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Concentration of statolith trace elements in the jumbo flying squid during El Niño and non-El Niño years in the eastern Pacific

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Statoliths of the jumbo flying squid *Dosidicus gigas* (Cephalopoda: Ommastrephidae) in the eastern Pacific in 1995, 1996 (non-El Niño years) and 1997 (El Niño year) were analysed to observe whether unusual temperature increases due to El Niño was recorded in the concentration of trace elements. In addition to calcium (the major element), trace elements of manganese (Mn), iron (Fe), copper (Cu), zinc (Zn), and strontium (Sr) were detected. Strontium concentration in the calcified tissue of some aquatic animals changes with environmental variables. However, yearly comparisons revealed that Sr concentration did not significantly differ between the El Niño year and non-El Niño years. Instead, the Sr concentration differed with squid habitats. Strontium concentration in statoliths of *D. gigas* from Peruvian waters (high salinity) was significantly higher than those from Costa Rican waters (low salinity) regardless of El Niño.

INTRODUCTION

Levels of trace elements in calcified tissues showed a correlation with environmental data such as temperature for coral skeletons (Smith et al., 1979), bivalve shells (Masuda, 1976) or fish otoliths (Radtke, 1990) and salinity for anadromous fish otoliths (Secor et al., 1995; Radtke et al., 1996). These relationships allow calcified tissue to be used as a tool for reconstructing the life histories of aquatic animals in nature.

We have measured the trace elements in squid statoliths, with the goal of reconstructing migratory routes and habitat use of this group. Strontium concentration in statoliths of the Japanese common squid (*Todarodes pacificus* Steenstrup, 1880) varies with the temperature of their habitats (Ikeda et al., 1998). Furthermore, statolith strontium concentration in squid correlates with habitat diversity of species (e.g. inshore vs offshore (Ikeda et al., 1997)). However, mechanisms of elemental deposition in calcified tissues are still unknown since elemental composition seems to be affected also by other factors such as age (Kalish, 1989), stress (Kalish, 1992) or metamorphosis (Ohtake et al., 1997). This prevents calcified tissue from being easily used for life history reconstruction (Campana, 1999). Therefore, studying the elemental dynamics in statoliths has a dual purpose.

The jumbo flying squid (*Dosidicus gigas* Orbigny, 1835) is the largest ommastrephid and is endemic to the eastern Pacific from Baja California to northern Chile (Nesis, 1983). Considering its one year life span (Masuda et al., 1998) as well as its limited habitat in the eastern Pacific (Nesis, 1983), a generation of *D. gigas* is exposed to unusually warm temperatures during an El Niño year. We therefore compared the trace elements in statoliths of *D. gigas* living during an El Niño year with those from non-El Niño years to observe whether the environmental change appears in the elemental deposition.

MATERIALS AND METHODS

Statoliths of adult female *Dosidicus gigas* (ML 230–509 mm) caught by jigging from the following sites and years were analysed: (i) Peruvian waters in 1995 (non-El Niño year: 5°00′S 87°00′W on 27 September, 8°00′S 85°00′W on 17 November, 10°00′S 84°00′W on 19 November); (ii) Peruvian waters in 1997 (El Niño year: 3°35′S 83°00′W on 18 October, 3°35′S 85°00′W on 19 October, 5°30′S 85°00′W on 24 October, 7°30′S 84°00′W on 29 October); (iii) Costa Rican waters in 1996 (non-El Niño year: 6°53′N 96°27′W, 7°18′N 99°42′W on 15 October); and (iv) Costa Rican waters in 1997 (El Niño year: 7°00′N 95°00′W on 19 November, 7°00′N 91°00′W on 22 November, 9°00′N 97°01′W on 20 November). Based on the long-term record, Peruvian waters are cool and high saline whereas Costa Rican waters are warm and low saline (Fiedler et al., 1992). Temperature and salinity at collection sites were recorded only in 1997. Morphometric measurements were taken for 37 *D. gigas* specimens (ten specimens each for sample nos. 1, 2, 4 and seven specimens for sample no. 3). The maturity was judged according to Ikeda et al. (1991). A pair of statoliths was extracted and preserved in liquid paraffin until the elemental analysis was performed.

The elements of the surface of an intact statolith were analysed by PIXE (particle induced X-ray emission) in the Division of Nuclear Engineering of Kyoto University.

Table 1. *Means, standard deviations and number (N) of individuals for trace elements in statoliths of female jumbo flying squid* Dosidicus gigas *in the eastern Pacific.*

Site/Environment, Year	Trace elements Mean ±SD (ppm)									
	Mn	N	Fe	N	Cu	N	Zn	N	Sr	N
Peru/non-El Niño, 1995	19	1	37 ±7.9*[1]	10	16 ±6.2*[2]	9	18 ±7.7*[4]	8	9399 ±524*[5]	10
Peru/El Niño, 1997	16 ±1.9	3	76 ±63*[1]	10	37 ±33*[2]	10	22 ±22*[4]	6	9184 ±609*[6]	10
Costa Rica/ non-El Niño, 1996	13 ±0.1	2	50 ±42	7	19 ±6.9*[3]	7	17 ±9.6	6	7800 ±505*[5],*[7]	7
Costa Rica/El Niño, 1997	16 ±0.1	5	57 ±46	10	41 ±48*[3]	10	19 ±11	7	8356 ±295*[6],*[7]	10

*[1], *[2], *[3], *[4], statistically differs between two samples, *F*-test, $P<0.05$; *[5], *[6], *[7], statistically differs between two samples, *t*-test, $P<0.05$.

Details of preparation of target sample and analytical condition for PIXE have been fully described elsewhere (e.g. Ikeda et al., 1997, 1998) except that a 40 μC beam charge was applied. The computer programs PIXAN (Clayton, 1986) and NIST (National Institute of Standard and Technology, US Department of Commerce) argillaceous limestone were respectively used for counts and as a standard for estimation of concentrations (Ikeda et al., 1997, 1998). The minimum threshold level for each trace element presently measured by PIXE is as follows: Mn, 9–16 ppm; Fe, 7–13 ppm; Cu, 6–11 ppm; Zn, 6–12 ppm; Sr, 18–43 ppm.

RESULTS AND DISCUSSION

Since *Dosidicus gigas* undertakes deep diel vertical maigrations (Yatsu et al., 1999), ambient temperature in their environment varies widely within 24 hours. However, the values for statolith elemental concentrations must include integrated values that cover several days history, for the PIXE that we applied in the present study beamed several microns depth from the statolith surface (i.e. several increments from the edge). Thus, we observed relatively long-term trends in statolith elemental concentrations of *D. gigas* in relation to integration of ambient temperature between the bathypelagic layer and surface layer.

Although 33 out of 37 individuals were mature, a wide range of body sizes existed in the Peruvian samples (ML 230–509 mm). Yet all individuals examined fit with an identical growth pattern and maturation process. Thus, we directly compared these individuals that had originated from different sources.

Figure 1 shows trace element concentrations in statoliths of sample nos. 1–4. Since detectable trace elements whose counts were under the detection limit have been omitted, the numbers of several elements such as Mn, Cu and Zn are low (see N of each element in Figure 1 and Table 1). Strontium concentration in statoliths of *D. gigas* from Peruvian waters in the El Niño year about 200 ppm lower than in non-El Niño years but this was not statistically significant (Figure 1, Table 1). However, this relationship was opposite in Costa Rican samples with a statistically significant level (*t*-test, $P<0.05$; Figure 1, Table 1). More importantly, the Sr of Peruvian samples was significantly higher (~1000 ppm) than the Costa Rican samples in the El Niño year and the non-El Niño years (*t*-test, $P<0.05$; Figure 1, Table 1).

Manganese concentration in Costa Rican samples was higher in the El Niño year than in non-El Niño years (Figure 1, Table 1). But since the number of individuals having Mn above detection limits was small (two and five for 1996 and 1997 samples, respectively), any conclusions must be drawn carefully. Although it was not statistically significant, concentration of Fe, Cu and Zn were higher in the El Niño year than in non-El Niño years (Figure 1, Table 1). Additionally, variation in concentration differed between these two periods. Significantly wider variations were observed for Cu concentration of both Peruvian and Costa Rican samples in the El Niño year (*F*-test, $P<0.05$; Figure 1, Table 1). This tendency was also observed in Fe and Zn of Peruvian samples in the El Niño year (*F*-test, $P<0.05$; Figure 1, Table 1).

Strontium concentration in *D. gigas* statoliths was compared with temperature and salinity between the sea surface and 300 m at each collecting site (data not shown). A difference in Sr between Peruvian samples and Costa Rican samples (Figure 1, Table 1) was not clearly observed in relation to the temperature at any depths examined. The difference of Sr concentrations between Peruvian samples and Costa Rican samples was related to salinity. Sr concentration of Costa Rican individuals living in low salinity areas (<35 psu) was low whereas it increased in Peruvian individuals living in high salinity areas ($\geqslant$ 35 psu).

Based on the negative relationship between ambient temperature and Sr concentration in coral skeletons (Smith et al., 1979) or fish otoliths (Radtke, 1990), *D. gigas* statoliths Sr were expected to be lower during El Niño years when temperature increases ~2.5°C over non-El Niño years (Fiedler et al., 1992). However, this was not observed for *D. gigas* in the 1997 El Niño year. Instead, Sr concentration varied according to habitat. Salinity-dependent change of Sr concentration in calcified tissue was reported for anadromous fish (Secor et al., 1995; Radtke et al., 1996). In our pilot study (Ikeda et al., 1997), Sr concentration of the flying squid (*Sthenoteuthis oualaniensis* Lesson, 1830) from the Arabian Sea, Indian Ocean and Pacific Ocean differed with salinities. In the same study, Sr concentration of mature *D. gigas* was slightly lower in Peruvian individuals (8476 ±100 ppm) than in Costa Rican individuals (9228 ±113 ppm) (Ikeda et al., 1997). This contrasts with the present results, but that pilot study used a collection site in Peruvian waters located closer to coastal side where there is an increased influence of low salinity waters from land (Ikeda et al.,

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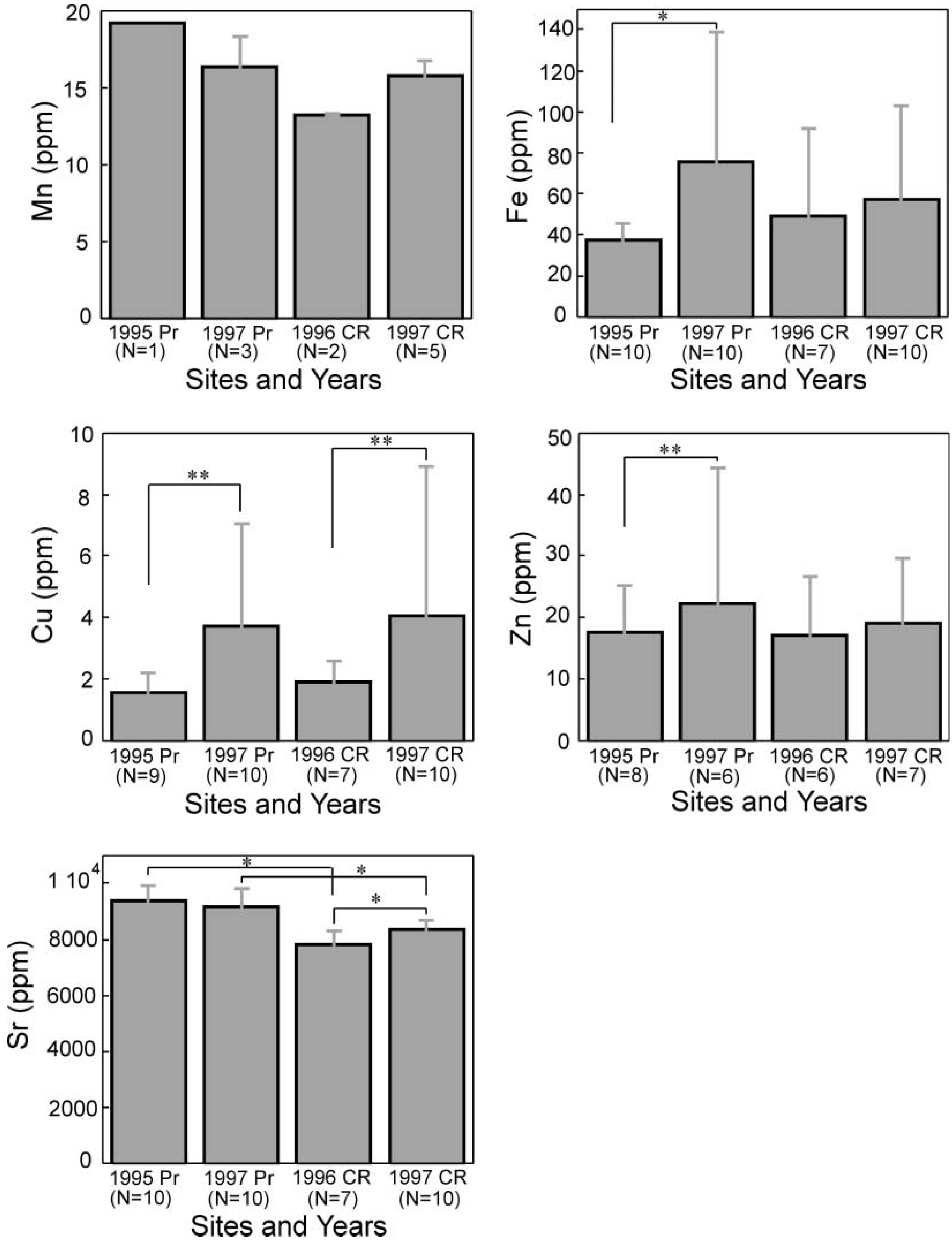

Figure 1. Comparison of concentration of statolith trace elements in *Dosidicus gigas* occurring in Peruvian waters (Pr) and Costa Rican waters (CR) in 1995, 1996 (non-El Niño years) and 1997 (El Niño year). Vertical bars indicate standard deviation. **t*-test, $P<0.05$; ***F*-test, $P<0.05$.

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1997). In summary, Sr incorporation in statoliths was not affected by the temperature increase of an El Niño event, but it did reflect a salinity change between different habitats in the eastern Pacific. However, the reason why Costa Rican individuals in non-El Niño years showed lower Sr concentrations than in the El Niño year cannot be explained. We could not also explain causes for the variation of other trace elements (Mn, Fe, Cu, Zn) because of small number of individuals having been detected with these elements.

In conclusion, Sr concentration appears to be associated with salinity of the waters from which *D. gigas* is taken, regardless of El Niño.

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