements in that area. Regardless of the species and the origin, Cd appeared to be
353 associated to cytosolic proteins involved in detoxification functions. The presence of Cu
354 and Zn on organites and membranes might be due to their essentiality.

356 **ACKNOWLEDGEMENTS**

357
358 We thank the ‘Fiskirannsoknarstovan’ (Torshavn, Faroe Islands) and IFREMER
359 (Direction des Ressources Halieutiques, Nantes) for facilitating collections of the
360 scallops on the RVs Magnus Heinasson and Gwen-Drez. This work was financially
361 supported by the “Conseil Régional Poitou-Charentes” and Rhodia. We are grateful to
362 the anonymous referees of this manuscript for their fruitful criticism.

364 **REFERENCES**

- Alber, M., Valiela, I., 1996. Utilization of microbial organic aggregates by bay scallops, *Argopecten irradians* (Lamarck). *J. Exp. Mar. Biol. Ecol.* 195, 71-89.
- Ballan-Dufrançais, C., Jeantet, A.Y., Feghali, C., Halpern, S., 1985. Physiological features of heavy metal storage in bivalve digestive cells and amoebocytes : EPMA and factor analysis of correspondences. *Bio. Cell.* 53, 283-292.
- Bargagli, R., Nelli, L., Ancora, S., Focardi, S., 1996. Elevated cadmium accumulation in marine organisms from Terra Nova Bay (Antarctica). *Polar Biol.* 16, 513-520.
- Berkman, P.A., Nigro, M., 1992. Trace metal concentrations in scallops around Antarctica: extending the Mussel Watch Programme to the Southern Ocean. *Mar. Pollut. Bull.* 24 (6), 322-323.
- Bryan, G.W., 1973. The occurrence and seasonal variation of trace metals in the scallops *Pecten maximus* (L.) and *Chlamys opercularis* (L.). *J. Mar. Biol. Assoc. U.K.* 53, 145-166.
- Bryan, G.W., 1976. Some aspects of heavy metal tolerance in aquatic organisms. In : Lockwood APM (ed) Effects of pollutants on aquatic organisms. Academic Press, London, p 7-34
- Bustamante, P., 1998. Etude des processus de bioaccumulation et de détoxification d'éléments traces (métaux lourds et terres rares) chez les mollusques céphalopodes et bivalves pectinidés. Implication de leur biodisponibilité pour le transfert vers les prédateurs. PhD thesis, University of La Rochelle, France
- Bustamante, P., Chérel, Y., Caurant, F., Miramand, P. 1998a. Cadmium, copper and zinc in octopuses from Kerguelen Islands, Southern Indian Ocean. *Polar Biol.* 19, 264-271.

- Bustamante, P., Caurant, F., Fowler, S.W., Miramand, P. 1998b. Cephalopods as a vector for the transfer of cadmium to top marine predators in the north-east Atlantic Ocean. *Sci Total Environ.* 220, 71-80.
- Bustamante, P., Germain, P., Leclerc, G., Miramand, P., 2002a. Concentration and distribution of ^{210}Po in the tissues of the scallop *Chlamys varia* and the mussel *Mytilus edulis* from the coasts of Charente-Maritime (France). *Mar. Pollut. Bull.* 44(10), 997-1002.
- Bustamante, P., Cosson, R.P., Gallien, I., Caurant, F., Miramand, P., 2002b. Cadmium detoxification processes in the digestive gland of cephalopods in relation to accumulated cadmium concentrations. *Mar. Environ. Res.* 53, 227-241.
- Bustamante, P., Morales, F., Mikkelsen, B., Dam, M., Caurant, F., 2004. Individual and population significance of trace elements bioaccumulation in the grey seal *Halichoerus grypus* from the Faroe Islands. *Mar. Ecol. Prog. Ser.* 267, 291-301.
- Caurant, F., Amiard, J.C., Amiard-Triquet, C., Sauriau, P.G., 1994. Ecological and biological factors controlling the concentrations of trace elements (As, Cd, Cu, Hg, Se, Zn) in delphinids *Globicephala melas* from the North Atlantic Ocean. *Mar. Ecol. Prog. Ser.* 103, 207-219.
- Cubadda, F., Conti, M.E., Campanella, L. 2001. Size-dependent concentrations of trace metals in four Mediterranean gastropods. *Chemosphere* 45, 561-569.
- Dam, M., 2000. Integrated ecological monitoring in the coastal zone; Environmental Pollutants. The Food and Environmental Agency of the Faroe Islands, Report no. 2, 97p
- Evtushenko, Z.S., Belcheva, N.N., Lukyanova, O.N., 1986. Cadmium accumulation in organs of the scallop *Mizuhopecten yessoensis*. II. Subcellular distribution of metals and metal-binding proteins. *Comp. Biochem. Physiol.* 83C, 377-383.

427

428 Evtushenko, Z.S., Lukyanova, O.N., Belcheva, N.N., 1990. Cadmium bioaccumulation in
 429 organs of the scallop *Mizuhopecten yessoensis*. *Mar. Biol.* 104, 247-250.

430

431 Fowler, B.A., Gould, E., 1988. Ultrastructural and biochemical studies of intracellular
 432 metal-binding patterns in kidney tubule cells of the scallop *Placopecten magellanicus*
 433 following prolonged exposure to cadmium or copper. *Mar. Biol.* 97, 207-216.

434

435 Francesconi, K.A., Moore, E.J., Joll, L.M., 1993. Cadmium in the saucer scallop,
 436 *Amusium balloti*, from western Australian waters: concentrations in adductor muscle and
 437 redistribution following frozen storage. *Aust. J. Mar. Fresh. Res.* 44, 787-797.

438

439 George, S.G., 1980. Correlation of metal accumulation in mussels with the mechanisms
 440 of uptake, metabolism and detoxification: biochemical and ultrastructural studies.
 441 *Thalassia jugoslav.* 16, 347-365.

442

443 George, S.G., Pirie, B.J.S., Coombs, T.L., 1980. Isolation and elemental analysis of
 444 metal-rich granules from the kidney of the scallop, *Pecten maximus* (L.). *J. Exp. Mar.*
 445 *Biol. Ecol.* 42, 143-156.

446

447 Grant, J., Cranford, P.J., 1991. Carbon and nitrogen scope for growth as a function of diet
 448 in the sea scallop *Placopecten magellanicus*. *J. Mar. Biol. Assoc. U.K.* 71, 437-450.

449

450 Lukyanova, O.N., Evtushenko, Z.S., 1989. Binding of zinc and cadmium with
 451 cytoplasmic proteins in the Yezo scallop at the increased concentrations of zinc in water.
 452 *Sov. J. Mar. Biol.* 15, 306-311.

453

454 Mart, L., Nürnberg, H.W., 1984. Trace metal levels in the eastern Arctic Ocean. *Sci.*
 455 *Total Environ.* 39, 1-14.

456

457 Mauri, M., Orlando, E., Nigro, M., Regoli, F. 1990. Heavy metals in the Antarctic scallop
 458 *Adamussium colbecki*. *Mar. Ecol. Prog. Ser.* 67, 27-33.

459

460 Petri, G., Zauke, G.P., 1993. Trace metal in the crustaceans in the Antarctic Ocean.
 461 *Ambio* 22, 529-536.

462

463 Quéro, J.C., Vayne, J.J., 1998. Les fruits de mer et plantes marines des pêches françaises.
 464 Delachaux & Nestlé, Lausanne-Paris, 256 p.

465

466 Stepnowski, P., Skwarzec, B., 2000. A comparison of ^{210}Po accumulation in molluscs
 467 from the southern Baltic, the coast of Spitsbergen and Sasek Wielki Lake in Poland. *J.*
 468 *Environ. Radioact.* 49, 201-208.

469

470 Stone, H.C., Wilson, S.B., Overnell, J., 1986. Cadmium binding components of scallop
 471 (*Pecten maximus*) digestive gland. Partial purification and characterisation. *Comp.*
 472 *Biochem. Physiol.* 85 C, 259-268.

473

474 Uthe, J.F., Chou, C.L., 1987. Cadmium in sea scallop (*Placopecten magellanicus*) tissues
 475 from clean and contaminated areas. *Can. J. Fish. Aquat. Sci.* 44, 91-98.

476

477 Viarengo, A., Canesi, L., Mazzucotelli, A., Ponzano, E. 1993. Cu, Zn and Cd content in
 478 different tissues of the Antarctic scallop *Adamussium colbecki* : role of the
 479 metallothionein in heavy metal homeostasis and detoxification. *Marine Ecology Progress*
 480 *Series* 95, 163-168.

481

482 Zar JH (1996) Biostatistical Analysis, 3rd ed. Prentice-Hall, Upper Saddle River, NJ

483

484 Zauke, G.P., Savinov, V.M., Ritterhoff, J., Savinova, T. 1999. Heavy metals in fish from
 485 the Barents Sea (summer 1994). *Sci. Total Environ.* 227, 161-173.

Table 1. Comparison of trace elements concentrations ($\mu\text{g}\cdot\text{g}^{-1}$ dry wt) of dogfish liver DOLT-2 (NRCC), and dogfish muscle (NRCC) determined in the present study with certified values.

Metals	DOLT-2 (n=5)		DORM-2 (n=5)	
	Certified values	Present study	Certified values	Present study
Cd	20.8 ± 0.5	19.7 ± 0.6	0.043 ± 0.008	0.042 ± 0.014
Cu	25.8 ± 1.1	24.9 ± 1.2	2.34 ± 0.16	2.30 ± 0.22
Zn	85.8 ± 2.5	84.5 ± 2.8	25.6 ± 2.3	26.3 ± 1.8

492 Table 2. Mean $\pm$ SD of Cd, Cu, and Zn concentrations ($\mu\text{g}\cdot\text{g}^{-1}$ dwt) in the organs and tissues of three scallop species from the Bay of
493 Biscay and the Faroe Islands. N : number of pools (sum of the individuals)

Element Species	Location	Digestive gland	Kidneys	Gonad	Gills	Muscle	Remaining tissues	Whole soft parts
Cd								
<i>Aequipecten</i>	Bay of Biscay	27.5 $\pm$ 4.24	21.1 $\pm$ 3.15	3.99 $\pm$ 3.17	7.41 $\pm$ 0.03	0.70 $\pm$ 0.24	4.74 $\pm$ 2.13	5.70 $\pm$ 1.21
"	Faroe Islands	123 $\pm$ 14	159 $\pm$ 80	3.54 $\pm$ 0.89	8.46 $\pm$ 3.38	0.49 $\pm$ 0.09	10.5 $\pm$ 2.84	38.7 $\pm$ 11.1
<i>Chlamys varia</i>	Bay of Biscay	40.0 $\pm$ 4.43	38.8 $\pm$ 11.1	2.11 $\pm$ 0.27	4.12 $\pm$ 0.39	0.54 $\pm$ 0.08	2.06 $\pm$ 0.32	7.69 $\pm$ 0.77
<i>Pecten maximus</i>	"	264 $\pm$ 33	70.6 $\pm$ 12.6	5.28 $\pm$ 5.44	4.68 $\pm$ 2.26	2.01 $\pm$ 1.07	3.58 $\pm$ 0.60	29.7 $\pm$ 12.0
Cu								
<i>Aequipecten</i>	Bay of Biscay	43.6 $\pm$ 19.5	507 $\pm$ 144	8.1 $\pm$ 0.6	7.1 $\pm$ 0.7	1.7 $\pm$ 0.9	4.5 $\pm$ 0.8	15.0 $\pm$ 4.6
"	Faroe Islands	14.0 $\pm$ 0.8	106 $\pm$ 49	6.5 $\pm$ 0.7	4.7 $\pm$ 0.2	1.0 $\pm$ 0.1	2.5 $\pm$ 0.1	7.6 $\pm$ 2.3
<i>Chlamys varia</i>	Bay of Biscay	88.1 $\pm$ 13.8	142 $\pm$ 20	29.6 $\pm$ 6.0	8.1 $\pm$ 0.8	1.8 $\pm$ 0.2	5.5 $\pm$ 0.4	19.2 $\pm$ 1.7
<i>Pecten maximus</i>	"	40.7 $\pm$ 7.8	13.5 $\pm$ 2.0	19.7 $\pm$ 16.1	5.3 $\pm$ 2.4	1.2 $\pm$ 0.3	3.4 $\pm$ 0.3	6.5 $\pm$ 1.6
Zn								
<i>Aequipecten</i>	Bay of Biscay	198 $\pm$ 47	31053 $\pm$ 8147	195 $\pm$ 16	384 $\pm$ 74	79 $\pm$ 17	200 $\pm$ 35	437 $\pm$ 159
"	Faroe Islands	77 $\pm$ 14	6632 $\pm$ 3664	120 $\pm$ 15	96 $\pm$ 7	39 $\pm$ 4	105 $\pm$ 32	193 $\pm$ 106
<i>Chlamys varia</i>	Bay of Biscay	149 $\pm$ 27	24107 $\pm$ 3465	239 $\pm$ 45	232 $\pm$ 99	101 $\pm$ 13	181 $\pm$ 61	781 $\pm$ 120
<i>Pecten maximus</i>	"	804 $\pm$ 92	7278 $\pm$ 3041	254 $\pm$ 105	143 $\pm$ 4	64 $\pm$ 7	87 $\pm$ 6	235 $\pm$ 110

494

Table 3. Body distribution of Cd, Cu, and Zn (% of the wet weight) in the organs and tissues of three scallop species from the Bay of Biscay and the Faroe Islands. N : number of pools (sum of the individuals)

Species	Location	Digestive gland	Kidneys	Gonad	Gills	Muscle	Remaining tissues
Cd							
<i>Aequipecten</i>	Bay of Biscay	75 ± 8	4 ± 3	5 ± 2	3 ± 1	8 ± 3	12 ± 2
"	Faroe Islands	90 ± 3	5 ± 3	1 ± 0	1 ± 0	< 1	3 ± 1
<i>Chlamys varia</i>	Bay of Biscay	80 ± 3	8 ± 2	< 1	2 ± 0	4 ± 1	5 ± 1
<i>Pecten maximus</i>	"	93 ± 1	2 ± 1	< 1	< 1	3 ± 1	1 ± 0
Cu							
<i>Aequipecten</i>	Bay of Biscay	52 ± 9	37 ± 6	5 ± 3	1 ± 1	8 ± 5	3 ± 1
"	Faroe Islands	61 ± 4	18 ± 10	7 ± 3	4 ± 1	5 ± 2	5 ± 2
<i>Chlamys varia</i>	Bay of Biscay	74 ± 7	12 ± 3	2 ± 0	1 ± 0	5 ± 10	6 ± 1
<i>Pecten maximus</i>	"	70 ± 6	2 ± 2	11 ± 8	3 ± 3	11 ± 3	3 ± 1
Zn							
<i>Aequipecten</i>	Bay of Biscay	1 ± 1	97 ± 1	1 ± 0	1 ± 0	< 1	1 ± 0
"	Faroe Islands	17 ± 6	53 ± 18	6 ± 4	5 ± 2	9 ± 4	9 ± 5
<i>Chlamys varia</i>	Bay of Biscay	5 ± 1	72 ± 4	1 ± 0	2 ± 1	14 ± 3	7 ± 2
<i>Pecten maximus</i>	"	14 ± 11	81 ± 14	3 ± 1	1 ± 0	1 ± 1	1 ± 0

499 Table 4. Proportion of Cd, Cu, and Zn in the cytosol of the digestive gland cells (% of the
500 wet weight) of three scallop species from the Bay of Biscay and the Faroe Islands. N :
501 number of individuals

Species	Location	N	Cd	Cu	Zn
<i>Pecten maximus</i>	Bay of Biscay	23	72 ± 5	43 ± 4	38 ± 7
<i>Chlamys varia</i>	Bay of Biscay	40	78 ± 5	25 ± 8	41 ± 3
<i>Aequipecten opercularis</i>	Faroe Islands	10	80 ± 7	35 ± 16	50 ± 11

502

Table 5. Mean $\pm$ SD of Cd, Cu, and Zn concentrations ($\mu\text{g}\cdot\text{g}^{-1}$ dwt) in different scallop species from various locations. N: sample size.

Species	Location	N	Cd	Cu	Zn	Reference
Digestive gland						
<i>Amusium balloti</i>	Australia	10	111 ^a	-	-	Francesconi et al. 1993
<i>Adamussium colbecki</i>	Antarctic	30	142 $\pm$ 57	12.6 $\pm$ 3.3	74.9 $\pm$ 25.4	Mauri et al. (1990)
"	"	6	26.51 $\pm$ 6.09 ^a	3.52 $\pm$ 0.49 ^a	17.42 $\pm$ 2.91 ^a	Viarengo et al. (1993)
<i>Aequipecten opercularis</i>	Northeast Atlantic	31	123 $\pm$ 14	14.0 $\pm$ 0.8	77 $\pm$ 14	Present study
"	English Channel	11	27	36.7 $\pm$ 11.4	132 $\pm$ 26	Bryan (1973)
"	Bay of Biscay	11	27.5 $\pm$ 4.24	43.6 $\pm$ 19.5	198 $\pm$ 47	Present study
<i>Chlamys varia</i>	"	41	40.0 $\pm$ 4.43	88.1 $\pm$ 13.8	149 $\pm$ 27	"
<i>Pecten jacobus</i>	Mediterranean Sea	30	41.0 $\pm$ 18.2	16.6 $\pm$ 6.6	124 $\pm$ 55	Mauri et al. (1990)
"	"	6	7.19 $\pm$ 1.23 ^a	3.13 $\pm$ 0.55 ^a	28.63 $\pm$ 3.29 ^a	Viarengo et al. (1993)
<i>P. maximus</i>	English Channel	11	321	57.9 $\pm$ 27.4	407 $\pm$ 123	Bryan (1973)
"	Bay of Biscay	11	264 $\pm$ 33	40.7 $\pm$ 7.8	804 $\pm$ 92	Present study
<i>Placopecten magellanicus</i>	Northwest Atlantic	6	94.68 $\pm$ 8.42 ^a	-	-	Uthe & Chou (1987)
Kidney						
<i>Adamussium colbecki</i>	Antarctic	30	11.6 $\pm$ 3.3	4.0 $\pm$ 1.7	199 $\pm$ 89	Mauri et al. (1990)
<i>Aequipecten opercularis</i>	Northeast Atlantic	31	159 $\pm$ 80	106 $\pm$ 49	6632 $\pm$ 3664	Present study
"	English Channel	11	41	1285 $\pm$ 591	40800 $\pm$ 7290	Bryan (1973)
"	Bay of Biscay	11	21.1 $\pm$ 3.15	507 $\pm$ 144	31053 $\pm$ 8147	Present study
<i>Chlamys varia</i>	"	41	38.8 $\pm$ 11.1	142 $\pm$ 20	24107 $\pm$ 3465	"
<i>Pecten jacobus</i>	Mediterranean Sea	30	10.7 $\pm$ 4.0	17.5 $\pm$ 10.9	2790 $\pm$ 1340	Mauri et al. (1990)
<i>P. maximus</i>	English Channel	11	79	20.8 $\pm$ 10.3	19300 $\pm$ 4800	Bryan (1973)
"	Bay of Biscay	11	70.6 $\pm$ 12.7	13.5 $\pm$ 2.0	7278 $\pm$ 3041	Present study
<i>Placopecten magellanicus</i>	Northwest Atlantic	6	62.61 $\pm$ 25.33 ^a	-	-	Uthe & Chou (1987)

^a: values expressed relatively to wet weight.