Distribution, demography, and discard mortality of crabs caught as bycatch in an experimental pot fishery for toothfish (*Dissostichus eleginoides*) in the South Atlantic

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Abstract—Between March 2000 and April 2001 two commercial fishing vessels fished for toothfish (*Dissostichus eleginoides*) off South Georgia using pots. A significant number of lithodid crabs (three species of *Paralomis* spp.) were caught as bycatch. *Paralomis spinosissima* occurred in shallow water, generally shallower than 700 m. *Paralomis anamerae*, not previously reported from this area and therefore representing a considerable southerly extension in the reported geographic range of this species, had an intermediate depth distribution from 400 to 800 m. *Paralomis formosa* was present in shallow waters but reached much higher catch levels (and, presumably, densities) between 800 and 1400 m. Differences were also noted in depth distribution of the sexes and size of crabs. Depth, soak time, and area were found to significantly influence crab catch rates. Few crabs (3% of *P. spinosissima* and 7% of *P. formosa*) were males above the legal size limit and could therefore be retained. All other crabs were discarded. Most crabs (>99% of *P. formosa*, >97% of *P. spinosissima,* and >90% of *P. anamerae*) were lively on arrival on deck and at subsequent discard. Mortality rates estimated from re-immersion experiments indicated that on the vessel where pots were emptied directly onto the factory conveyor belt 78–89% of crabs would survive discarding, whereas on the vessel where crabs were emptied down a vertical chute prior to being sorted, survivorship was 38–58%. Of the three, *P. anamerae* was the most vulnerable to handling onboard and subsequent discarding. *Paralomis spinosissima* seemed more vulnerable than *P. formosa*.

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The Commission for the Conservation of Antarctic Marine Living Resources (CCAMLR) and its Scientific Committee were pioneers in the development of the "ecosystem approach" for the management of fisheries. Using this approach the Commission is bound to consider the impact of any fishery on both the target, dependent, and related species. Currently, the most important fishery in CCAMLR waters is the longline fishery for Patagonian toothfish (*Dissostichus eleginoides*) and fishing grounds near South Georgia Island and Shag Rocks in CCAMLR subarea 48.3 (South Atlantic sector) are among the most important. Mitigation measures, including requirements for setting at night, in the winter, and with specialized gear, have been introduced to reduce incidental mortality of birds being hooked by longlines. However, these measures impose severe operational restrictions on the fishery, and low levels of bird mortality still occur (CCAMLR[1]).

Pot fishing for toothfish has recently been tried around South Georgia (Agnew et al., 2001), and although pots do not catch birds, they do take lithodid crabs as bycatch. Crabs are largely a "nuisance" catch when fishing for toothfish, but this bycatch is clearly of concern in relation to crab populations, and must be considered within the CCAMLR's ecosystem approach. A small amount of exploratory crab fishing has already taken place around South Georgia Island and Shag Rocks. Only 798 metric tons (t) of crabs have been taken in directed crab fisheries since 1992; by the FV *Pro Surveyor* (July–August 1992; 299 t; CCAMLR[2]), the FV *American Champion* (September 1995–January 1996; 497 t; CCAMLR[3]), and the FV *Argos Helena* (August 1999; 2 t) (CCAMLR[4]). A pot fishery for toothfish is likely to take place in deep water where current longline fishing concentrates (around the 1000 m contour: Agnew et al., 1999) rather than in shallower waters (<400 m) where crab fishing has taken place (Otto and Macintosh, 1996; Watters, 1997). Toothfish pot fishing may therefore impact different crab population components from those impacted by the crab fishery.

We investigated the likely effects of toothfish pot fishing on crabs caught as bycatch on board two commercial fishing vessels. These vessels conducted three separate trials fishing for toothfish around South Georgia between March 2000 and April 2001. This paper reports on the species of crab taken during these trials, as well as the distribution of crabs and their biological characteristics. In common with many other crab fisheries (Hoggarth, 1991; Schmidt and Pengilly, 1993) retention size limits are set for the fishery around South Georgia. Only males greater than 102 mm carapace width for *Paralomis spinosissima* and 90 mm for *P. formosa* may be retained. All undersize and female crabs from both the toothfish pot fishery and the crab fishery must be discarded. We also report results of experiments on survival of such discards.

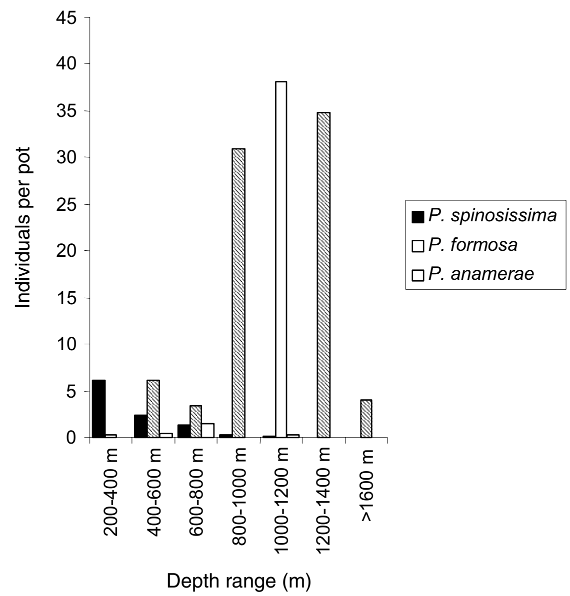

Figure 1

Catch in numbers per pot of the three dominant crab species by depth range as found during fishing operations of the *Argos Georgia* from May to April 2000. Pots were set between 211 m and 1651 m depth.

Methods

During the first cruise (March to May 2000), two observers were deployed on board the FV *Argos Georgia* (cruise G1). Detailed information was collected on the number of toothfish and the numbers and species composition of crabs caught in the pots. Information was also collected on fishing results, such as catch rates, fish bycatch, and the commercial viability of this fishing method (Agnew et al., 2001), and the diet of toothfish (Pilling et al., 2001). In the second and third toothfish pot cruises single observers were deployed on the *Argos Georgia* (cruise G2) and another vessel, the FV *Argos Helena* (cruise H), which fished simultaneously from January to April 2001. Fishing gear and the configuration of gear was similar for all three cruises. The semiconical pots of approximately 80 cm height were constructed of steel frames and covered with 80-mm polysteel (Movline) mesh. A collapsible funnel entrance was situated on the side of the pot, orientated horizontally, and tapering to the pot's interior. A drawstring held the bottom mesh together in the middle. This configuration allowed the pots to be emptied easily when hauled aboard and to be stacked on top of each other when not in use. A panel was sewn into the pots by using biodegradable sisal twine to ensure that crabs could eventually escape from lost pots and to prevent "ghost fishing." However, catch handling methods were different on the two vessels; the pots were emptied directly onto the factory conveyor belt on the *Argos Georgia* and emptied down a chute to the factory level on the *Argos Helena*.

During the first cruise (March to May 2000) depth of fishing, determined as water depth by onboard echo sounders, was related to the species of crab caught. *Paralomis spinosissima* were generally caught in relatively shallow waters, whereas *P. formosa* tended to be caught in much greater numbers in deeper waters (Fig. 1). *Paralomis anamerae*

[1] CCAMLR (Commission for the Conservation of Antarctic Marine Living Resources). 1999. Report of the Working Group for Fish Stock Assessment, 110 p. Annex 5 in the report of the eighteenth meeting of the Scientific Committee. CCAMLR, P.O. Box 213, North Hobart, Tasmania 7002, Australia.

[2] CCAMLR. 1992. Report of the working group for fish stock assessment, 164 p. Annex 5 in the Report of the eleventh meeting of the Scientific Committee. CCAMLR, P.O. Box 213, North Hobart, Tasmania 7002, Australia.

[3] CCAMLR. 1997. Report of the working group for fish stock assessment, 169 p. Annex 5 in the Report of the sixteenth meeting of the Scientific Committee. CCAMLR, P.O. Box 213, North Hobart, Tasmania 7002, Australia.

[4] CCAMLR. 2000. CCAMLR statistical bulletin, 153 p. CCAMLR, P.O. Box 213, North Hobart, Tasmania 7002, Australia.

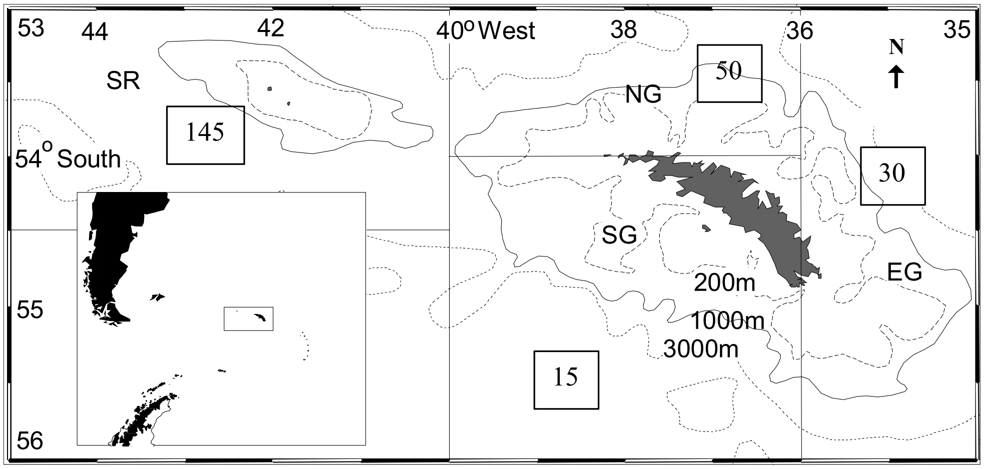

Figure 2

Map of areas used in the study. SR=Shag Rocks, NG=North South Georgia, EG=East South Georgia, SG=South South Georgia, and the 200-m, 1000-m and 3000-m bathymetric contours are shown. The total number of hauls in each of these areas were as follow: SR=145, NG=50, EG=30, and SG=15. Inset shows the position of the study area in relation to the South Atlantic.

(Macpherson, 1988) were caught at intermediate depths. Other influences on crab catch rates were investigated by using two cruises in 2001, which covered the study area more evenly (most hauls in cruise G1 were concentrated in a small area around southeast Shag Rocks; see Fig. 2). For each species two generalized linear models were constructed with Splus statistical software (version 2000, Mathsoft Engineering & Education, Inc., Cambridge, UK): a binomial link model for the probability of encountering a crab of that species (*pe*) and a Gaussian link model for the natural logarithm of CPUE (catch in numbers per pot) for all nonzero catches. Both models were of the form $\lambda = p_1 \times$ depth$+p_2 \times$area$+p_3 \times$vessel$+p_4 \times$soak time, where for the binomial models, λ was set to 1 if crabs had been caught and 0 if they had not, and for the Gaussian models, λ was set to ln(numbers per pot) for all sets catching crabs. Area and vessel parameters were factors. Depth and soak time were modeled as linear continuous variables, except in the case of the Gaussian model for *P. formosa*, where a third-order polynomial best described the relationship between CPUE and depth. Predictions from the two models were combined to predict crab catch rates per pot,

$$\hat{U} = p(e) \times \exp[\hat{u} \pm 1.96 \times SE],$$

where $\hat{u}$ = the predicted ln(CPUE) from the Gaussian model; and
SE = the standard error from the Gaussian model.

Biological data were collected from all crabs in randomly selected pots. Carapace widths, carapace lengths, chela height, and chela length were measured to the nearest millimeter below by using calipers. Weights were measured to the nearest 5 g below with spring-balanced scales. Sex, maturity stage, condition of the carapace, and an index of vitality (Table 1) were recorded for a subsample of crabs, selected as a random portion across species from the contents of selected pots. Identification of the uncommon species, *Paralomis anamerae*, *Neolithodes diomedeae,* and *Lithodes murrayi*, was confirmed by using dried specimens in London (at Imperial College and the British Museum of Natural History).

Male size at maturity was determined from the allometric relationship between carapace length (L) and right (dominant) chela size (height, CH, or length, CL). The slope of the L-CH or L-CL relationship is assumed to change when crabs reach maturity. Around South Georgia, Otto and Macintosh (1996) used L and CH to determine the size at maturity of male *P. spinosissima,* and around the Falkland Islands Hoggarth (1991) used L and CL. For both *P. spinosissima* and *P. formosa* we found that the intersection of the two lines corresponding to the onset of maturity was not easy to identify from the relationship between CL and L. We therefore used CH in our relationships. Following the methods of Somerton and Otto (1986), two linear regression lines were fitted to natural logarithms of L and CH or CL. These lines represent juvenile and adult phases in the L-CH or CL relationship and intersected at a point taken as the L at which males became mature. The regression lines of best fit were determined by minimizing the combined residual sums of squares, and standard errors were estimated by using 500 bootstraps (sampling with replacement).

Females were classified into two categories, "eggs absent" and "eggs present." The vast majority of "eggs absent" females were small immature animals, but some large animals were also encountered in this category. Consequently, for estimating size at maturity, females in the "eggs present" category were defined as "mature" and those in the "eggs absent" category were classified as "immature" up to the size at which the proportion of females with eggs (i.e. mature) reached 90%, after which they were classified as "mature without eggs." Female size at maturity was deter-

Table 1
Relative index used for assessing vitality in *Paralomis* spp.

Vitality index	Description	Characteristics
1	Lively	Limbs supported and held out. Limbs resist manipulation. Crabs actively pinch objects. Can hang on smooth end of forceps by 1 claw (weakest on large crabs).
2	Lively but limp	Legs hang when picked up. Claws weak and can be opened—not capable of supporting own weight on forceps. Mouthparts move, indicating life when submerged in seawater.
3	Dead	No signs of life. Mouthparts do not move when submerged.
4	Dead and eaten	Only shell or carapace remaining.

mined by plotting the proportion of mature females against size (carapace width) and determining the point of 50% maturity (Sm_{50}). Logistic curves of the form [$proportion\ mature = 1/(1 + \exp(-r(carapace\ width - Sm_{50})))$] were used to estimate 50% maturity (Sm_{50}) and its standard error by using the nonlinear fitting function in Splus.

Three different experiments were conducted between March 2000 and April 2001 to assess crab discard survival rates. During cruise G1 a number of alive and active crabs from one haul were tagged through one of the lateral plates of the abdomen with Hallprint plastic T-bar tags and maintained in running seawater before they were placed in pots prior to the next setting. Once these pots were rehauled, the vitality of the tagged crabs was assessed by using the four point relative scale shown in Table 1. A control group of crabs were similarly tagged and kept onboard in running seawater to monitor any effect that tagging might have had on survival. Survival experiments conducted on cruises G2 and H differed in that crabs were selected at random and included individuals that were already "limp" prior to re-immersion. Crabs were tagged with thin strips of masking tape around their legs prior to re-immersion. To ensure that the same crabs were assessed for vitality after rehauling, pots were marked and sealed off to prevent any new captures.

Estimates of the total survival that can be expected after discarding were made in the following manner. By observing crabs on arrival on deck we determined the proportion of animals that arrived on deck as lively ($lively_o$), or limp ($limp_o$), or dead. Using the data from the survival experiments we set $p(lively,lively)$ as the probability that a lively animal that is discarded will recover to a lively condition (this was estimated by calculating the proportion of experimentally re-immersed lively animals that were recovered as lively). We defined $p(limp,lively)$ similarly. The proportion of discarded animals that were lively and would continue to be lively is $lively_o \times p(lively,lively)$ and the proportion of discarded animals that were limp but would recover to a lively condition is $limp_o \times p(limp,lively)$. The overall survivorship, S, is then

$$S = lively_o \times p(lively,lively) + limp_o \times p(limp,lively).$$

In our experiments, some of the damage may have occurred on rehauling the pots after re-immersion, a situation that would not normally occur once crabs have been discarded. $p(lively,lively)$ can be corrected for this by adding to it the proportion of animals that were not lively when first hauled (i.e. $1 - lively_o$), termed the rehaul correction. For instance, suppose that 1% of the crabs were not lively on the first hauling, and in the experiment 4% of the re-immersed lively crabs were not lively on recovery. The rehaul correction would indicate that 1% of the re-immersed crabs would have been damaged anyway simply by the hauling process, and that therefore the correct damage rate attributed simply to the initial capture and discarding would be 3%.

Results

Crab catch

The majority of the bycatch comprised two species of lithodid crabs (Anomura: Lithodidae), *Paralomis spinosissima* and *P. formosa*. Both species have been previously reported in catches around Shag Rocks and South Georgia (Otto and Macintosh, 1996) and have formed a large proportion of the total catch of crab (Table 2). Crab species formed 69.5% of the total weight of all species caught, including toothfish, and 98.2% of the total numbers of individuals caught.

Three other species of crab were also identified during the pot trials. The most abundant of these was *Paralomis anamerae* (Macpherson, 1988), which like the other *Paralomis* species, was subject to detailed biological sampling. 12,370 individuals of this species (1 721 kg) were caught. All individuals were discarded because they were smaller than the minimum size limit for the smaller of the two regulated species, *P. formosa*. Two other species, *Neolithodes diomedeae* and *Lithodes murrayi*, were also caught in small numbers.

Distribution

Crab distribution was investigated for the areas as defined in Figure 2. There were too few data from South of South Georgia; therefore the analysis was restricted to data from Shag Rocks, North South Georgia, and East South Georgia. A few pot strings had been left for several days because

Table 2

Species proportion (no. of crabs and percentage) and discard rates for crabs caught during the pot trials around South Georgia during the period March 2000 to April 2001.

	Number kept	Number discarded	% total crab catch by number	% total crab catch by weight	Discard rate
Paralomis formosa	22,803	300,660	70.1%	63.1%	93%
Paralomis spinosissima	3576	121,580	27.1%	35.4%	97%
Paralomis anamerae	0	12,370	2.7%	1.4%	100%
Neolithodes diomedeae	0		<0.1%	<0.1%	
Lithodes murrayi	0		<0.1%	<0.1%	

Table 3

The results of fitting generalized linear models on the probability of encountering crabs, and the catch rate of crabs (numbers per pot) for nonzero catches. ANOVA results: the significance of adding each parameter to the general linear model is presented. For the binomial model of the probability of encounter, a chi-squared significance test was used; for the Gaussian model of ln(CPUE) an F test was used. Coefficients $p_1..p_4$ are given with standard error in parentheses. For those models including "area" the standard case was for East South Georgia (EG), and the parameters for North South Georgia and Shag Rocks (NG, SR) are given. Analyses were performed with Splus statistical software. Final models were constructed by using only the significant parameters (italicized in this table). n = number of crabs in sample. Poly (1), Poly (2), and Poly (3) are the coefficients of each of the three orders in a 3rd order polynomial.

Parameter	Probability of encountering *P. formosa*	Ln(CPUE) for nonzero catches of *P. formosa*	Probability of encountering *P. spinosissima*	Ln(CPUE) for nonzero catches of *P. spinosissima*
ANOVA results				
n	101	91	101	82
Depth (m)	*<0.001*	*<0.001*	*<0.001*	*<0.001*
Area	>0.05	>0.05	>0.05	*<0.01*
Vessel	>0.05	>0.05	>0.05	>0.05
Soak time (h)	>0.05	*<0.05*	>0.05	*<0.01*
Coefficients $p_1.p_4$				
n	101	91	101	82
Intercept	–2.2358 (1.4373)	1.7229 (0.4301)	8.5065 (1.5822)	3.217 (0.4877)
Depth (m)	0.0098 (0.0035)	Poly(1): 4.6387 (5.3605) Poly(2): –8.4647 (6.2257) Poly(3): –1.3614 (4.4808)	–0.0106 (0.0022)	–0.0055 (0.0008)
Area				NG: 1.1304 (0.3241) SR: 1.2771 (0.2875)
Soak time (h)		0.0447 (0.0221)		0.0638 (0.0191)

of bad weather, and to eliminate these the maximum soak time was limited to 39 hours. The mid-depth of the set (average of the depth at the start and end of the set) was used to indicate setting depth, and the analysis was restricted to sets whose depth range was less than 200 m. The data from 45 sets (19% of total) were omitted from analyses because they did not meet these criteria for area, depth, or soak time.

For the binomial encounter models, the only significant factor was depth (Table 3). For the Gaussian catch per pot model, depth, and soak time were significant for both species and area was significant for *P. spinosissima*. However, the depth effects were opposite for the two species, so that *P. spinosissima* decreased in abundance with depth and *P. formosa* increased in abundance with depth, at least up to about 1000 m depth (Fig. 3). There were insufficient data from the cruises in 2001 to establish the effect of depths shallower than 300 m and deeper than 1100 m, although the limited sampling at depths greater than 1200 m in year 2000 (Fig. 1) suggests that catch rates of *P. formosa* would continue to decline at these depths, as suggested by the generalized linear models in Figure 3.

The sex ratio of *P. formosa* was skewed towards males in shallow water (<800 m) and females in deep water (Fig. 4). The mean size of *P. formosa* of both sexes also decreased significantly with an increase in depth (Fig. 5). Although catch rates in numbers were usually much higher in deeper water, smaller crabs of no commercial value often dominated catches. Only about 38% of *P. spinosissima* sampled between 200 and 400 m were males, whereas this proportion increased to about 76% in depths of 600 to 800 m (Fig. 4). The mean carapace width of males remained relatively constant between 200 to 800 m, but female *P. spinosissima* decreased in size with an increase in depth (Fig. 5).

Size frequencies

Males achieved larger sizes than females in all three species (Fig. 6). Only 5.7% of the sampled *P. spinosissima* individuals were of legal size (carapace width greater than 102 mm), of which only 6% were females. A difference was also noted in the percentage of legal-size *P. spinosissima* for the different areas: 10% at South Georgia and only 3.8% at Shag Rocks. For *P. formosa* only 11.6% (n=1012) were larger than the minimum legal size of 90 mm. Of these legal crabs only 6% (n=63) were females, indicating that few females would be processed if carapace width was the only criterion used to select crabs that could be taken legally. No obvious difference was noted in the percentage of legal-size crabs caught in the two main fishing areas.

Although a legal-size limit is not specified for *P. anamerae* (sizes ranged from 39 to 96 mm), only two crabs (0.2% of sample) were larger than the legal limit for *P. formosa* (90 mm). A peak in the length distribution of this species occurred between 55 and 57 mm, and few crabs were larger than 77 mm.

Differences in the size-frequency distribution of the sexes was more pronounced for *P. formosa* than for the other two species; females peaked at 65–72 mm and males peaked at between 85 and 90 mm carapace width (Fig. 6). For *P. spinosissima* female size distribution peaked between 78 and 82 mm and males peaked at 87 to 92 mm carapace width (Fig. 6). Males and females of *P. anamerae* had a relatively even size distribution up to carapace widths of 65 mm. Most of the larger crabs were males; only 6.8% of individuals larger than 65 mm were females. Maximum widths recorded were 121 mm (*P. spinosissima*), 120 mm (*P. formosa*), and 91 mm (*P. anamerae*).

Size at maturity

There was no significant difference between female size at maturity at Shag Rocks and South Georgia for either species (t-tests on Sm_{50} estimated by fitting logistic models to the proportion mature at size, P>0.05). The close allometric relationship found between carapace width and length (Table 4) made it possible to alter between these two types of measurements (Table 5). Combining the two areas, female size at maturity was 55.1 mm carapace length (57.1 mm carapace width) for *P. formosa* and 61.2 mm carapace length (67.7 mm carapace width) for *P. spinosissima* (Fig. 7). These sizes are very similar to the 61.7 mm

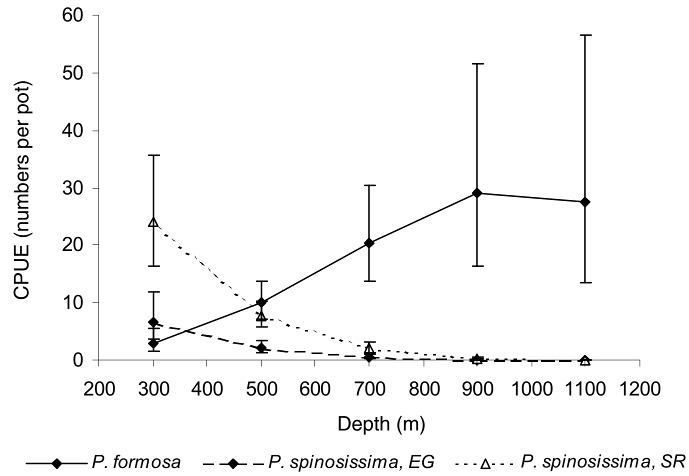

Figure 3

General-linear-model–predicted CPUE (numbers per pot) for the two species (*Paralomis formosa* and *P. anamerae*) at different depths standardized for a soak time of 18 h (the average used in the study). For *P. spinosissima* predictions at East South Georgia and Shag Rocks are presented separately (EG, SR, respectively).

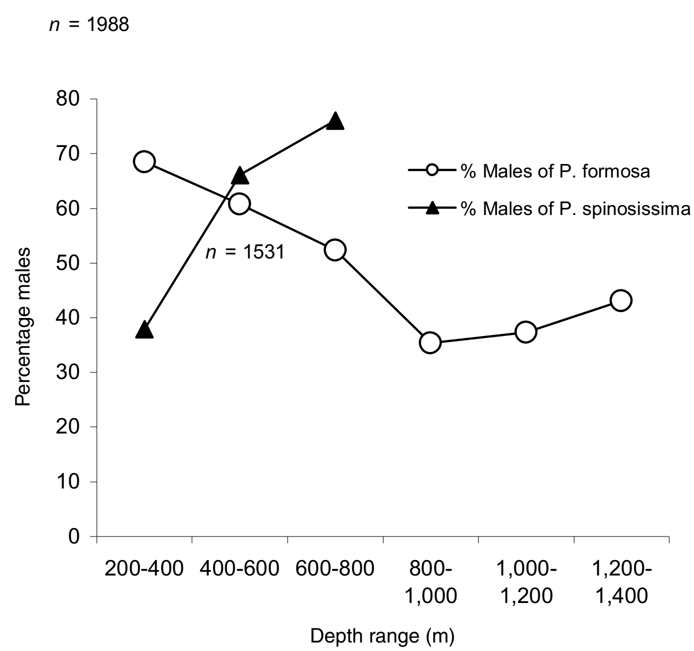

Figure 4

The percentage of males of *Paralomis formosa* and *P. spinosissima* found at different depth ranges during random sampling of the crab bycatch; all data from cruises G1 (*Argos Georgia* cruise 1), G2 (*Argos Georgia* cruise 2), and H (*Argos Helena* cruise) were used.

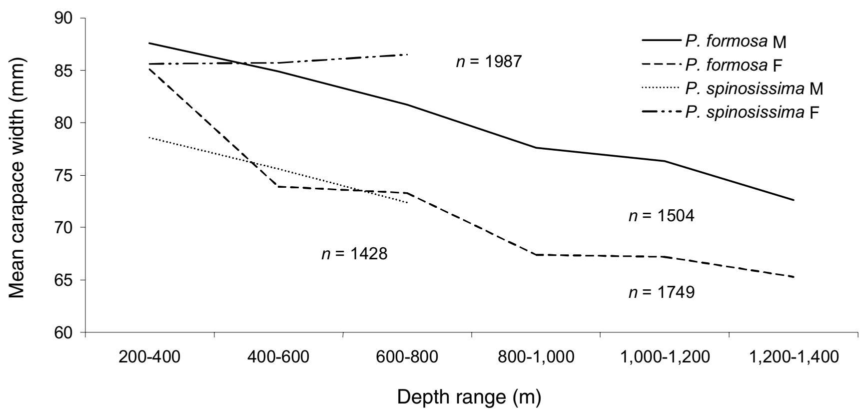

Figure 5

Mean carapace width of the males (M) and females (F) of *P. formosa* and *P. spinosissima* found at different depth distributions.

Table 4

Parameters of the regression *carapace width* = *carapace length* × slope + intercept (all ages and sexes combined). *n* = number of crabs in sample.

Species	Intercept	Slope	Correlation coefficient	*n*
P. spinosissima	6.457	0.994	0.977	367
P. formosa	1.976	1.032	0.969	351
P. anamerae	5.700	0.917	0.979	28

Table 5

The size at maturity (Sm_{50}) for males and females of both *Paralomis* species. The standard errors (SE) for male carapace lengths are shown in parentheses.

	P. spinosissima		*P. formosa*	
	Carapace length (mm)	Carapace width (mm)	Carapace length (mm)	Carapace width (mm)
Males	67.3 (0.10)	73.4	64.0 (0.16)	68.0
Females	61.2	67.7	55.1	57.1

carapace length reported by Otto and MacIntosh (1996) for *P. spinosissima* from Shag Rocks and South Georgia.

Unfortunately, owing to limited sampling of male crabs around South Georgia, estimates of male sexual maturity were only available for Shag Rocks. Too few samples of *P. anamerae* were available for determination of the onset of female or male maturity in either area. Male size at maturity (Sm_{50}) was determined at a carapace length of 67.3 mm (SD=2.3 mm derived from bootstrap resampling with replacement) for *P. spinosissima* and at 64.0 mm (SD= 3.6 mm) for *P. formosa* (Fig. 8).

Crab survival rate

Approximately 5000 crabs were examined for carapace damage on the cruises in 2001. The results (Table 6) indicated that the level of visible damage to these crabs prior to discarding was very low (2% of crabs of all species). The vitality of these crabs was also assessed (according to the index in Table 1). Most crabs were lively on arrival on deck and prior to discard (Table 6). Differences were, however, noted in both carapace condition and the vitality of crabs between the two fishing vessels. Pairwise χ^2 comparisons

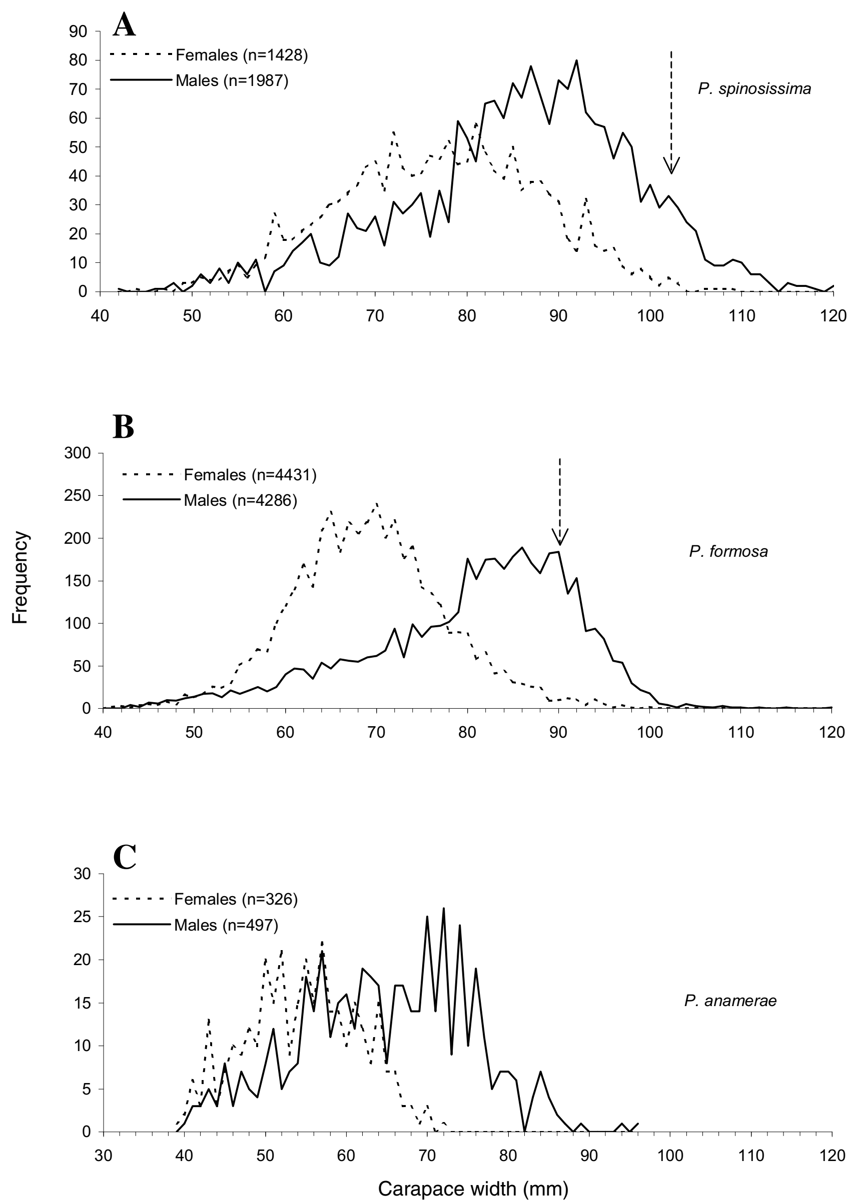

Figure 6

Carapace-width frequency distribution for the three *Paralomis* species (mm). (**A**) *P. spinosissima*, (**B**) *P. formosa*, (**C**) *P. anamerae*. The minimum legal size (102 mm for *P. spinosissima* and 90 mm for *P. formosa*) is indicated with a vertical line and arrow.

between the vitality indices of *P. formosa* and *P. spinosissima* clearly showed that both species displayed significantly lower vitality on the *Argos Helena* than on the *Argos Georgia* (Table 7).

The processing environment of the two vessels may explain these differences. On the *Argos Helena* crabs were likely to sustain more damage as pots were emptied down a vertical chute before entering the processing area below deck. On the *Argos Georgia* pots were emptied on a horizontal conveyer belt leading to the factory. Interestingly, there was no significant difference between the vitality displayed by *P. anamerae* between the two vessels, although this may be a result of the smaller sample size for this species. For the *Argos Georgia*, the vitality of *P. anamerae* was significantly lower than for either *P. formosa* or *P. spinosissima*.

The results of the three survival experiments are shown in Table 8. Experiment 1 re-immersed only lively crabs and included a control set of animals retained on deck in a large tank for the same length of time as the re-im-

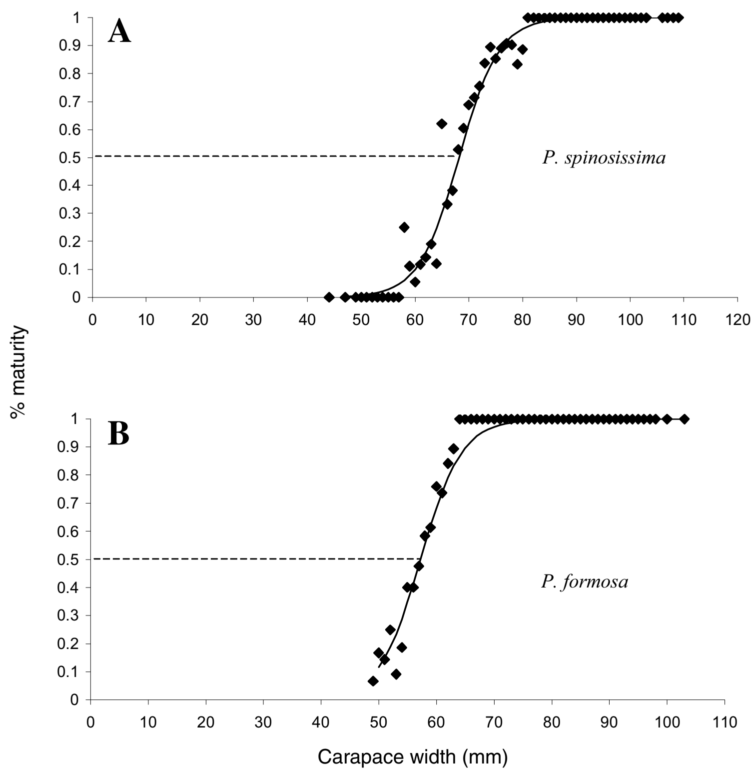

Figure 7

Size at female maturity for (**A**) *P. spinosissima* and (**B**) *P. formosa*. The size at maturity L($_{50}$) carapace width was 67.7 mm and 57.1 mm for the two species, respectively.

Table 6

The number and percentages of crabs of the different species assessed for carapace condition and vitality prior to being discarded during 2001 (G2=*Argos Georgia* cruise no. 2, H=*Argos Helena*).

	Carapace condition					Vitality index						
	Damaged		Undamaged			Lively		Limp		Dead		
Species and cruise	No.	%	No.	%	Total	No.	%	No.	%	No.	%	Total
Paralomis formosa												
G2	48	1.9	2431	98.1	2479	2294	98.9	26	1.1	0	0.0	2320
H	23	2.7	814	97.3	837	745	97.4	19	2.5	1	0.1	765
Total	71	2%	3245	98%	3316	3039	98%	45	1%	1	0%	3085
Paralomis spinosissima												
G2	17	1.5	1143	98.5	1160	1122	98.4	17	1.5	1	0.1	1140
H	18	2.0	874	98.0	892	767	94.8	39	4.8	3	0.4	809
Total	35	2%	2017	98%	2052	1889	97%	56	3%	4	0.2%	1949
Paralomis anamerae												
G2	0	0.0	45	100.0	45	31	86.1	5	13.9	0	0	36
H	2	2.7	72	97.3	74	62	92.5	5	7.5	0	0	67
Total	2	2%	117	98%	119	93	90%	10	10%	0	0%	103

Table 7

Results of pairwise χ^2 comparisons of the vitality of crabs on first being caught by different cruises (from Table 6). G2 = *Argos Georgia* cruise no. 2 and H = *Argos Helena*, F = *P. formosa*, S = *P. spinosissima*, A = *P. anamerae*. χ^2 values are given, together with significance, df = 2 for all except italicized results, when df was 1 because of the absence of any dead crabs in the comparisons. NS = not significant.

	G2-F	H-F	G2-S	H-S	G2-A
G2-F					
H-F	10.49, $P<0.01$				
G2-S	2.9, NS	—			
H-S	—	6.99, $P<.05$	20.7, $P<0.001$		
G2-A	*35.2, P<0.001*	—	29.2, $P<0.001$	—	
H-A	—	5.5, NS	—	1.14, NS	*0.49, NS*

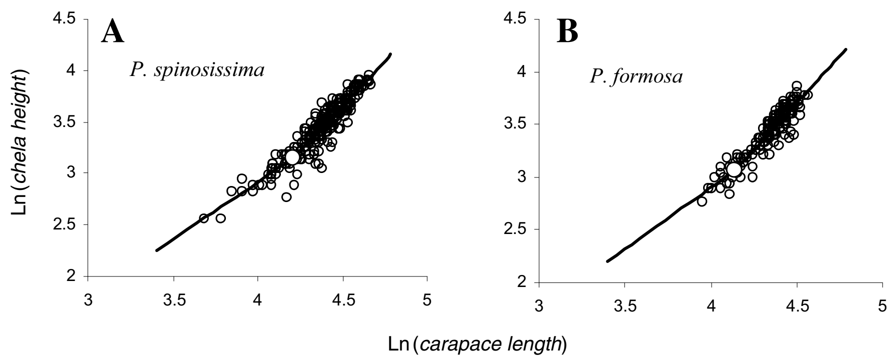

Figure 8

Chela allometry in male (**A**) *P. spinosissima* and (**B**) *P. formosa* sampled at Shag Rocks in 2001. The intersections of fitted curves were used to determine size at maturity.

mersion process. Out of the 35 lively control animals a similar proportion died during the experiment as in the re-immersed group (8%), but a lower proportion of the control group were lively following the experiment (63%). The lower proportion of lively animals in the control group may have been a result of interruptions in the supply of oxygenated water and the continual disturbance on deck due to the ship's motion. Consequently, controls were not performed in experiments 2 and 3.

Experiments 2 and 3 took a random sample of lively and limp crabs and subjected them to re-immersion. The proportions of lively crabs at the beginning of the re-immersion experiments were lower than the proportions estimated for the population as a whole in Table 6, with the exception of *P. spinosissima* in experiment 2. However, sample sizes were much smaller in the experiments and the crabs were subject to greater handling times than those assessed in Table 6; therefore the results presented in Table 6 are more likely to be representative of the condition of discarded crabs than results presented in Table 8.

In experiment 1 on cruise G1, no limp animals were subjected to re-immersion. In comparing the results of immersing lively animals, there was no significant difference between the results for experiment 1 and 2 (cruises G1 and G2 on the *Argos Georgia*) for either *P. formosa* or *P. spinosissima*. Combining the results of the experiments for G1 and G2, there was a significantly lower vitality after re-immersion for both species on the *Argos Helena* compared with the *Argos Georgia* (Table 7). On the *Argos Georgia* there was no significant difference in vitality after re-immersion between *P. formosa* and *P. spinosissima*, whereas on the *Argos Helena* vitality for *P. spinosissima* was significantly lower than vitality for *P. formosa*. These results are similar to the initial assessment of vitality prior to re-immersion (Table 6), where significantly fewer *P. spinosissima* were lively in comparison with *P. formosa* on the *Argos Helena*, but there was no difference between the two species on the *Argos Georgia*.

A single re-immersion experiment performed on 15 *P. anamerae* crabs (11 were "lively" and 4 were "limp"), on the *Argos Helena* in April 2001, resulted in a mortality rate of 73%. Only 27% of the crabs that were "lively" before re-immersion were still "lively" after the rehaul. Although more data need to be collected on the survival rate of this species, this high mortality rate, together with the higher incidence of individuals of *P. anamerae* found to be "limp" during vitality assessments (Table 8; 10% compared to 3% of *P. spinosissima* and 1% of *P. formosa*), seems to indicate that this bycatch species might be particularly vulnerable to onboard handling and discarding.

Crabs that were physically damaged (i.e. had missing legs or cracked carapaces) before being subjected to re-immersion were less likely to survive than undamaged crabs. Of the 19 damaged *P. spinosissima* (13 of these were "lively" and 6 were "limp"), 58% did not survive re-immersion and only 32% of these were still "lively." The effect of damage

Table 8

Results of survival-rate experiments. For each experiment the number of re-immersions is given, together with the total number of crabs in lively and limp condition that were re-immersed and their condition on rehauling the crab pots after re-immersion.

	Number of re-immersions	Number of crabs	Initial condition	Condition after re-immersion		
P. formosa						
Experiment 1				Lively	Limp	Dead
(cruise G1)	2	30	Lively	20	6	4
		0	Limp	0	0	0
Experiment 2				Lively	Limp	Dead
(cruise G2)	6	98 (93%)	Lively	81	11	6
		7	Limp	4	1	2
Experiment 3				Lively	Limp	Dead
(cruise H)	3	49 (91%)	Lively	27	21	1
		5	Limp	0	2	3
P. spinosissima						
Experiment 1				Lively	Limp	Dead
(cruise G1)	2	42	Lively	35	3	4
		0	Limp	0	0	0
Experiment 2				Lively	Limp	Dead
(cruise G2)	6	60 (100%)	Lively	55	5	0
			0Limp	0	0	0
Experiment 3				Lively	Limp	Dead
(cruise H)	10	167 (88%)	Lively	71	67	29
		23	Limp	1	6	16

Table 9

Estimation of total survival rate for *P. formosa* and *P. spinosissima* based on results from re-immersion experiments. Because there was no significant difference between the responses of lively animals between experiments 1 and 2, these data were pooled to give a single estimate for the *Argos Georgia.* On the *Argos Georgia* no limp *P. spinosissima* were encountered during the re-immersion experiments; therefore *p(limp,lively)* was set equal to *p(limp,lively)* from experiment 3. Three calculations are presented: the first according to the text description without the rehaul correction, the second including this rehaul, and the third where the original proportions of lively animals $p(lively_o)$ were used from the experimental data in Table 8 rather than the data from the larger sample in Table 6.

	$p(lively_o)$ from Table 6, without rehaul correction	$p(lively_o)$ from Table 6, with rehaul correction	$p(lively_o)$ from Table 8, without rehaul correction	$p(lively_o)$ from Table 8, with rehaul correction
P. formosa				
Argos Georgia	78.7%	79.8%	77.5%	83.7%
Argos Helena	53.7%	56.2%	50.0%	58.4%
P. spinosissima				
Argos Georgia	86.9%	88.5%	88.2%	88.2%
Argos Helena	40.5%	45.4%	37.9%	48.5%

was not so pronounced for *P. formosa*, although of the 12 crabs that were damaged prior to re-immersion (10 were "lively" and 2 were "limp"), only 58% were "lively" upon recovery. The mortality rate of 17% for damaged specimens was more than double the 8% overall mortality found during re-immersion experiments for this species. Most of the dead crabs examined after re-immersion had been attacked by isopods and amphipods and only the shell remained. It is possible that these organisms were in fact responsible for killing the crabs, particularly where damage to the shell allowed access to the softer tissues of the crab.

Calculations of survival rate are given in Table 9 both with and without the re-haul correction. As discussed above, the more accurate estimate of $lively_o$ is probably from Table 6 because of the additional handling stress associated with the experiment. However, Table 9 also presents results obtained from data in Table 8 to estimate this probability. The results suggest that the survival rate of discarded crabs would be high on the *Argos Georgia*, between 77% and 88% for both *P. formosa* and *P. spinosissima* (77–84% for the former, 87–88% for the latter). On the *Argos Helena* discard survival rate was much lower, 50–58% for *P. formosa* and 38–49% for *P. spinosissima*.

Discussion

Crab species

Three previously unreported or rarely reported crab species, *Paralomis anamerae*, *Neolithodes diomedeae* (Benedict, 1894), and *Lithodes murrayi* (Henderson, 1888), were found in our study. The most abundant of these was *P. anamerae*, found at mid-range depths. The only other record of *P. anamerae* is the original description of the species based on four specimens obtained from the continental shelf of Argentina at depths of 132–135 m (Macpherson, 1988). The specimens obtained from South Georgia, at depths of 530–1210 m, therefore represent a considerable southerly extension in the reported geographic distribution of this species, as well as a notable increase in its bathymetric range. López Abellán and Balguerias (1994) reported both *P. spinosissima* and *P. formosa* from a 1986–87 trawl survey on the shelf, but no other species of crabs.

A certain amount of confusion surrounds the identification of *Paralomis* species around South Georgia. *Paralomis aculeata* is found in the CCAMLR database, but almost certainly because of its inclusion in the FAO species identification guide for the Southern Ocean (Arnaud 1985, in Fischer and Hureau, 1985), attributed to Henderson (1888). This species is not mentioned in Macpherson (1988), even as a junior synonym. Conversely, none of the *Paralomis* species identified in the present paper appear in Fischer and Hureau (1985). It is not clear, therefore, which species of *Paralomis* CCAMLR scientific observers have been identifying as *P. aculeata.* Twenty-two specimens of *N. diomedeae* were collected at depths ranging from 420 to 1294 m. This species has previously been recorded from South Georgia (Macpherson, 1988).

Sixteen *L. murrayi* specimens were found on southeast Shag Rocks and west South Georgia, approximately 60 nmi apart, at depths of between 450 m and 605 m. *Lithodes. murrayi* is mainly reported from the southern Indian Ocean around Prince Edward, Crozet, and Possession Islands, as well as Macquarie Islands, Mozambique Channel, and southern New Zealand at depths of 35–200 m (Hale, 1941; Yaldwyn and Dawson, 1970; Arnauld, 1976; Arnauld and Do-Chi, 1977; Kensley, 1977). However, it has been reported in small numbers in CCAMLR statistical catch records from 1993–94, 1997–98 and 1998–99 and by CCAMLR observers (CCAMLR[1]). We have confirmed the identification and the extension of the range of this species to South Georgia. Klages et al. (1995) reported on the distribution of *L. murrayi* off Peter Island, close to the Antarctic continent between 180 and 260 m depth, and a circum-Antarctic distribution has been claimed for the species (Macpherson, 1988). The present study therefore represents the greatest depth recorded for it.

Distribution

Catch rates of *P. spinosissima* encountered in our study were lower than experienced in the September 1995–January 1996 crab fishery by the FV *American Champion.* Watters (1997) reported that average catch rates of legal-size male *P. spinosissima* were between 14.2 and 28.4 males per pot in the Shag Rocks and northwest South Georgia areas (53.5–54°S, 37–40°W). Although the toothfish pots operated by the *Argos Georgia* from March and May 2000 produced catch rates between 0.5 and 4 crabs/pot, the proportion of legal-size males was very low (3%), resulting in legal (retained) crab catch rates of less than 1/pot (note that the retention rates given in Table 2 are lower than those calculated from the length-frequency sampling, Fig. 6). Retention rates for the 1992 FV *Pro Surveyor* cruise (July–August 1992) were 36% (Otto and MacIntosh[5]). The retention rates on the Argos Helena's experimental crab fishery in 1999 were much lower than this (8% and 14% for *P. spinosissima* and *P. formosa* respectively) (Purves[6]). The low retention rate is most likely to be a consequence of the pot design used on vessels G and H, where the collapsible funnel entrances might have restricted the catch to smaller size crabs.

A further feature of the *American Champion* crab fishery was the restriction of fising effort to depths of less than 500 m. The present trials were targeted at toothfish rather than crabs and were conducted according to an experimental plan that distributed fishing effort over time, area, and the full depth range of longlines used in the main toothfish fishery. Accordingly, fishing occurred over a much wider depth range than was used by the previous crab fisheries. Our very high catch rates of *P. formosa* in deep water were therefore not reported by Watters (1997). However, even our catch rates did not result in high numbers of retained legal-size crabs on the *Argos Georgia* because the proportion legally permitted was only 10.5%. Interestingly, even in shallow water (400–800 m) *P. formosa* appeared to be more common than *P. spinosissima*. Only in waters less than 400 m deep did *P. spinosissima* become the dominant species. This finding confirms the results of Watters (1997) who found that *P. spinosissima* catch rates declined at depths deeper than 300 m. Catch rates of *P. spinosissima* were low even in these depths (5 crabs/pot). Only 9 of the total of 110 sets of the Argos Georgia were conducted in depths shallower than 400 m because the main target of the fishery was toothfish.

The differences found in our study in the distribution by depth of the different sexes and sizes of crabs might

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[5] Otto, R. S., and R. A. MacIntosh. 1992. A preliminary report on research conducted during experimental crab fishing in the Antarctic during 1992 (CCAMLR Area 48). Document WG-FSA-92/29, 20 p. CCAMLR, P.O. Box 213, North Hobart, Tasmania, Australia.

[6] Purves, M. G. 1999. Report of the South African designated CCAMLR observer on board the British registered longliner "Argos Helena" in Statistical Subarea 48.3, 31 August to 23 September 1999, 13 p. CCAMLR, P.O. Box 213, North Hobart, Tasmania, Australia.

indicate that recruitment of *P. formosa* takes place in deeper water. This conclusion is based on a decrease in size with increasing depths, the higher proportion of females encountered in deeper water, and increasing crab densities at depth. For *P. spinosissima* this trend was not so pronounced, although crabs of this species were also generally of a smaller size in deeper water. However, contrary to the case with *P. formosa*, females were more prevalent in shallower water. Very few females of *P. spinosissima* were encountered in deep water. These rather unusual findings might suggest ecological partitioning of the benthic habitat, and warrant further investigation.

Another unexpected result of our work was the discovery of a third species of *Paralomis, P. anamerae*, at intermediate depths. This species was apparently not present in the *American Champion* or *Pro Surveyor* catches, presumably again because of the depth restriction in these cruises.

Maturity

For *P. spinosissima* our estimate of 67.3 mm carapace length at 50% male maturity is similar to the 66.4 mm carapace length found by Otto and MacIntosh (1996) at Shag Rocks for this species. Unfortunately, as can be seen from Figure 8, relatively few small *P. formosa* males were encountered and size at maturity for this species (64.0 mm carapace length) is likely to have been poorly estimated in our analysis. However, if it is assumed that male *P. formosa* mature at the same size in relation to female *P. formosa*, as in the case of *P. spinosissima*, the female maturity data presented in Table 5 would suggest that male *P. formosa* would mature at 60.4 mm carapace length (64.3 mm carapace width) rather than the 64.0 mm shown in Figure 8.

Watters and Hobday (1998) have also examined size at maturity for *P. spinosissima* and *P. formosa*, although their samples were taken from South Georgia rather than Shag Rocks. Using a method based on finding the maximum of the second derivative of smoothing spline fits to chela height and carapace width data, they found that size at morphometric maturity for *P. spinosissima* was 73 mm carapace length. This size is similar to that which Otto and Macintosh (1996) obtained for *P. spinosissima* at South Georgia using the same technique as we did. Watters and Hobday's (1998) results for *P. formosa* are, however, for a higher size at maturity (80 mm carapace length) than that for *P. spinosissima*, which would seem to be at variance with our results and the apparent relative sizes of the two species (see Fig. 6 and CCAMLR[2]).

The minimum size limits for crabs at South Georgia were set by CCAMLR in 1992 but, in common with many crab stocks (Schmidt and Pengilly, 1993), these measures were not accompanied by rigorous analysis of the effectiveness of these measures in meeting management objectives. For *P. spinosissima*, Otto and Macintosh's[5] male maturity results for *P. spinosissima* were used, and allowing males at least one opportunity to breed and an assumed growth per moult of 15%, minimum size limits were calculated as 94 mm and 84 mm carapace width at South Georgia and Shag Rocks, respectively (CCAMLR[2]). These results are very similar to our own, but the CCAMLR limit of 102 mm width was based on the then-existing processing requirements rather than on these calculations. Our results suggest, allowing at least one opportunity to breed, that the limit should be 83 mm for *P. spinosissima*. For *P. formosa*, taking our more conservative figure of 64.0 mm carapace length at 50% maturity, the catch size limit should be set at 78 mm carapace width (the less conservative figure, 60.4 mm carapace length, would suggest a size limit of 74 mm carapace width).

Hoggarth (1991) reviewed minimum size limits for a number of stocks of lithodid crabs and found that minimum legal sizes were about 70% of the maximum size for males, which would suggest 85 mm and 84 mm carapace width for *P. spinosissima* and *P. formosa,* respectively. It should, however, also be taken into account that these estimates were probably biased because of the greater sampling effort made at Shag Rocks. Note that the length-frequency distribution for *P. formosa* in Figure 6B appears to indicate a lower maximum size for males of this species than for males of *P. spinosissima*. However, the largest *P. formosa* actually encountered was 120 mm carapace width. Furthermore, Figure 6B seems to be truncated at the larger sizes, suggesting perhaps that a proportion of the large adult population was not encountered during fishing.

Discard mortality

Our results demonstrate that, although a high proportion of crabs is likely to survive the physical strain of being hauled to the surface from potentially great depths, some undersize individuals and nontarget females can be expected to die following discarding. The most significant factor affecting discard survivorship was handling on board the vessel. On the *Argos Georgia,* where crabs were unloaded from pots and sorted on a conveyor belt, survivorships were high, up to 88%, and *P. spinosissima* survived better than *P. formosa.* By contrast, on the *Argos Helena*, where crabs went down a chute prior to processing, survival rate was between 38% and 58% and *P. formosa* survived considerably better than *P. spinosissima*. In general, *P. anamerae* was the most vulnerable species, followed by *P. spinosissima*, and the least vulnerable—*P. formosa*.

Studies of the discard mortality of lithodid crabs in North Pacific fisheries have produced a variety of results. Stevens (1990) found that crabs discarded from commercial sole trawls suffered high mortalities (47.3%), but Byersdorfer and Watson[7] and Zhou and Shirley (1995) both reported relatively low mortalities (<2%) resulting from handling when fishing with pots. Our results support these previous studies and extend them to the Antarctic, clearly indicating that where handling on a pot vessel is reduced, mortalities are relatively low (<15% mortality). When crabs are

[7] Byersdorfer, S., and L. J. Watson. 1992. A summary of biological data collected during the 1991 Bristol Bay red king crab tagging study. Technical Fishery Report 92-14, 30 p. Alaska Department of Fish and Game, Division of Commercial Fisheries, P.O. Box 25526, Juneau, AK 99802-5526.

handled on a pot vessel, as they would be on a trawl vessel, mortalities are higher.

Other factors, which could not be tested in the re-immersion experiment, may also affect the rate of crab survival. We re-immersed crabs in pots, whereas normally they would be simply dropped into the sea and would be subject to predation from birds and fish before they reached the bottom. The effect of discarding crabs away from their original habitat is unknown, but our results demonstrate a clear depth separation between the two species; therefore one would expect at least an energetic cost if crabs have to relocate. The crabs subjected to re-immersion experiments were sampled immediately before being discarded. They might suffer further damage through the actual discard process; for instance Stevens (1990) speculated that, while traveling through offal chutes, they could become entangled in machinery or suffer further damage upon impact with the surface of the water. Ideally crabs should have been sampled after being through the full discarding procedure, but this was not practical. Finally, eggs often became dislodged during handling and this loss possibly impacted reproductive success.

Zhou and Shirley (1995) presented results that indicate that there are no long-term effects of handling on crab survival, feeding rate, or crab condition; therefore we might reasonably expect that the survival rates seen in our experiments would also be the relevant long-term survival rates. However, even with relatively low discard mortality, the impacts of repeated catching and discarding of individuals will have a cumulative effect on crab populations. Both retained and discarded bycatch should therefore continue to be reported and be incorporated into crab population models. The presence of such a large discarded bycatch might provide the opportunity for the retention (and removal from the population) of parasitized crabs, as suggested by Basson (1994).

Crabs are an inconvenience in a fishery targeting toothfish. *In situ* observations made during the AUDOS experiments on the UK's January 2000 survey confirm that toothfish seek to avoid direct contact with crabs (Yau et al., 2002), although crabs do form a component of their food (Pilling et al., 2001). An inverse relationship was found in the present study between toothfish numbers in pots and crab numbers in pots, suggesting toothfish avoid pots with large crab populations (Fig. 9). Therefore, conducting the toothfish pot fishery in an area of low crab abundance is sensible, and our data do suggest that, at intermediate depths, the crab catch should be low and composed primarily of large *P. formosa*. Avoidance of areas of high crab bycatch will also reduce the mortality associated with discarding female and undersize male crabs. These discard levels are very high (>93%)—considerably higher than those in the Bering Sea (85%: Stevens, 1996). Such high discard levels could be reduced further by developing new pot designs to limit crab catches to larger, legal-size animals—for instance designs with excluder panels (Stevens, 1996)—or perhaps by reducing the minimum size limit.

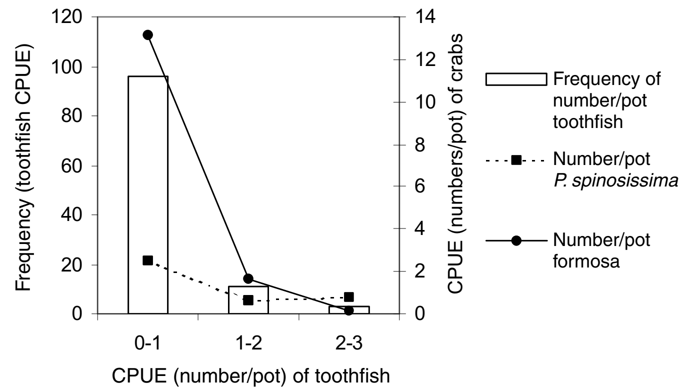

Figure 9

The frequency distribution of the number of toothfish caught per pot compared with the CPUE's of *Paralomis spinosissima* and *P. formosa* (numbers/pot) and of toothfish (*Dissostichus eleginoides*) catches (numbers/pot), as found during the first cruise of the *Argos Georgia* during March to May 2000.

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