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HARDENING OF RED KING CRAB *PARALITHODES CAMTSCHATICUS* (TILESIUS, 1815) SHELLS AFTER MOLTING

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ABSTRACT

Shell hardness was measured with a durometer for female red king crabs, *Paralithodes camtschaticus*, held in the laboratory over variable periods up to 107 days after molting. The data were fit best by a hyperbolic equation, with parameters $\beta_0 = 0.216$ and $\beta_1 = 0.019$ ($R^2 = 0.976$, $n = 199$), and an asymptotic value of 50.7 durometer units (DU). The time required to reach 90% of complete shell hardness ($H_{90} = 45.6$ DU) was calculated to be 74.2 days. Molting dates for all crabs were hindcast using the last measurement that was less than H_{90} and were within 2.5 ± 6.4 days (mean ± SE, $n = 34$) of the actual molting date.

KEY WORDS: Anomura, molting, *Paralithodes camtschaticus*, red king crab, shell hardness

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INTRODUCTION

Hardness or condition of the exoskeleton is a useful indicator of molt stage and suitability for harvest in fisheries for large decapods such as crabs or lobsters. After molting, it may take several months for the shell to reach its maximum intermolt hardness, during which the shell is weak and vulnerable to damage. Recently molted crabs, indicated by soft shells, have undergone a process of muscle atrophy and water absorption and as a result have reduced meat yield (Dufour et al., 1997; Foyle et al., 1989) and may be more subject to either cannibalism in pots, or damage on deck. Hard shelled crustaceans can withstand the rigors of a fishery, including capture, processing, and shipping, better than new shelled animals. Many crabs and lobsters are not retained after capture because they are below legal size or belong to a non-targeted species, and such ''bycatch'' can suffer increased damage when discarded if their shells are too soft. Hard shells also indicate that meat yield has reached a level sufficient for commercial processing. Management of eastern Canada snow crab *Chionoecetes opilio* (Fabricius, 1788), requires crabs to be in a hardshell condition, such that meat yields are about 20% of total weight; this requires that the fishery remain closed for at least 2 months after molting (Bailey and Elner, 1989). Shell hardness is also an important criterion for determining the functional maturity of crabs, since only hardshell male Tanner crabs *Chionoecetes bairdi* Rathbun, 1924 are found in mating pairs (Paul et al., 1995; Stevens et al., 1993). Problems arise when trying to define a ''hard shell''; such definitions are generally subjective, and may require pressing, squeezing, bending or breaking the shell. Setting fishing seasons with fixed opening dates is also problematic because the timing of molting may vary annually, and may be delayed by several months, or even skipped in cold years (Otto et al., 1990). Molt stages can be determined reliably by examining the morphology of setae attached to the mouthparts under a microscope (Moriyasu and Mallet, 1986; O'Halloran and O'Dor, 1988). However, this cannot be done in the field, and collecting, archiving, and processing hundreds or thousands of such specimens is usually not possible during survey cruises.

One way to determine shell hardness objectively is by use of a hand-held gauge (the durometer). These have been tested for their utility in determining shell hardness of snow crabs (Dufour et al., 1997; Foyle et al., 1989; Hebert et al., 2002) and Dungeness crabs *Cancer magister* Dana, 1852 (Hicks and Johnson, 1999). Shell hardness in American lobsters *Homarus americanus* H. Milne Edwards, 1837 has been measured with an industrial instrument (the ''instron''), but this requires removing a piece of shell and compressing it until it fractures (Donahue et al., 1998).

Fisheries for red king crabs *Paralithodes camtschaticus* (Tilesius, 1815) and blue king crabs *P. platypus* (Brandt, 1850) in the US Eastern Bering Sea usually occur in the late autumn (October or November). This schedule allows crabs that have molted in the spring enough time to reach maximum hardness and meat fullness. Stock assessment surveys are conducted by the National Marine Fisheries Service (NMFS) in the summer, and usually encounter crabs that have recently molted (Rugolo et al., 2006). Exoskeleton condition of crabs is determined by biologists using a 5-point scale that rates shells on their hardness, degree of discoloration, epiphytes, spine sharpness, and bacterial degradation (Ernst et al., 2005; Fonseca et al., 2008; Nevissi et al., 1996). Such information can tentatively be used to estimate the timing of recent molting activity, but the precision of such estimates is poor due to the subjective nature of the data and differences in experience level of the observer. Knowing the approximate time of molting can be useful for determining the effect of climate variability on reproductive activities. Furthermore, fishing seasons are often set to meet political or industry objectives, rather than

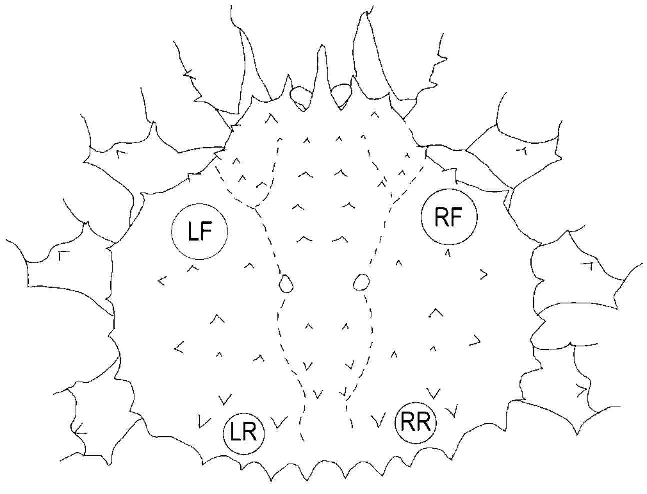

Fig. 1. Outline of king crab carapace showing regions (circles) where durometer readings were made. LF, left front; RF, right front; LR, left rear; RR, right rear.

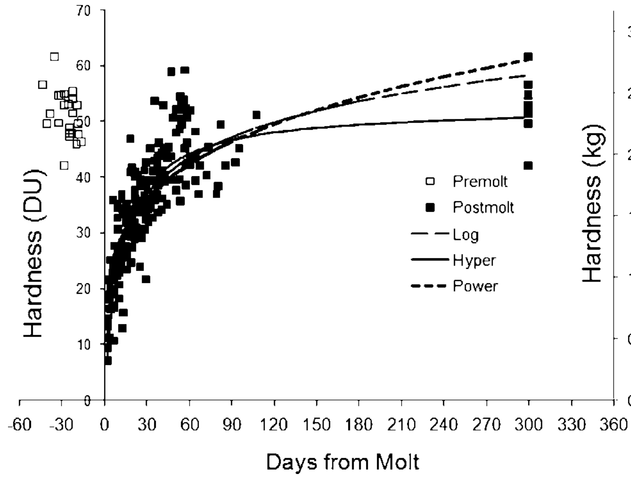

Fig. 2. Hardness of red king crab shells in durometer units (DU) or kg at different times before (□) and after (■) molting. Eleven measurements taken ≥28 days before molting were included at far right for calculation of regression equations. Regression using the hyperbolic model produced an asymptotic hardness value (50.7 DU), whereas the log and power models lack an asymptote, so were rejected.

being based on biological criteria. Therefore it is important to have an understanding of the time course needed for crab shells to reach a level of hardness that will withstand the rigors of fishing activities.

Shell hardness or condition is also an indicator of post-molt age. In crustaceans that undergo a terminal molt, such as crabs of the genus *Chionoecetes*, males may live many years after their molt to maturity. Estimates of post-molt age can be made using radiometric techniques by analyzing the decay of ^{228}Th to ^{228}Ra; maximum ages range from 4.9 years for *Chionoecetes bairdi* to 6.8 years for *Chionoecetes opilio* (Ernst et al., 2005; Nevissi et al., 1996). More recently, Fonseca et al. (2008) estimated maximum post-molt ages up to 7.7 years in *Chionoecetes opilio* using measurements of dactyl wear in tagged animals. These methods have not been applied to king crabs however, because they continue to molt throughout their lives.

This study was undertaken to determine the time required for hardening of red king crab shells. Although only males are captured in this fishery, females are often subject to handling and discarding. During the course of other research activities (Stevens and Swiney, 2007), we had the opportunity to measure shell hardness on 34 female red king crabs that molted in the laboratory.

Materials and Methods

A total of 34 adult female red king crabs were held in filtered running seawater at the Kodiak Fisheries Research Laboratory of the National Marine Fisheries Service (NMFS) until they molted in March-April of 2003, and for up to four months afterward. Shell hardness was measured using a durometer (Model CRB-01, Pacific Transducer Corp, Los Angeles, CA). This instrument was manufactured to encompass a range of hardness exhibited by shells of the Dungeness crab *Cancer magister* (Hicks and Johnson, 1999). It consisted of a circular gauge attached to a 100 mm steel neck, containing a rounded 3 mm indenter that protruded slightly from the neck. When the indenter is pressed against a surface, the gauge needle points to a number on the scale (from 0 to 100), and a moveable finger remains fixed at the highest reading after the pressure is relieved. The gauge was calibrated so that a reading of 100 was equal to 4.54 kg (10 lb) of force. Because of a linear relationship between readings and force, each durometer unit is equivalent to 1% of the maximum, or 0.0454 kg (0.1 lb). Several different locations were tested for hardness on the shell of the crabs including the inside of the largest (crusher) claw, and different locations on the carapace. Repeated use of the durometer at the same location on the same animals tends to cause weak spots in the exoskeleton (Foyle et al., 1989). Therefore, rather than using a single location, readings were taken at four different regions of the carapace, between the spines, including the left front (LF), right front (RF), left rear (LR), and right rear (RR) (Fig. 1). The durometer was pressed against the shell until the needle reading did not increase further, and the shell began to flex. Readings from all four locations on each crab were then averaged for each observation. Shell hardness was measured on each crab starting on the second day post-molt; crabs were then arbitrarily split into two groups, and subsequent measurements for each group were all taken weekly on the same day, either Tuesday or Thursday.

All crabs were measured from the right front eyesocket to the rear margin of the carapace (carapace length, CL) prior to molting. Eight crabs molted prior to the first day of hardness testing (11 February 2003), so premolt values were not obtained for them. Most (24) of the remaining crabs were tested on 11 February, and then weekly after molting, until the first week of May. Nonlinear regression was used to fit durometer readings to shell age (days since molting), using Systat 11 (SYSTAT Software Inc., Richmond, CA). Three models were tested including:

Logarithmic $Y = \beta_0 + \beta_1 * \ln(X)$
Hyperbolic $Y = X/(\beta_0 + \beta_1(X))$
Power $Y = \beta_0 X^{\beta 1}$

where X = days, and Y = hardness (in DU).

Results

A total of 188 postmolt measurements were obtained on 34 female red king crabs ranging from 114 to 160 mm postmolt CL (mean ± 1.0 SD; 130.7 ± 9.8 mm). Individual crabs were measured from 3 to 8 times, with an average of 5.6 measurements per crab. Mean sizes, dates of molting, and other ancillary data were reported separately (Stevens and Swiney, 2007) so are not repeated here. The average molt date was 3 March, and median was 7 March, 2003. Shell hardness averaged 15.4 durometer units (DU) (0.700 kg) at 4 days after molting, and increased rapidly to an asymptotic value of 51.0 DU (2.315 kg; Fig. 2). Few crabs were measured more than 70 days postmolt, but some (the early molters) were measured up to 107 days postmolt. Both the logarithmic and power regression lines increased continuously and did not provide an asymptote, so both were considered inappropriate. The best fit to postmolt data was obtained using the hyperbolic regression ($F = 3469$, $R^2 =$ 0.974 raw, 0.675 corrected, $n = 188$). Parameter estimates (mean ± SE) obtained by this method were $\beta_0 = 0.207 \pm 0.016$, and $\beta_1 = 0.019 \pm 0.001$, and were both significantly different from 0.

Premolt measurements were obtained over a period of 16 to 43 days (mean 27.0 ± 7.5) before molting and had a mean hardness of 51.1 ± 4.2 DU (2.319 ± 0.191 kg), but were not used in the initial regression estimation. They appear to demonstrate a decline in hardness over that period due to resorption of calcium prior to the molt, but this may also be an artifact. For comparative purposes, premolt measurements taken ≥28 days before molting ($n = 11$) were assumed to represent the normal shell hardness of intermolt crabs, and were included in a modified regression analysis as if they occurred one month before the next molt, i.e., at an expected shell age of 10 months or 300 days in 2004 (Stevens and Swiney, 2007). The results of this analysis improved the fit to the hyperbolic equation slightly ($F =$ 3966, $R^2 = 0.976$ raw, 0.710 corrected, $n = 199$) and produced similar parameters ($\beta_0 = 0.216 \pm 0.014$, and $\beta_1 = 0.019 \pm 0.000$). Therefore it seems reasonable to conclude that the selected premolt data probably represented normal intermolt shell hardness, before it began to decline prior to the molt.

Predicting the time of complete hardness is not possible with asymptotic equations, and 50% hardness is not a useful value, but 90% hardness (H_{90}) should be a value at which the exoskeleton is strong enough to resist the rigors of fishing or handling. The maximum hardness (asymptote) predicted by the combined hyperbolic equation was 50.7 DU (2.301 kg), and the value of H_{90} was 45.6 DU (2.071 kg). The time required to reach H_{90} was calculated by inverting the hyperbolic equation:

$$X = \beta_0/((1/Y)-\beta_1)$$

where X = days, and Y = hardness (45.6 DU). and was equal to 74.2 days.

Discussion

Shells of female king crabs reached almost complete hardness within 11 weeks after molting. The mean level measured on the top surface of king crabs (51 DU or 2.315 kg) was lower than that measured on the lateral underside of the carapace of Dungeness crabs (Hicks and Johnson, 1999). Hicks and Johnson (1999) measured 24 crabs at monthly intervals, but did not test their crabs until 1 month after molting, and assumed an early inflection point. They used a cumulative logistic model to fit their data and derived an asymptote of 82.2 DU (3.732 kg). By inverting their regression equation, I calculated that a Dungeness crab would reach H_{90} (74.0 DU or 3.359 kg) after 181 days. In contrast, our data for king crab do not exhibit an inflection immediately after molting and could not be fit with a logistic model.

Foyle et al. (1989) tested durometers of different force ranges for their utility in measuring hardness of snow crab. They found that a gauge with a maximum range of 7 lbs (3.178 kg) was most useful when applied to the underside of the claw, and obtained maximum readings of 85-90 DU (2.781 kg), i.e., harder than king crab shells, but less hard than Dungeness crab shells. Foyle et al. (1989) did not determine the time course of shell hardening, but found that shell hardness was correlated with meat yield for morphometrically mature male crabs. They also determined that hardshell crabs could be defined as those with a reading >72 DU (on a scale of 100, or 2.288 kg), whereas softshell and morphometrically immature crabs all had readings below that level. Dufour et al. (1997) also compared meat yield to shell hardness using the same durometer as Foyle et al. (1989) and found that crabs with hardness <60 DU (1.907 kg) had a meat content of 28.3 ± 4.5%, whereas those with hardness >90 DU (2.860 kg) had a significantly greater meat content of 43.1 ± 3.5%. A cutoff value of 60 DU also separated old-shell crabs (shell category 4 or 5) that have started to become soft. A regression equation was derived employing wet weight and shell hardness that explained 90% of variation in meat yield. Dufour et al. (1997) subjected recently caught snow crabs to handling and air exposure, followed by immersion for 24-72 hours; overall mortality for "white crabs" (recently molted crabs with hardness <68 DU or 2.161 kg) was 14.3% vs 2.2% for hardshell crabs, i.e., 7 times greater. Hebert et al. (2002) measured shell hardness of snow crabs through a complete molt cycle and found that adolescent crabs ranged from 31.2 DU in stage B_1 to 62.6 DU in stage C_4 (0.992 to 1.989 kg), whereas for adults, shell hardness ranged from 29.0 to 71.7 DU (0.922 to 2.279 kg) in those same stages.

The predictive ability of data obtained in the present study might have been improved if measurements had been taken over a longer time period. Nonetheless, some king crabs reached hardness levels >51 (the asymptote) within 60 days. Applicability of these data to male crabs is also unknown. However, there is no particular reason to believe that the shells of male and female king crabs differ in hardness, at least during the first year after molting. Large males may not molt for 2 years or more, and it could be argued that they might continue to harden, but the available evidence for Dungeness crabs (Hicks and Johnson, 1999) and the author's personal experience with king crabs suggests that little hardening occurs after 6 months. In contrast, snow crab shells continue to harden for an extended period after molting (Fonseca et al., 2008), reaching a peak hardness of 83.4 DU (2.65 kg) in shell condition 3 at an estimated post-molt age of 3.6 years, after which shell hardness declines linearly. The radiometric aging technique is dependent on the assumption that all calcium in the exoskeleton is incorporated during a relatively brief hardening period, so an extended period of hardening would lead to underestimates in the radiometric age of shells (Fonseca et al., 2008).

A long standing problem with field surveys of king crabs is the inability to distinguish the reproductive history of female crabs. Snow crabs undergo a terminal molt (Conan and Comeau, 1986; Tamone et al., 2005) and Tanner crabs probably do as well (Somerton and Meyers, 1983), making it possible to distinguish primiparous (first spawning) from multiparous (multiple spawning) females by the condition and coloration of the shell (Stevens et al., 1993). However, prior to producing a clutch of eggs, red king crabs must molt every year (Stevens and Swiney, 2007), and blue king crabs every other year (Stevens, 2006), so it is not possible to distinguish primiparous and multiparous females by their shell conditions. During the NMFS stock assessment surveys, most king crabs are captured within 3 months after molting. Primiparous king crabs generally molt and extrude a new clutch of eggs in February, whereas multiparous crabs molt up to two months later (Stevens and Swiney, 2007). Therefore, it should be possible to distinguish these two types of crabs as modes in the frequency distribution of shell hardness, or by hindcasting the probable molting date using individual shell hardness data, if obtained prior to reaching the asymptotic value. Hicks and Johnson (1999) conducted a similar hindcasting exercise for Dungeness crab to determine the probable distribution of molting dates, and found distinct differences between years. Data from the present study were used to hindcast molting dates by selecting the last hardness measurement for each king crab that was less than H_{90} (45.6 DU). Estimated molting dates calculated in this manner were within 2.5 ± 6.4 days (mean $\pm$ SE, $n = 34$) of the actual molting date, i.e., not significantly different.

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