



Port of Juneau

March 26, 2010

Dennis J. McLerran, Regional Administrator
U.S. EPA, Region 10
1200 Sixth Avenue, Suite 900
Seattle, Washington 98101-3140

Subject: March 2, 2010 Douglas Harbor Letter

Dear Mr. McLerran,

Per your March 2, 2010 letter, we understand that EPA is objecting to the rebuild of Douglas Boat Harbor as proposed by CBJ because it will “result in substantial and unacceptable impacts to aquatic resources of national importance.”

In 1962, the U.S. Army Corps constructed the harbor basin and entrance channel at Douglas Harbor. In 1963, the State of Alaska and the City of Douglas installed moorage floats and associated utilities for about 100 boats.

CBJ wishes to replace the 1963 moorage floats because they are dilapidated and have life-safety issues. CBJ is proposing to reestablish the harbor’s design depth, as the basin has filled-in over time due to glacial rebound and other factors. Our proposed action consists of dredging the basin and disposing of the dredge materials in the middle of Gastineau Channel at an area used twice before for the same purpose, removing the old float system, and installing a new moorage float system and utilities.

We appreciate your national viewpoint and responsibility. However, we recommend you visit the project site so you can see it firsthand. The project area is far from pristine. Douglas Harbor is within an area that was heavily impacted by extensive hard rock mining during the early part of the last century. Douglas Harbor is located on mine tailings, as is the general area surrounding the project. Tailings are the likely source of the mercury that is the concern.

Moreover, the proposed disposal site for the dredge materials is under one of the busiest waterways in Alaska and is also adjacent to the marine outfall of the Juneau Douglas

Municipal Wastewater Treatment Plant. We do not consider this to be an area of aquatic resources of national importance. We recognize there may be legitimate concerns with our proposed action, but we do not believe that substantial and unacceptable impacts to aquatic resources of national importance is one of them.

After carefully reviewing the technical aspects of your letter and attachments, it appears your primary concern relates to human health, and more specifically whether our proposed action increases the ability of ambient mercury present in the submerged sediments to affect the residents of Juneau.

I want to assure you that the CBJ Assembly and the CBJ Docks and Harbors Board share the same concern. Prior to submitting our application, we carefully considered whether our proposed action would impact the residents of Juneau. We concluded that our proposed action would not. Had we felt there was the slightest possibility of risking the health of our residents, we would not have submitted the application.

You have made many assumptions in order to arrive at your judgment concerning the efficacy of our proposed action. The most startling is your assumption about the amount of fish that the average Juneauite consumes from Douglas Harbor and the disposal site. On page 2 of the attachment 1 to your letter, you present recommended fish consumption values ranging from 43.4 to 469 lbs/year. Based on this range, you are recommending that a regulatory decision be made using a consumption rate of 141 lbs/year.

As we understand it, EPA is thus assuming that

1. Juneau residents consume on average 141 lbs/yr of seafood per year;
2. this entire amount comes from the harbor and the disposal site; and
3. the consumed seafood comes from species that have been at the sites long enough to bio-accumulate significant levels of mercury in their edible tissues.

These assumptions simply do not stand up to critical analysis. While average seafood consumption in Juneau is surely higher than the US average of 16.6 lbs per year, we know of no data supporting the idea that it would be nearly nine times higher, as your 141 lbs per year figure suggests. Moreover, little to none of the seafood consumed by Juneauites comes from these sites. The salmon and halibut that are the most popular locally caught species are highly migratory. Very little of the seafood actually

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consumed is derived from sedentary, benthic species that could even potentially remain at the sites long enough to bio-accumulate significant amounts of mercury.

But, putting aside the debate over the assumptions, we think the issue boils down to a rather simple question. Does a plausible food web connection exist between the dredge sediments and the residents of Juneau? We think not. Here is why.

The Docks and Harbors Board runs Douglas Harbor and is intimately familiar with the waterway at the disposal site. Our knowledge of the use of these areas is first hand and extensive. We are not aware of anyone harvesting seafood from either the harbor or the disposal site in any appreciable quantity. This is why, despite extensive local media coverage of our proposed action, very few residents of Juneau have expressed concern. The fact is that Juneauites fish at places where the fishing is good and that is not in Douglas Harbor or near the proposed disposal site.

While kids do fish in Douglas Harbor, their endeavors could hardly be described as harvesting fish meals. A better description would be playing on the docks. Generally speaking we discourage fishing within the local harbors for several reasons. There are electrical cables and other underwater obstructions that fishing lines can snag, and casting in close quarters on the docks presents safety issues to other harbor users.

If necessary, in order to address this issue, we can ban fishing within the harbor or post advisories concerning fish meal harvesting. We have the authority to establish such a restriction, and the ability to enforce it as our staff visits the facility several times a day. From a risk management standpoint, we think the likelihood of routine fish meal harvesting in the harbor is near zero and advisory signs would be a more than adequate risk management measure.

As stated previously, the disposal site is located under one of the busiest waterways in Alaska. Because of the extensive vessel traffic, it is impractical to fish or to set pots in this area. We have data to backup this claim. The Marine Exchange of Alaska tracks AIS equipped vessels into and out of the Juneau Harbor. AIS is required equipment on SOLAS vessels, such as cruise ships and tugs. In attachment 1, you will find AIS tracks at the disposal site for the 2009 summer months. Recognize this represents only a fraction of the vessel traffic over the disposal site. Most of the vessel traffic, fishing and recreational vessels, are not required to carry AIS. As one local mariner observed, "fishing there (at the disposal site) would be like playing Frisbee on I-5."

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We also looked at habitat with the help of the Alaska Department of Fish and Game (ADF&G). As you know, ADF&G tracks commercial and recreational fishing. In addition, habitat experts from ADF&G conducted a dive survey of the proposed disposal site. A complete report of their assessment will be available shortly. In short, ADF&G pointed out in permit meetings that the most probable fish consumption from the subject areas for the average Juneauite is near zero. This is based on harvest data, actual observation over a number of years, and the fact that the habitat at both sites is considered by ADF&G as low value habitat for both recreational and commercial species. We agree with their finding.

From a risk management standpoint, ADF&G also pointed out that the species of concern are shellfish. Other harvestable species such as salmon and halibut are highly migratory and do not spend enough time at either site to accumulate elevated mercury levels into their tissue. ADF&G specifically noted that Dungeness and Tanner crab are the harvestable species of concern near the disposal site. They further noted that crab habitat studies published by the National Marine Fisheries Service/Auke Bay Laboratory show that the disposal site is deeper than critical habitats for Dungeness crabs and shallower than critical habitats for Tanner crabs (see exhibit 2). Also, published studies show that the grain size characteristics of sediments at the disposal site and the dredge sediments are not favorable for either species.

We think the preponderance of evidence shows that the likelihood of prolonged, day-in and day-out consumption of seafood from either the harbor or the disposal site is most likely zero. We note this evidence includes habitat evaluation and fish consumption opinions provided by the Alaska Department of Fish and Game, crab habitat studies published by the Auke Bay Laboratory, the vessel traffic documented by the Marine Exchange of Alaska and actual observations of the harbor and proposed disposal site for many years.

To further our risk management standpoint, we argue that your approach to estimate risk using the reference dose for chronic oral exposure is probably not appropriate in this case. As you know, the reference dose you used is intended for multi-year, day-in and day-out ingestion of seafood with elevated methyl mercury content. We do not see any evidence to support that we have day-in and day-out consumption of fish meals derived from either the harbor or the disposal site. Using commercial crab harvest data, ADF&G estimated a worst case harvest level from the disposal site at 3 crabs per year. Using this harvest rate and the same approach you used in Table 1 of Enclosure 1 of

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your letter yields a site-specific allowable tissue concentration (ATC) of 3 ppm methyl mercury wet weight, which is significantly higher than our site-specific test results.

In this hypothetical worst-case scenario, we believe the appropriate regulatory level is the FDA action level of 1 ppm methyl mercury wet weight instead of the ATS method you employed. On page 1 of Enclosure 2 of your letter, you note that our site specific effects based testing for Douglas demonstrates compliance with this level. We concur with your finding and believe it is the best way to assess methyl mercury consumption risk associated with our proposed action.

We are hopeful this letter addresses your concerns and would ask that you withdraw your March 2 objection to our proposed action after you take into account this new information.

Sincerely,



Jim Preston, Chair

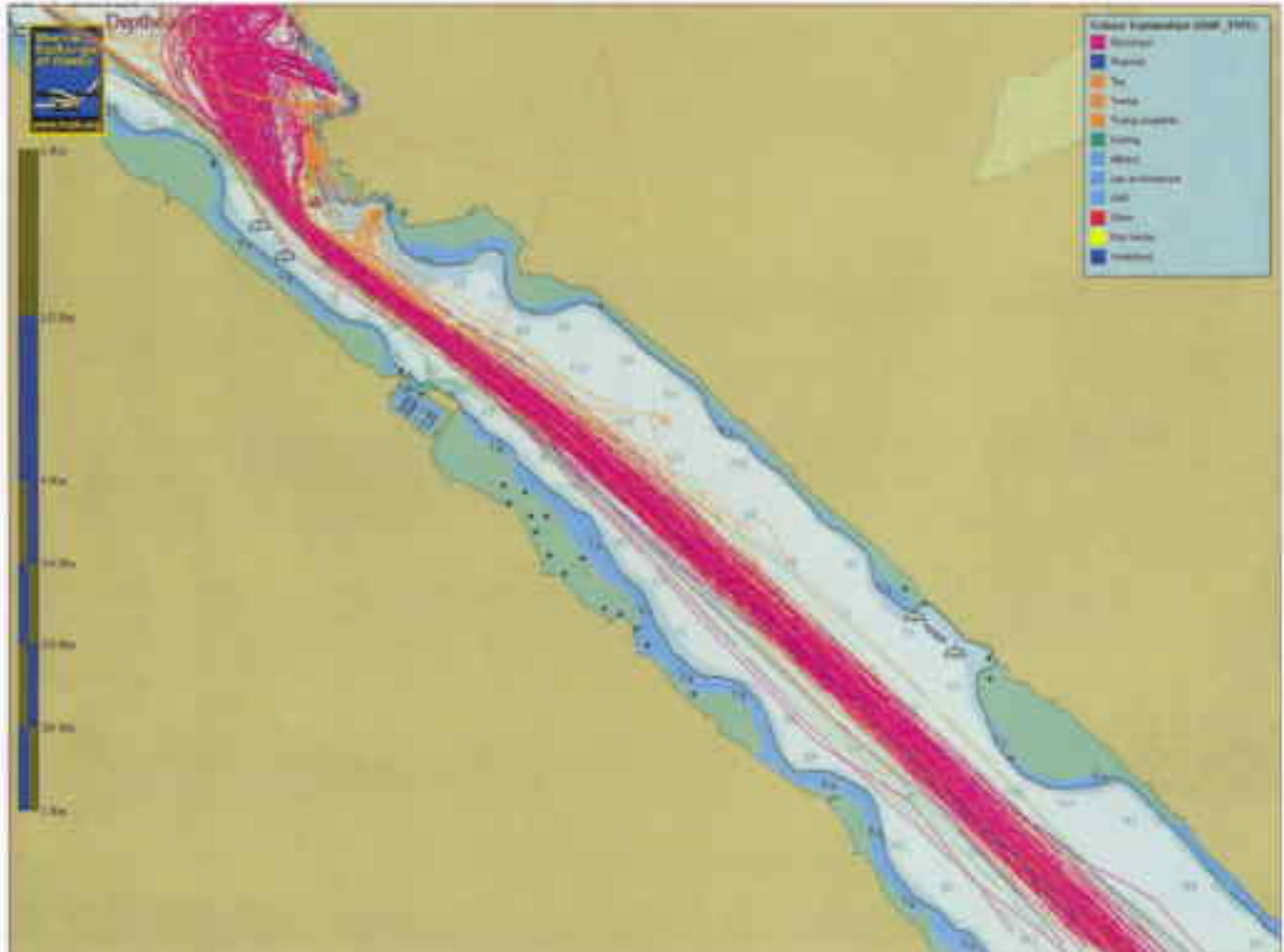
Docks and Harbor Board

cc: Colonel Reinhard W. Koenig
CBJ Assembly
Governor Sean Parnell
Juneau Delegation to the Alaska Legislature
Alaska Delegation to the U.S. Congress

Attachment 1.
Vessel AIS Tracks

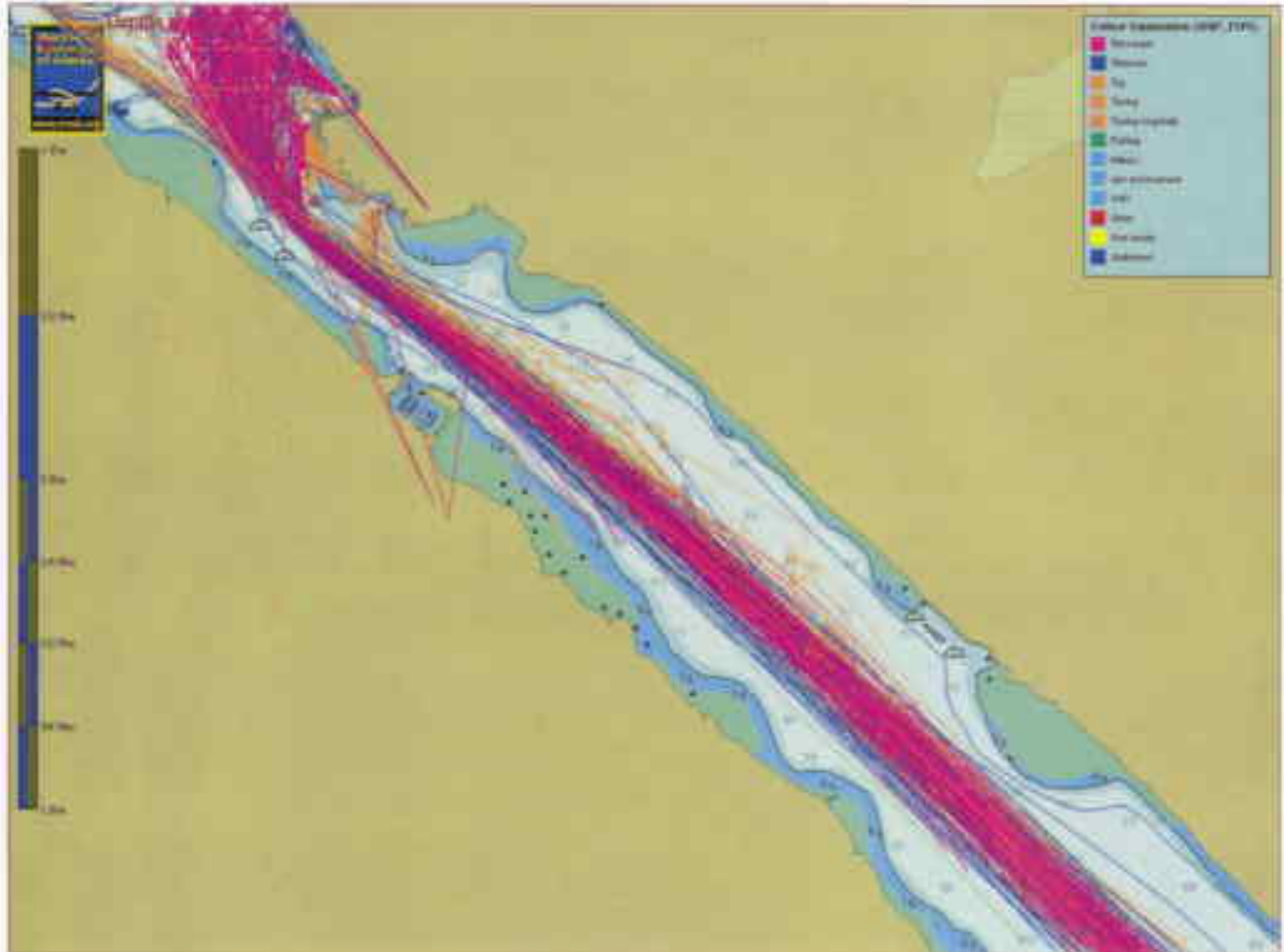
Historical Track

Area : POJ Gastineau Study
Start : 1st May, 2008 00:00
End : 1st June, 2008 00:00



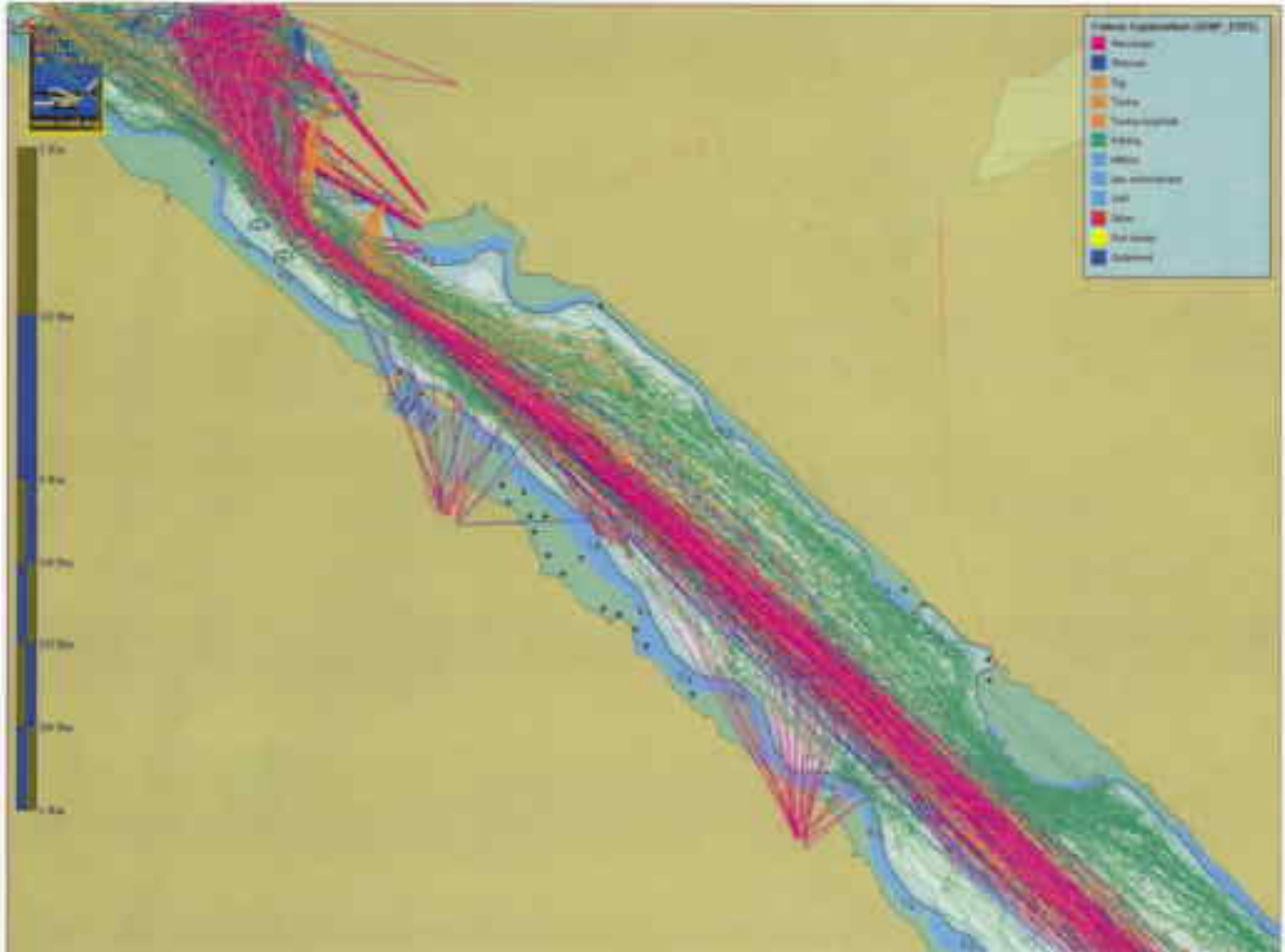
Historical Track

Area : POJ Gastineau Study
Start : 1st June, 2008 00:00
End : 1st July, 2008 00:00



Historical Track

Area : POJ Gastineau Study
Start : 1st July, 2008 00:00
End : 1st August, 2008 00:00



Attachment 2.

Auke Bay Laboratory Crab Studies

BEHAVIOR OF FEMALE DUNGENESS CRABS, *CANCER MAGISTER*, IN A GLACIAL SOUTHEAST ALASKA ESTUARY: HOMING, BROODING-SITE FIDELITY, SEASONAL MOVEMENTS, AND HABITAT USE

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ABSTRACT

Aspects of the behavior of ovigerous Dungeness crabs (*Cancer magister*) were studied in Fritz Cove, Alaska. To test fidelity and homing ability of crabs to their brooding site, we ultrasonically tagged eight ovigerous crabs and transplanted them 1.4 km from their brooding site. Eight ultrasonically tagged control crabs were returned to the brooding site. Crab movements were subsequently monitored weekly from late February to October to determine activity patterns and seasonal shifts in depth distribution and habitat use. Seven females transplanted away from the brooding site homed back to that site within 13 to 20 d. Ovigerous female crabs showed fidelity to the head of the cove and ranged a maximum of 3.4 km. Crabs had distinct seasonal patterns of depth distribution, habitat use, and activity which were related to reproductive status. The general pattern for female crabs was: (1) a relatively inactive period during winter and early spring at depths greater than -16 m; ovigerous crabs were typically buried during this period in a dense aggregation; (2) an abrupt movement into shallow water (less than -10 m) during mid-April and residence there until late June; this movement was coincident with the spring phytoplankton bloom and initiation of larval hatching; and (3) increased activity beginning in July with movement back to deeper water presumably to forage. Females that molted prior to oviposition did so between late May and September. Females occupied depths between +1.6 and -107.3 m. Home ranges were small (< 4% of the total cove habitat) and varied with crab size; smaller crabs had larger home ranges. Ovigerous females brooded embryos in a small, discrete area of unconsolidated, homogeneous, fine sand. These sediments were also highly permeable. Annual use of the main brooding area was documented for a 12-year period and emphasizes the importance of this essential habitat.

Adult female Dungeness crabs, *Cancer magister* Dana, 1852, have a more variable reproductive phenology than other large commercially important crab species in Alaska. Females oviposit for the first time at about 118-mm carapace width (CW) (personal observations) and molt annually (Hankin *et al.*, 1985). Molt probabilities approach zero at a size of about 155- to 160-mm CW (Lehman and Osborn, 1970; Mohr and Hankin, 1989). Females are only inseminated while soft-shelled (Hartnoll, 1969) but are capable of fertilizing consecutive egg clutches using stored sperm without an intervening molt (Hankin *et al.*, 1989). Size-specific fecundities of females using stored sperm are reduced compared to females that molt and mate (Hankin *et al.*, 1989). Tag-recovery data indicate that most adult females oviposit annually in northern California (Hankin *et al.*, 1989), but there is evidence that some females in Alaskan bays may not oviposit annually

(Swiney and Shirley, 2001). Furthermore, unlike many other species, female Dungeness crabs that brood clutches during consecutive years are nonovigerous for an extended period (several months) between eclosion and oviposition.

We previously documented that ovigerous Dungeness crabs in Southeast Alaska have distinct seasonal patterns of habitat use, depth distribution, and activity (Stone and O'Clair, 2001). These patterns are associated with major life history events. Females are inactive while brooding eggs in dense aggregations between approximately September and April. Brooding aggregations have been documented for Dungeness crabs elsewhere in Southeast Alaska and in Washington and northern California (Diamond and Hankin, 1985; Dinnel *et al.*, 1987; Armstrong *et al.*, 1988; O'Clair *et al.*, 1996; Scheduling *et al.*, 2001). Because egg brooding was restricted to a small proportion (< 10%) of the total

habitat within the study site, we concluded that ovigerous females showed selective behavior for that habitat. We hypothesize that this habitat has specific characteristics which are optimal for brooding eggs. Although O'Clair *et al.* (1996) found repeated use of the same brooding sites between years in Glacier Bay, Alaska, which they equated with high site fidelity, we know of no study that has experimentally evaluated the fidelity of individual Dungeness crabs to a brooding site or tested the ability of *C. magister* to home to a brooding site.

Objectives of this study were to 1) test fidelity and homing ability of ovigerous Dungeness crabs to a brooding site and 2) investigate movements and habitat use of ovigerous Dungeness crabs in a southeast Alaska estuary with particular emphasis on the period between broods. We investigated site fidelity and homing behavior by transplanting ultrasonically tagged ovigerous crabs away from a brooding aggregation. We also measured sediment and oceanographic characteristics in the area where crabs formed a brooding aggregation to determine if unique properties existed there that were beneficial to ovigerous crabs and their developing embryos.

MATERIALS AND METHODS

This study was conducted in Fritz Cove, 11 km north of Juneau, Alaska (Fig. 1), which has a water surface area of about 8 km² at mean higher high water (MHHW). Fritz Cove is a small estuary located off a system of large, fjord-type channels. The deepest area of the cove is about 105 m, and about 12% of the cove is intertidal habitat. Most of the subtidal area of the cove deeper than -20-m mean lower low water (MLLW) is covered with glacial silt. The cove is strongly influenced by fresh water: both the large, glacial Mendenhall River and the clearwater Fish Creek empty into the head of the cove. Several watersheds empty into Gustineau Channel, a large tidal channel, which flows into the head of the cove. A strong buoyant plume estuarine front (Langier, 1992) is prominent, especially along the northern portion of the cove, between June and October. The cove is closed to commercial fishing for Dungeness crabs but is an important area for recreational fisheries.

We chose to study the behavior of ovigerous Dungeness crabs with biotelemetry rather than a population survey so as to minimize disturbance of the crabs when they were in the brooding aggregation. A population survey would have necessitated periodic excavation of a large number of individuals to determine the presence or absence of individually marked crabs. This activity would have affected crab behavior and perhaps violated the study.

Ovigerous female crabs were collected by SCUBA divers on 19 February 1991 and transported to the Auke Bay Laboratory for tagging. All crabs were collected from a previously identified brooding aggregation area near the head of the cove at a depth of about -20 m (Fig. 1). Six-



Fig. 1. Study area at Fritz Cove, near Juneau, Alaska, where movements of ovigerous female Dungeness crabs tagged with ultrasonic transmitters were monitored. The open square shows where experimental crabs were collected, and the solid square shows the release position for transplanted crabs. Triangles mark the stations where oceanographic profiles of the water column were collected. Depth contours are in meters.

teen crabs were randomly assigned to two release-location groups. Eight control crabs were returned to the site of collection within the aggregation area, and a treatment group was transplanted 1,390 m 265°T from the collection site at a depth of -74 m (Fig. 1). Control crabs ranged from 120.2 to 163.7-mm CW (\bar{x} = 144.2 mm) and weighed (wet weight) between 320 and 794 g (\bar{x} = 569 g). Transplant crabs ranged from 122.6 to 136.6-mm CW (\bar{x} = 130.8 mm) and weighed between 343 and 493 g (\bar{x} = 426 g). All tagged crabs had full egg clutches, no missing appendages, or significant exoskeleton erosion. *Carcinomegites errant*, a known predator of Dungeness crab eggs from California to Alaska (Wickham, 1986; O'Clair and Fretz, 1988), were not found in eggs sampled from each tagged crab.

Ultrasonic transmitters with a two-year life expectancy were attached directly to the carapace in the cervical groove between the gastric and cardiac regions with non-toxic SeaGoin' Poxxy Quik 5-min epoxy putty. Each transmitter (Sonotronics model CHP-87) had a unique aural code and a range of about 2 km. Tags were 105 mm long, 16 mm in diameter and weighed 12 g in water (less than 3.75% of the total body weight of the smallest crab tagged). Crabs were held in flow-through aquaria in the laboratory for 48 h prior to release to ensure tag adherence to the carapace. Control crabs were carried to the sea bottom in canvas bags and released by divers. Transplant crabs were released at the water surface over a bottom 74 m in depth. Crabs were released on 21 February 1991.

Positions of the crabs were fixed weekly through 17 October 1991. We surveyed the cove in a small boat to monitor crab movements. We used an ultrasonic receiver (Sonotronics model USR-4D) and directional hydrophone

(Sonotronics model DH-2) to locate crabs. A small float was deployed after the boat was positioned over a crab. The boat was maintained at this float while its position was fixed by measuring angles between three shoreward markers with a beam-converging sextant used as a pelorus (O'Clair *et al.*, 1990). The positions of the shoreward markers were fixed using standard surveying techniques. We estimated an error of ± 8.8 m associated with this "mark-on-top" method by calculating the mean distance between fixes ($n = 27$) for stationary derelict tags (Stone and O'Clair, 2001).

Depth was measured with a Hummingbird Model 4080D depth finder. A Seabird Electronics Seacat Profiler was used to collect temperature, salinity, density, and dissolved oxygen (DO) profiles of the water column at six stations throughout the cove. Physical oceanographic parameters at depths occupied by crabs were estimated from the profile at the nearest station to each crab. Oxygen saturation values were calculated from the tables provided in Weiss (1970).

Divers used SCUBA and a submersible receiver/dropphone (Sonotronics model USR-88) to recover derelict transmitters (i.e., detached from live crabs) and to periodically observe tagged crabs within diving depth (< -35 m). Density of crabs within the brooding aggregation was measured during March 1999 by divers. Divers descended onto the aggregation with a 2-m² cage designed to capture and retain all crabs within its perimeter. In September 2000, undisturbed core samples were collected within the brooding aggregation by forcing 250-ml plastic jars (10-cm height by 5.5-cm diameter) into the sediment. Three replicate samples were collected at 5 locations: 1) center of aggregation at 16-m depth, 2) upslope from the brooding aggregation at 4-m depth, 3) outside the deepest boundary of the brooding aggregation at 26-m depth, 4) approximately 30 m south of the aggregation along the same isobath, and 5) approximately 30 m north of the aggregation along the same isobath. Permeability was measured with a combination permeameter using a constant head permeability test. Compressive strength (internal friction) of sediments was determined with a hand-held penetrometer. Sediments were analyzed for grain size composition by wet sieving and graded using the Wentworth classification scale (Holme and McIntyre, 1971). Sorting was calculated with the Inclusive Graphic Standard Deviation (Gray, 1981) with higher values indicating greater grain-size variability. Slope of the sea floor at the aggregation site was determined by measuring the change in depth at 5-m intervals.

Statistical Analyses

The initial distance and angle of movement from each release point (Fig. 1) was measured for each tagged crab, and the mean angle ($\bar{\alpha}$) and angular deviation (γ) was calculated for each of the two groups (transplant and control) (Zar, 1996). Rayleigh's test was used to determine if the control group had movement significantly different from random after release (i.e., directed movement) and tests $H_0: \rho = 0$ vs. $H_a: \rho \neq 0$, where ρ is the population concentration parameter (Zar, 1996). The V -test of circular uniformity was used to determine if the transplanted group had a mean direction of movement to the collection area and tests $H_0: \rho = 0$ vs. $H_a: \rho \neq 0$ and $\mu_0 = 85^\circ\text{T}$, where μ_0 is the expected angle of movement (Zar, 1996).

The home range for each crab was estimated with two methods: 1) the minimum convex polygon method (MCP)

(Worton, 1987), and 2) location fixes were fitted to a bivariate probability density function or utilization distribution (UD) (Worton, 1989) using a least squares cross validation smoothing parameter (Silverman, 1986) to calculate a fixed kernel home range. Two utilization distributions were calculated for each crab: the Minimum Area vs. Probability (0.95 (MAP 0.95), and the MAP 0.50. The MAP (0.95) accounts for 95% of the space utilization and describes "the area traversed by an individual in its normal activities of food gathering, mating, and caring for young", while the MAP (0.50) accounts for 50% of the space utilization and is used to describe core areas of use (Anderson, 1982). Activity rate was calculated as distance moved divided by time between successive observations. A principal component analysis was used to reduce the dimension of the sediment data from five variables to one principal component. Equality of principal component means for the five sites was tested with one-way analysis of variance (ANOVA). The principal component mean of the brooding aggregation site was compared to the principal component means of the four nearby sites using Fisher's least significant difference test (Chew, 1985). The α -level was 0.05.

RESULTS

Transplant Experiment

Tagged crabs released in the collection area had limited initial movement (Fig. 2A). The mean distance moved by these crabs after 6 d was 76 m (range = 11 to 324 m). Mean angle of movement was 305°T ($\gamma = 75^\circ$). Movement was not significantly different from random (Rayleigh's $z = 1.5$, $P > 0.20$) for this group of crabs. All crabs remained in the general area of the aggregation site until June.

Females displaced 1,390 m 265°T from the brooding aggregation moved a mean distance of 1,096 m (range = 931–1,300 m) after 6 d (Fig. 2B). Mean angle of movement was 63°T ($\gamma = 29^\circ$). Movement of this group of crabs was significantly different from random and directed towards the collection site at 85°T ($V = 6.5$, $P < 0.001$). One transplanted female initially behaved differently than the other seven crabs. That crab moved 948 m at an angle of 340°T from the transplant site within 6 d and remained in that area until moving back to the aggregation site after 75 d. The remaining transplant crabs were in the immediate area of the aggregation site within 20 d and several were located within the center of the aggregation after 13 d.

Seasonal Movements and Habitat Use

Seasonal patterns of depth distribution, habitat use, and activity (Fig. 3) of individual females monitored between 97 and 378 d (Table 1) followed a general pattern that can

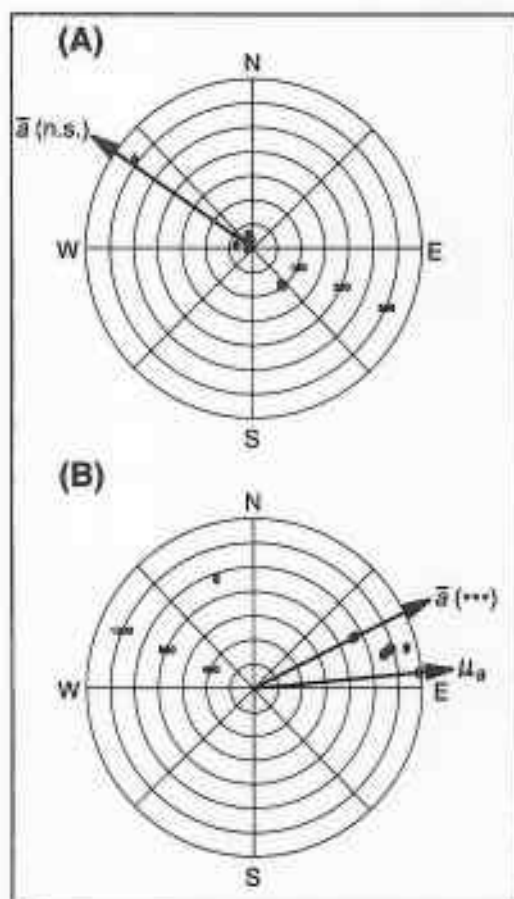


Fig. 2. (A) Dispersal of eight ultrasonic-tagged female Dungeness crabs 6 d after release to the original collection site within a brooding aggregation in Fritz Cove. (B) Dispersal of eight ultrasonic-tagged ovigerous female Dungeness crabs 6 d after being displaced 1,390 m (265 °T) from a brooding aggregation in Fritz Cove. Each black oval represents the position of one crab relative to the release position 6 d after release. The shaded oval in (B) represents the position of the collection site. $\bar{\alpha}$ is the mean angle of movement relative to true north, and μ_a is the direction to the collection site. The significance of Rayleigh's test is shown next to $\bar{\alpha}$ in both panels (n.s. = not significant, *** = $P < 0.001$). Concentric circles are 50 m (A) and 200 m (B) apart.

be divided into three phases. First, crabs were relatively inactive during winter until early April when crabs occupied depths generally greater than about -16 m. Crabs were typically buried close to one another at the aggregation site during this period and were brooding embryos. Second, crabs exhibited abrupt movement into shallow water (< -10 m) during mid-April and residence there until late June. The onset of this movement was coincident with the spring phytoplankton

bloom, and larvae hatched mostly during or after the secondary bloom (Ziemann *et al.*, 1991) in the latter part of this period. Female mortality was high at the end of this period (see below). During the third phase, crabs showed increased activity beginning in late June and gradually moved into deeper water.

Individual females ranged in depth from +1.6 to -107.3 m. Females occupied mean depths between -27 and -15 m during winter, and moved into shallow waters during April through July (Fig. 3A). In late July, depth distribution became more variable as sample size decreased and females dispersed to forage, molt, and mate (Fig. 3A). Females were generally inactive during winter with a sharp, brief increase in activity as they moved into shallow water in spring (Fig. 3B). Female crabs were relatively inactive during the period of larval hatch (April through June), but activity increased again and became more variable in late June (Fig. 3B).

Female crabs had very small home ranges (Table 2), and none moved farther than 3.4 km from the brooding aggregation area at the head of the cove. Home range size was not dependent on length of time an individual's movements were monitored ($r^2 = 0.01$, $P = 0.69$). Home range size varied inversely with crab size; small crabs had larger home ranges than large crabs ($r^2 = 0.31$, $P = 0.025$). Home ranges calculated as 95% utilization distributions ranged from 22,706 to 2,095,728 m² and represented between 0.04% to 3.3% of the total cove habitat, respectively (Table 2).

All 16 tagged crabs spent at least a brief period in the intertidal zone during this study. Although the majority of visits to the intertidal zone were in late April and May, several crabs moved into the intertidal zone in June through September. Three tagged crabs molted in the intertidal zone between 29 May and 28 September (Fig. 4). One other female died while attempting to molt there on 17 July. The nine that molted or initiated ecdysis did so in shallow water ($\bar{x} = 7.9$ m, range = +0.9 to -20.4 m). Crabs that molted ($\bar{x} = 138.0$, range = 122.6–161.8-mm CW) did not differ in premolt size from crabs that skipped a molt ($\bar{x} = 136.8$, range = 120.2–163.7-mm CW) (ANOVA, $P = 0.86$).

Four of the seven crabs that did not molt during this study returned to the brooding aggregation area between 28 August and 25 October after occupying deeper water during

Table 1. Carapace width (CW), duration of tracking, and fate of 16 ovigerous female Dungeness crabs monitored with ultrasonic biotelemetry in Fritz Cove, Alaska. All crabs were released on 21 February 1991. Crabs at large were still at liberty and apparently moving at the time of last position fix.

Crab no.	CW (mm)	Duration (d)	Fate of crab
384	131.4	97	Molted on 5/29/91 at +0.9 m
267	144.3	105	Molted on 6/06/91 at -0.9 m
2237	161.8	127	Molted on 6/28/91 at -13.4 m
555	130.5	148	Died molting on 7/17/91 at 0 m
375	154.8	157	Molted on 7/28/91 at -10.4 m
366	130.1	160	Molted on 7/31/91 at -8.3 m
456	130.5	187	Molted on 8/27/91 at -19.6 m
249	122.6	198	Molted on 9/07/91 at -20.4 m
2228	135.8	219	Molted on 9/28/91 at +0.9 m
2246	120.2	223	At large in deep water, ovigerity unknown
276	126.8	223	At large in deep water, ovigerity unknown
447	133.1	223	At large in aggregation area, ovigerous by 9/20/91
348	136.6	223	At large in deep water, ovigerity unknown
258	137.6	238	At large in aggregation area, ovigerity unknown
294	139.6	238	Crab recovered in aggregation area, ovigerous by 10/17/91
465	163.7	378	Crab recovered in aggregation area, ovigerous by 10/30/91

summer. We confirmed that three of these individuals were ovigerous at that time, but could not determine the reproductive status of the fourth crab. The remaining three crabs were in deep water when weekly tracking was suspended; their reproductive status was unknown.

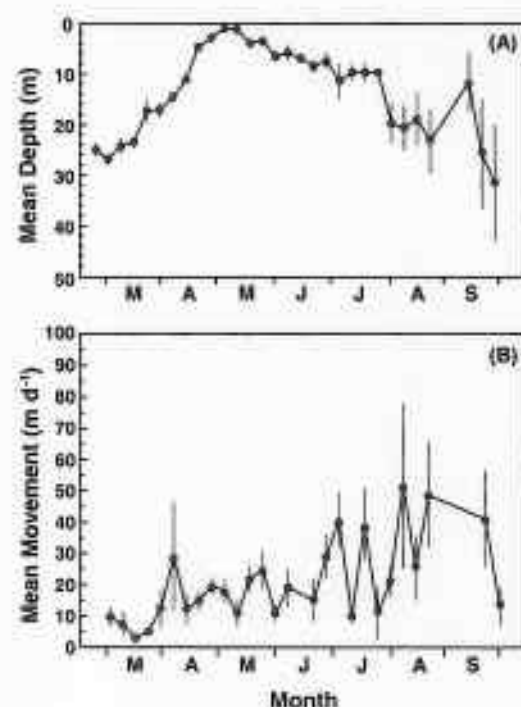


Fig. 3. Mean depth (A) and mean activity rate (B) of ultrasonic-tagged female Dungeness crabs (\pm standard error of the mean) between February and early October 1991.

Oceanographic Influences on the Brooding Aggregation

Annual physical and chemical oceanographic patterns in Fritz Cove were similar and consistent during the two years they were measured (Figs. 5, 6). Three prominent features of the oceanography of Fritz Cove are 1) a strong primary phytoplankton bloom beginning each April (Ziemann *et al.*, 1991) producing elevated DO concentrations in

Table 2. Home ranges of 16 ovigerous female Dungeness crabs monitored with ultrasonic biotelemetry in Fritz Cove, Alaska. Home ranges were estimated using 1) minimum convex polygons (MCPs), and 2) fixed kernel utilization distributions measured as minimum area vs. probabilities (MAPs). MCP100d is for the first 100 d excluding the first week after release.

Crab no.	Home range (m ²)			
	MCP	MCP100d	MAP (0.95)	MAP (0.50)
Controls				
384	20,852	20,852	22,706	2,319
267	48,279	48,279	71,927	8,610
2237	46,743	46,236	82,727	11,598
375	38,420	38,420	100,817	17,660
2246	567,110	32,671	611,700	118,466
258	269,880	18,154	218,396	25,518
294	146,592	50,695	544,042	87,797
465	71,873	13,597	145,653	24,105
Transplants				
555	641,471	39,550	578,344	78,966
366	1,508,924	38,764	2,095,728	378,679
456	1,152,099	69,980	779,564	129,616
249	1,044,994	42,906	1,136,614	151,531
2228	1,501,610	342,107	1,950,600	300,400
276	1,002,324	70,063	1,545,066	218,143
447	743,491	102,754	505,945	49,027
348	995,443	32,869	1,082,635	266,855

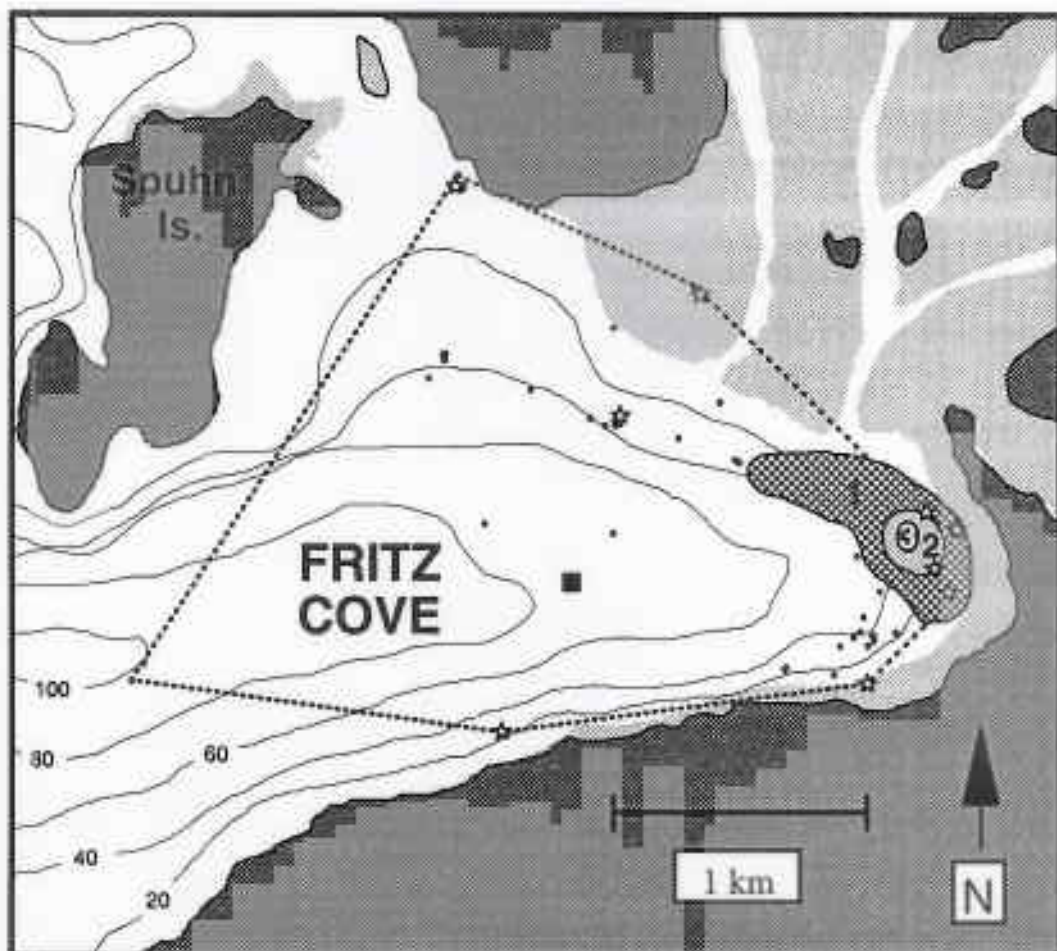


Fig. 4. Study area at Fritz Cove, near Juneau, Alaska, showing distribution of 16 ultrasonic-tagged female Dungeness crabs between February and October 1991. Distributions are based on 373 position fixes (small black circles mark the location of fixes not within the minimum area vs. probability (MAP) utilization distributions). The black square shows the release position for transplanted crabs. The dotted line encloses the minimum convex polygon estimate of the home range of all crabs combined. Polygons 1, 2, and 3 represent the MAP (0.95), the MAP (0.50), and the center of activity or mean position fix, respectively, for all crabs combined. The stars show where nine tagged females molted during this study. Depth contours are in meters.

shallow water, 2) decreased surface salinity caused by large volumes of fresh water from the glacially fed Mendenhall River and development of a pronounced halocline to ~30 m or deeper between May and November (Fig. 6), and 3) complete thermohaline mixing in November caused by cooling of surface waters, decrease in freshwater input, and surface mixing by storms (Bruce *et al.*, 1977). The water column is generally well mixed through March (Fig. 6).

Oceanographic properties measured near the center of the brooding aggregation during the two-year period between November 1989 and 1991 varied seasonally (Fig. 5). Temper-

ature and salinity during the brooding period varied over a fairly narrow range (3–9°C and 26–31.5 psu). The area was well-oxygenated during the entire brooding period (Fig. 5). These properties were more variable and extreme at depths shallower than the brooding aggregation.

During the brooding period, when crabs were relatively inactive and in close proximity to one another at the brooding site, they were exposed to similar levels of temperature, salinity, and DO, and therefore between-individual variation in these properties was low. Variability increased during the larval hatching and nonbrooding periods as crabs dis-

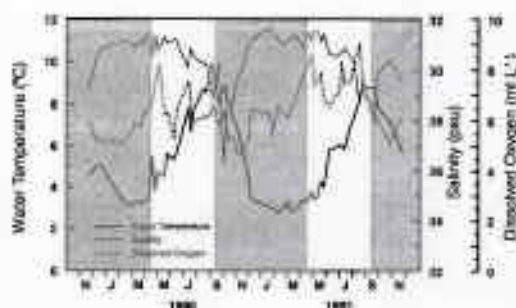


Fig. 5. Oceanographic properties measured near the center of the brooding aggregation site (-20 m) between November 1989 and November 1991. The shaded areas indicate the periods when ovigerous females were generally present at the site.

persed from the aggregation, and crabs did not appear to follow thermo- or halo-preferenda.

Brooding Aggregation Site Characteristics

The main aggregation site spanned depths between -16 and -26 m on a moderate slope (18–33°). The area of highest density was usually well-defined and small (12 m by 8 m) and changed seasonally with depth. Sediments collected within the brooding aggregation site had properties that differed from those collected at nearby locations where crabs did not aggregate (i.e., < 1 crab m⁻²) (Table 3). Sediments within the brooding aggregation site had a larger median particle size, were better sorted (more homogeneous), and had a smaller percentage of silt/clay (Table 3). Aggregation-site sediments were also much more permeable and had lower compressive strength values, indicating that they were less consolidated (Table 3). The first principal component of the natural-log transformed sediment data accounted for 74% of the total variance. Equality of principal component means for the five sites was rejected (ANOVA, $F = 6.6$, $d.f. = 4, 10$, $P = 0.007$). Further, the principal component

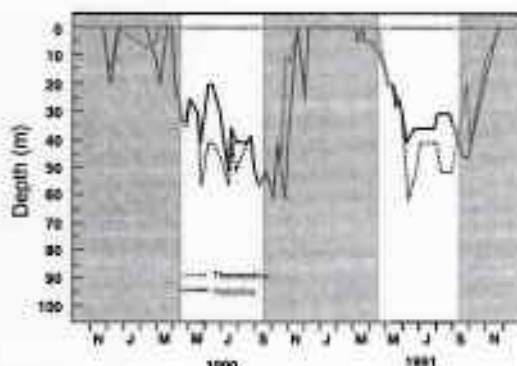


Fig. 6. Depth of the base of the thermocline and halocline between November 1989 and November 1991 at Fritz Cove. The shaded areas indicate the periods when ovigerous females were generally present at the brooding aggregation site.

mean of the brooding aggregation site was significantly different than the principal component means of the four nearby sites.

Mortality of Females After Larval Hatching

We began observing dead female crabs near the head of Fritz Cove in mid-April 1992. Although we made no attempt to quantify the mortality, we collected 49 dead crabs in the immediate area of the main aggregation site between 21 May and 26 June (Fig. 7). Only a few dead crabs were observed after 26 June. All crabs were nonovigerous, had matted pleopodal setae indicating that larval hatch was complete, and ranged in size from 128.9 to 173.0-mm CW (Fig. 7). Carcasses were found between -22 m and the intertidal zone, and 55% of the crabs were classified as skip-molts (i.e., had not molted within the past 365 d) using criteria similar to Hankin *et al.* (1989) (Fig. 7).

DISCUSSION

Brooding Site Fidelity and Homing

Ovigerous female Dungeness crabs in Fritz Cove, Alaska, repeatedly used the same site

Table 3. Median grain size, sorting, percentage silt/clay (< 63 μ m), coefficient of permeability (K), and compressive strength (C.S.) of sediment collected from the center and equidistant locations outside of the brooding aggregation site in Fritz Cove, Alaska. Sediments were graded using the Wentworth classification scale. Values are the mean of three replicate samples and (in parentheses) 1 standard error of the mean.

Location	Depth (m)	Median size (μ m)	Sorting (sp)	Silt/clay (%)	K (cm 10 ⁻⁶ s ⁻¹)	C.S. (kg cm ⁻²)
Center	-16	192 (0.8)	0.70 (0.01)	2.1 (0.19)	0.87 (0.28)	0.09 (0.04)
Above	-4	153 (3.6)	0.85 (0.02)	11.2 (0.85)	0.03 (0.01)	0.12 (0.04)
Below	-26	151 (8.8)	0.83 (0.05)	9.9 (2.42)	0.24 (0.12)	0.18 (0.06)
South	-16	164 (4.3)	0.77 (0.01)	6.4 (0.47)	0.07 (0.04)	0.27 (0.01)
North	-16	177 (5.5)	0.75 (0.02)	6.1 (0.52)	0.08 (0.02)	0.31 (0.06)

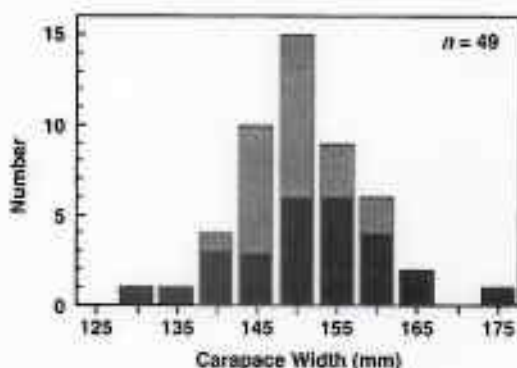


Fig. 7. Size-frequency distribution of dead female Dungeness crabs collected between 21 May and 26 June 1992 in Fritz Cove, Alaska. Shaded bars represent the number of crabs which molted within the previous year; solid bars represent the number of crabs which had not molted for a minimum of one year. n = number of crabs measured.

to brood developing embryos. Annual use of the main brooding area in Fritz Cove by ovigerous females was documented for the period 1989 to 2000 (Stone and O'Clair, 2001; Stone, personal observations). Furthermore, we confirmed that individual crabs used the same brooding area interannually. Four of the seven tagged crabs which did not molt during this study (three of which extruded eggs without an intervening ecdysis) had returned to the brooding aggregation area by October. Ovigerous crabs displaced 1,390 m away from the brooding aggregation homed back to that site within 13 to 20 d. The high cost of ultrasonic transmitters did not permit us to replicate the transplant experiment. We realize that the resulting pseudo-replication limited the generality of our conclusions, but nonetheless provided strong evidence of homing behavior in ovigerous Dungeness crabs in this one instance.

Crab Density and Brooding-Site Habitat Characteristics

Aggregations of buried ovigerous Dungeness crabs have previously been observed in Southeast Alaska (O'Clair *et al.*, 1996; Scheduling *et al.*, 2001), Washington (Dinnel *et al.*, 1987; Armstrong *et al.*, 1988), and northern California (Diamond and Hankin, 1985), but there is scant information on the density of crabs in the aggregations. O'Clair *et al.* (1996) quantified adult Dungeness crab dispersion at five sites in Glacier Bay, Alaska, and found that ovigerous crabs were more frequently and more strongly aggregated than

males and nonovigerous females, especially at smaller spatial scales (e.g., 20–80 m²). Re-examining the original transect data counts that formed the basis of the analyses reported in O'Clair *et al.* (1996), we calculated the density of the two most dense brooding aggregations observed in that study at 5.6 and 2.6 crabs m⁻². Scheduling *et al.* (2001) give estimates of 0.86 and 0.75 crabs m⁻² for the density of ovigerous Dungeness crabs in two aggregations that they studied in Southeast Alaska.

Our *in situ* observations indicate that females brooding eggs form densely packed aggregations and often appear to be stacked atop one another. Density of crabs measured within the brooding aggregation in Fritz Cove in 1999 was at least 20 crabs m⁻². This measurement was made in early March when most females were brooding eggs. Although a few nonovigerous females and males were found within this aggregation, most crabs (96%) were ovigerous females. Based on our calculation of the relationship between carapace width and carapace surface area for females found within this aggregation ($y = 1.27x - 82.6$, $r^2 = 0.96$), 21% of the area we sampled with the cage was covered by crab carapaces alone. Crab density we measured in the Fritz Cove brooding aggregation was much greater than that previously reported (O'Clair *et al.*, 1996; Scheduling *et al.*, 2001).

Ovigerous Dungeness crabs are intimately associated with benthic sediment. Females completely or partially bury in sediment while brooding embryos for about nine months in Alaska and may need to oviposit in a sand substratum to allow for complete cementation of the eggs to the pleopodal setae (Fisher, 1976; Wickham, 1979). Females ovipositing in the laboratory without access to sediment generally lose their entire clutch of eggs (Stone, personal observations).

Ovigerous crabs may aggregate where sediment is optimal for brooding embryos. O'Clair *et al.* (1996) speculate on the properties of the habitat that are favorable to Dungeness crabs for brooding eggs but provide no measurements of those properties. Optimal sediments should have high specific permeability, low compressive strength or consolidation, and consist of well-sorted fine sands (250–125 μ m). Sediments with these properties would have a high rate of replacement of capillary water (Webb, 1969),

thus providing a high rate of exchange of oxygen and metabolites. Very fine sediments such as muds, which have grains tightly packed together, have poor water circulation and often low oxygen tension (Gray, 1981). Sediment consolidation is important because capillary space changes with consolidation (Webb, 1969), and crabs can bury more easily in unconsolidated sands (Stone, personal observations). Sediments in the main aggregation area in Fritz Cove consisted of moderately well-sorted fine sand with a low proportion of silt/clay (Table 3). In addition, sediments within the aggregation area had low compressive strength, and we have often observed percolation (i.e., upwelling of water at the sediment interface) in sediments within the aggregation area. Sediments shallower, deeper, and to either side of the aggregation area where crabs were not aggregated (< 1 crab m^{-2}) had finer median particle sizes, a higher proportion of silt/clay, and were not as well sorted (Table 3). Sediment properties reported by Scheduling *et al.* (2001) at two aggregation sites in Southeast Alaska differed from those we report for the Fritz Cove aggregation site. In general, sediments at the two sites they investigated had finer median grain size, a higher proportion of the silt/clay fraction, and were not as well sorted. Scheduling *et al.* (2001) did not calculate sorting coefficients; these were calculated by us from the grain size percentages they presented. Moreover, in contrast to the present study, they found nearly identical grain size distributions within the aggregation and 20 m away from it.

Function of Brooding Aggregations

O'Clair *et al.* (1996) discussed two possible functions of the brooding aggregations they observed: 1) mutual enhancement of the brooding environment, and 2) group defense. Based on our measurements and observations, we conclude that crabs aggregate in sediments conducive to enhanced exchange of oxygenated near-bottom water with the pore-water surrounding their embryos. We have observed large numbers of ovigerous crabs using the same aggregation site between 1989 and 2000. Continual reworking of the sediment by large numbers of crabs presumably keeps the sediment well-sorted and unconsolidated. In addition, large numbers of non-ovigerous females used this same site to bury

during the nonbrooding period (summer) which should keep the sediments unconsolidated year-round.

Both male and female Dungeness crabs of all sizes bury in the substrate and by doing so may gain refuge from some predators. Ovigerous crabs that cannot move as quickly as nonovigerous crabs because they are encumbered by their egg clutches may, when disturbed by predators, confuse them by emerging from the sediment simultaneously and dispersing in all directions. We have witnessed this "confusion effect" (Hobson, 1978) on numerous occasions, when perhaps thousands of ovigerous crabs emerged from the sediment, reducing visibility instantly to near zero. Aside from this potential selective advantage of aggregating behavior, brooding sites themselves apparently do not function as refuges from predators or extreme oceanographic conditions. In fact, because the sites are highly predictable in space and time, they may confer a selective disadvantage on the crabs in the brooding aggregation. If discovered by a predator such as a sea otter, which would have easy access to crabs, the brooding aggregation would, at least in the short term, provide a ready and reliable source of prey. The sea otter(s) could quickly deplete the number of crabs in the aggregation during one brooding season. The number of crabs in the main brooding aggregation in one bay at Glacier Bay, Alaska, declined markedly after sea otters moved into the bay (O'Clair, personal observations).

Post Brooding-Period Mortality

In Southeast Alaska, females generally brood their eggs for eight to nine months between September and May or June (Stone and O'Clair, 2001). A consequence of the lengthy, over-winter brooding period in Alaska, may be a high mortality of females following larval hatching. The mortality of female crabs that we observed in late spring and early summer may be a common event in the life history of female crabs in Alaska. In the present study, ovigerous females were generally inactive but made periodic, short forays away from the aggregation area during the brooding period. They may forage during these infrequent forays. Schultz *et al.* (1996) present limited evidence from the field (one sampling date in April) which indicated that ovigerous females foraged less frequently than males.

Ovigerous crabs can survive in the laboratory after being starved for six months between December and May (Schultz *et al.*, 1996). Our hypothesis for the mortality we observed in this study is that after the larvae hatched (all carcasses collected had matted pleopodal setae), females were weak from a long, inactive period when energy reserves were exhausted due to starvation. As a result, some females died. Hankin *et al.* (1985) observed size-dependent declines in annual molting probabilities for female Dungeness crabs and concluded that adult females ultimately die of senescence. If senescence were solely responsible for annual mass mortality of females, then the majority of crabs should be older (i.e., very large or, if smaller, old-shelled). In this study, we observed mortality from at least several age-classes (Fig. 7), although, in general, crabs were from larger size-classes. These data implicate some other factor in addition to senescence, such as starvation during the brooding period, that contributed to the observed mass mortality. Stevens and Armstrong (1981) documented mass mortality of adult female Dungeness crabs (110–162-mm CW) along the southern Washington coast. The description of that account was similar to our observations albeit on a much larger scale. All females were nonovigerous and the mass mortality occurred in April, immediately after the egg-brooding period. They attributed the mass mortality to an unknown disease to which older animals were more susceptible.

Seasonal Movements

In this study, ovigerous females dispersed from the brooding aggregation and moved into shallow water (< 10 m) in mid-April and remained there through June. During mid-May we found hundreds of crabs exposed by low tides throughout the lower intertidal zone at the head of the cove. Most were buried deeply in coarse and median-fine sand, and about 80 percent of the crabs were ovigerous females. We observed no foraging behavior in these crabs. Larvae were hatched throughout this period, although peak hatching occurred in June. This movement into shallow water during the period of larval hatch is contrary to the offshore movement reported for females during the period of larval hatch in northern California and Washington (Diamond and Hankin, 1985; Orensanz and Gallucci, 1988).

Onshore movement in this study was coincident with the spring phytoplankton bloom and accompanying rapid increases in DO levels in shallow water. The larvae of some species of crabs begin hatching when exposed to certain chemical cues (Rittschof *et al.*, 1985). In this case, larval hatch might be initiated by high DO levels or some compound or byproduct of phytoplankton. Additionally, onshore movement by ovigerous females may accelerate embryo development in warmer, highly oxygenated water and ultimately retain hatched larvae within the bay.

Many of the crabs that we observed in the intertidal region during mid-May had been excavated from the sediment, and we observed bald eagles (*Haliaeetus leucocephalus*), northwestern crows (*Corvus caurinus*), and several species of gulls (*Larus* spp.) preying on the crabs and eating their eggs. Whatever the purpose of the sudden movement into shallow-water areas during this period, risk of predation is apparently high. Bird predation on Dungeness crabs has previously been reported on juveniles and on large crabs in poor health in the intertidal zone (Orensanz and Gallucci, 1988).

Essential Fish Habitat

The main goal of our study was to further our understanding of adult female Dungeness crab behavior during and after the period of egg brooding. Although this research is basic in nature, it has management implications as it relates to essential fish habitat (EFH). The Sustainable Fisheries Act of 1996 defines EFH as "those waters and substrate necessary to fish for spawning, breeding, feeding, or growth to maturity." As managers strive to apply this definition to individual species, they must consider which spatial scales are important to the key life-history stages of that species. For adult female Dungeness crabs we propose a hierarchy of three spatial scales for consideration by management in the definition of crab EFH. First, the broadest and therefore most conservative definition of EFH would include the area within the MCP for all tagged crabs. This area encompassed about 57% of the total cove habitat and probably included most of the habitat necessary for adult female crabs to complete major life-history requirements (i.e., spawning, breeding, feeding, and growth). The second, more restric-

tive definition of EFH would include only core areas of habitat use (i.e., the 95% and 50% habitat utilization kernels). These areas represented 3% and 0.9% of the total cove habitat, respectively, and accommodated spawning (embryonic development and eclosion). We also observed limited feeding and breeding (mating) in these core areas. The third and most restrictive definition of EFH would include only the area of the brooding aggregation where egg development, obviously critical to the continued existence of the population, repeatedly takes place. This area represented only a fraction of one percent of the total cove habitat.

Areas containing a large percentage of the brood stock of a population for a substantial part of the year (such as the brooding aggregations of Dungeness crabs) should rank high under the most restrictive definition of EFH. These areas are strong candidates for protection as reproductive refugia *sensu* Orensanz *et al.* (1998).

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Seasonal movements and distribution of Dungeness crabs *Cancer magister* in a glacial southeastern Alaska estuary

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ABSTRACT: The movements of 10 female and 8 male adult Dungeness crabs, *Cancer magister* (Dana, 1852), were monitored biweekly to monthly with ultrasonic biotelemetry for periods ranging from 73 to 555 d. Female and male crabs had different seasonal patterns of habitat use, depth distribution, and activity. The general pattern for female crabs was: (1) a relatively inactive period between November and mid-April at depths below 20 m; ovigerous crabs were typically buried during this period in a dense aggregation; (2) abrupt movement into shallow water (<8 m) in late April and residence there until early June; this movement was coincident with the spring phytoplankton bloom and initiation of larval hatching; (3) increased activity beginning in July with movement back to deeper water, presumably to forage. Females that molted prior to oviposition did so in June and July. Male crabs occupied deep water (>40 m) from November to April, then concentrated in shallow water (<25 m), segregated from females, until late July. Males were most active in late summer and moved into deeper water (>30 m) near the mouth of the cove in fall. The range of depths were -0.5 to -61.3 m for females and +0.1 to -89.0 m for males. Female crabs showed fidelity to the head of the cove and typically ranged only 1.5 km from there. Male crabs, however, moved up to 7.2 km from the head of the cove, but did not move close to the nearest established population of Dungeness crabs 9.6 km distant. The discrete population of adult Dungeness crabs in Fritz Cove may be representative of most Dungeness crab populations inhabiting shallow embayments of the coastal fjord system of southeastern Alaska.

KEY WORDS: Dungeness crab · Biotelemetry · Essential habitat · Migration

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INTRODUCTION

The Dungeness crab, *Cancer magister* (Dana, 1852), ranges from the Pribilof Islands, Alaska to Magdalena Bay, Mexico (Jensen & Armstrong 1987) and is exploited in commercial and recreational fisheries throughout most of this range. However, Dungeness crab populations do not show the same pattern of distribution throughout the species' range. In the southern part of the range, the coastline is more uniform and less frequently indented with bays and estuaries, and Dunge-

ness crabs inhabit more of the outer coast. In the northern part of the range, Dungeness crabs predominately inhabit bays and fjord-type estuaries. Distinct inland-water and outer coast populations are thought to occur in some areas of Washington and British Columbia (Orsanz & Gallucci 1988, DeBrosse et al. 1990, Dinnel et al. 1993). In northern California, some outer coast populations may be discrete and geographically isolated from one another (Diamond & Hankin 1985).

Oceanographic conditions vary greatly throughout the 3900 km latitudinal range of the Dungeness crab, and these conditions can affect the timing of life history events and rates of biological processes. Latitudinal variation exists in the timing of egg extrusion, larval

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hatching, mating, and ecdysis in adults (Cleaver 1949, Butler 1956, Gotshall 1978, Wild 1980, Diamond & Hankin 1985, Sulkin & McKeen 1996, Hankin et al. 1997). In general, the reproductive schedules for crabs from the southern end of the range occur earlier in the year than those from northern areas. Rates of embryonic development and larval growth also seem faster in the south. Water temperature affects the rates of egg and larval development (Wild 1980, Shirley et al. 1987) and growth of various instars (Orensanz & Gallucci 1988, Kondzela & Shirley 1993). Local variability within regions also occurs in the timing of these life history events, and this variability has been attributed to differences in water temperature between inshore and offshore areas (Sulkin & McKeen 1996). Because many fisheries are scheduled to avoid fishing activity during periods of high vulnerability and sensitive life history events (e.g., ecdysis and mating), knowledge of the local timing of these events is critical for effective management.

The magnitude of migrations made by some species of crabs may depend on local bathymetry and the spatial distribution of essential habitat (Wallace et al. 1949, Stone et al. 1992). We hypothesized that migrations made by Dungeness crabs in the deep fjord-type estuaries of southeastern Alaska are more restricted than those by crabs in oceanic environments. The objectives of this study were to determine the seasonal movements and habitat use of adult Dungeness crabs in 1 southeastern Alaska estuary and to relate them to life history events. We also investigated the relationship between these life history events and oceanographic conditions.

MATERIALS AND METHODS

This study was conducted in Fritz Cove, 11 km north of Juneau, Alaska (Fig. 1), which has a water surface area of about 8 km² at mean higher high water. Fritz Cove is a small estuary located off a system of large, fjord-type channels. The deepest part of the cove is greater than 100 m; about 12% of the cove is intertidal habitat. The cove is strongly influenced by several freshwater watersheds that empty into Gastineau Channel, including the glacial Mendenhall River and the clearwater Fish Creek (Fig. 1). A strong buoyant plume estuarine front (Largier 1992) is prominent, especially along the northern portion of the cove, between June and October. In general, sub-surface currents are weak, non-directional, and tidally derived (US Department of the Interior 1966). Most of the subtidal area of the cove deeper than 20 m below mean lower low water (MLLW) is covered with glacial silt. The cove is closed to commercial fishing for Dunge-

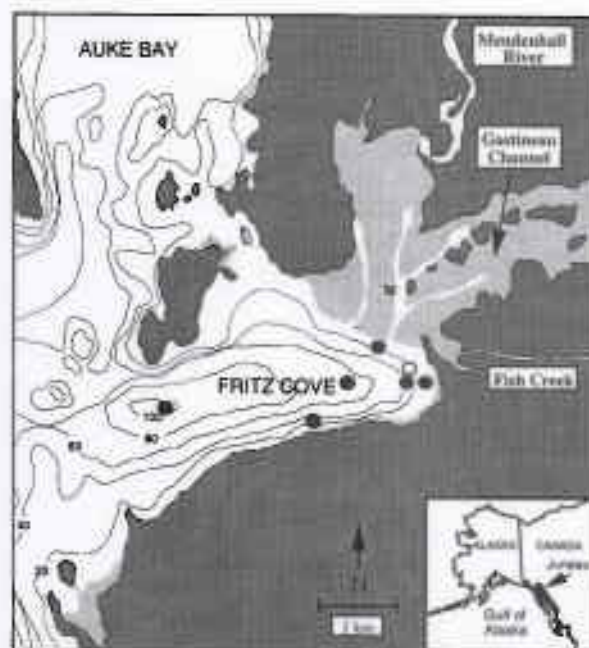


Fig. 1. Study area at Fritz Cove, near Juneau, Alaska, where the movements of adult *Cancer magister* fitted with ultrasonic transmitters were monitored. (O) Location of area where crabs were initially captured; (●) stations where oceanographic profiles of the water column were collected. Depth contours are in meters

ness crab but is used extensively for recreational crabbing.

Female and male *Cancer magister* were collected by SCUBA divers on 8 November and 10 October 1989 respectively, and brought back to the laboratory for tagging. All crabs were collected near the head of the cove (Fig. 1) at a depth of about 20 m, and upon release were returned to the bottom at the collection site by divers to minimize disorientation associated with release in an unfamiliar area (Powell 1964). Ultrasonic tags with a 2 yr life expectancy were attached to 5 female and 5 male crabs. Two additional females were tagged on 13 April and 3 additional females were tagged on 18 May, 26 June, and 11 July 1990 when divers recovered derelict tags (i.e., detached from live crabs). Two additional males were tagged on 13 April 1990 and 1 male was tagged on 11 July 1990. Female crabs ranged from 143.9 to 163.2 mm carapace width (CW) (\bar{x} = 153.0 mm) and weighed (wet weight) between 531 and 773 g (\bar{x} = 676 g). Male crabs ranged from 157.8 to 191.8 mm CW (\bar{x} = 179.7 mm) and weighed between 659 and 1182 g (\bar{x} = 976 g). All female crabs were ovigerous and had full or near-full egg clutches. Only crabs in good physical condition (i.e., no missing appendages or gross evidence of disease) were tagged.

Tags were attached directly to the carapace in the cervical groove between the gastric and cardiac regions with nontoxic SeaGoin' Poxy Quik 5 min epoxy putty. Each transmitter (Sonotronics Model CHP-87) had a unique aural code and a range of about 2 km. The tags were 105 mm long, 16 mm in diameter and weighed 12 g in water (<2.3% of the total body weight for female crabs and <1.8% for male crabs). Crabs were held in flow-through aquaria in the laboratory for at least 12 h prior to release to ensure tag adherence to the carapace.

Positions of the crabs were 'fixed' approximately monthly through winter and then biweekly thereafter. Movements were monitored by surveying the cove in a small boat. To locate crabs we used an ultrasonic receiver (Sonotronics Model USR-4D) and directional hydrophone (Sonotronics Model DH-2) with a beam width of plus/minus 6° at half-power points. A small float was deployed after the boat was positioned over a crab. The boat was maintained at this float while its position was fixed by measuring angles between 3 markers on shore with a beam-converging sextant used as a pelorus (O'Clair et al. 1990). We estimated an error of ± 8.8 m associated with this 'mark-on-top' method by calculating the mean distance between fixes ($n = 27$) for stationary derelict tags.

Depth was measured with a Hummingbird Model 4080D depth finder and is reported relative to MLLW. A Seabird Electronics Searat Profiler was used to collect temperature, salinity, density (σ_t), and dissolved oxygen profiles of the water column at 6 stations throughout the cove. Physical oceanographic variables at depths occupied by crabs were estimated from the profile at the nearest station to each crab. Divers used SCUBA and a submersible receiver/hydrophone (Sonotronics Model USR-88) to recover derelict transmitters and to periodically observe tagged crabs within diving depth (<35 m). *In situ* observations on tagged and untagged crabs included data on sediment type, crab associations, molting or mating behavior, oviposition, and the condition of the egg mass for ovigerous crabs (evidence of hatching, approximate degree of development).

Benthic sediment-core samples were collected from the top 10 cm of bottom sediment by SCUBA divers. Sediments were wet-sieved and graded using the Wentworth scale (Holme & McIntyre 1971).

All means of time-series variables (i.e., activity rate, depth, oceanographic data) are presented as the mean ± 1 SE of the mean. All movements were charted with a microcomputer design and drafting program (Autodesk 1988). The home range was estimated by the mini-

mum-convex polygon method (Worton 1987). Activity rate was calculated as distance moved in meters divided by time in days between successive observations.

RESULTS

The movements of 10 female and 8 male adult *Cancer magister* were monitored for periods ranging from 73 to 555 d (Table 1, Fig. 2). Female crabs were monitored for between 73 and 244 d and male crabs were monitored for between 75 and 555 d (Table 1, Fig. 2). Initially, we intended to monitor the movement of crabs through 1 complete reproductive cycle (12 mo), when biweekly tracking was suspended after 1 yr, however, only 3 of the original males and none of the original females had active transmitters attached. The signal from only 1 transmitter was lost during the entire study period (Table 1); this crab either moved out of the study area or the transmitter failed.

Female and male crabs had different seasonal patterns of habitat use, depth distribution, and activity. Female crabs followed a general pattern of seasonal movement and habitat use that could be divided into 3 phases: (1) a relatively inactive period between November and mid-April at depths below 20 m, when ovigerous crabs were usually buried in a dense aggregation; (2) abrupt movement into shallow water (<8 m) in late April and residence there until early June; onset of this movement was coincident with the spring phytoplankton bloom, and larvae hatched mostly during the latter part of this period; (3) increased activity beginning in July with gradual movement into deeper water.

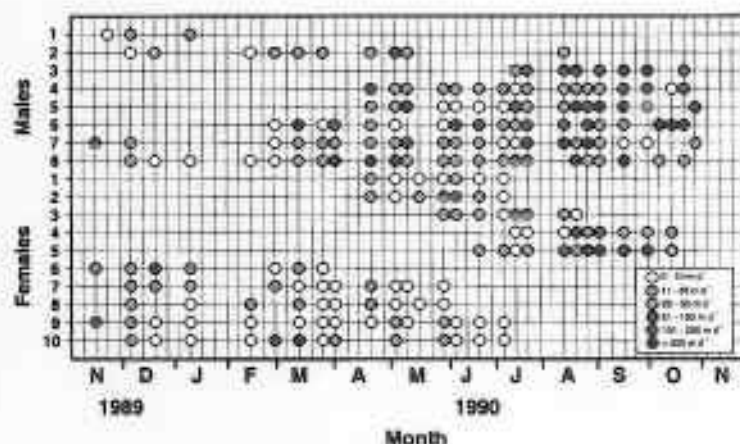


Fig. 2. *Cancer magister*. Tracking records for 18 crabs fitted with ultrasonic transmitters. Each symbol indicates when an individual crab's position was fixed. Crab numbers for females and males on ordinate correspond to order the crabs are listed in Table 1. Pattern of each circle indicates the activity rate (mean movement per day, $m d^{-1}$) for the period from the preceding position fix to the present position fix

Table 1. *Cancer magister*: Carapace width (CW), date of release, duration of tracking, home range (measured with the minimum convex polygon, MCP, method), and fate of 10 female and 8 male Dungeness crabs monitored with ultrasonic biotelemetry in Fritz Cove, near Juneau, Alaska. nm: not measured because of small sample size of position fixes (n = 4)

CW (mm)	Release date	Duration (d)	MCP (m ²)	Fate of crab
Female crabs				
155.4	13/4/90	73	65 012	Molted on 15/7/90 at -16.4 m
163.2	13/4/90	73	189 189	Molted on 11/7/90 at -8.9 m
143.9	18/5/90	96	339 335	At large ^a
155.2	11/7/90	98	185 855	At large ^a
151.8	26/6/90	113	1 341 330	At large ^a
159.4	9/11/89	141	407 290	Derelict tag – unknown cause
159.5	9/11/89	208	603 045	Molted on 5/6/90 at -5.5 m
144.7	9/11/89	210	151 401	Molted on 7/6/90 at -5.9 m
146.8	9/11/89	244	279 108	Molted on 15/7/90 at -21.0 m
149.9	9/11/89	244	444 479	Molted on 11/7/90 at -18.3 m
Male crabs				
191.8	30/10/89	75	nm	Signal lost
182.2	30/10/89	200	1 138 937	Octopus predation
180.0	11/7/90	212	3 186 250	At large ^a
157.8	13/4/90	301	1 326 617	Molted on 21/2/91 at -6.6 m
176.7	13/4/90	373	2 199 662	Crab and tag recovered
178.9	30/10/89	446	10 503 684	Molted on 18/1/91 at -39.9 m
185.2	30/10/89	446	3 290 968	At large ^a
182.6	30/10/89	555	4 603 538	At large ^a

^aCrabs at large were still at liberty and apparently moving at time of last fix

During winter, ovigerous female crabs generally remained near the head of the cove in a well-defined area at 20 to 25 m depth (Fig. 3A). Dive observations indicated that ovigerous females in dense aggregations were often completely buried in a mixture of moderately sorted fine sand and silt (median particle size = 138 μm ; Table 2) on a moderate slope (18 to 33%). Several crabs, however, made sporadic forays of less than 700 m during this 6 mo period (Fig. 3A).

During late April, female crabs moved abruptly into shallow water (<8 m) areas near the head of the cove (Fig. 3B). The onset of this movement was coincident with the spring phytoplankton bloom. Diver observations of ovigerous crabs indicated that larvae hatched throughout this period but mostly during the latter part of the period. By late June, all female crabs had matted setae on their pleopods, indicating recent larval hatching. Movements in shallow water were restricted.

By early June, many females had increased activity and began to move to deeper water (Fig. 3C). We presume that this movement to deeper water was associated with increased foraging or dispersal to molt and mate. Females that molted prior to egg extrusion did so between early June and mid-July at depths between 6 and 21 m (Table 1, Fig. 3C).

Male crabs occupied deep water (>40 m) from November to April (Fig. 4A), then concentrated in shallow waters (<25 m), typically segregated from females,

until late July (Fig. 4B). Diver observations made during this shallow-water phase indicated that males were loosely aggregated on the slope habitat and were shallowly buried in the sediment. Males were very active in late summer and moved into deeper water (>30 m) near the mouth of the cove, where 2 of the tagged crabs molted in January and February (Table 1, Fig. 4C).

Female crabs had smaller home ranges and moved shorter distances from the release site near the head of the cove than male crabs. Female crabs had home ranges of 0.65 to 1.34 km² (\bar{x} = 0.40 km²), whereas

Table 2. Particle-size analysis of sediment collected where ovigerous *Cancer magister* formed dense buried aggregations in Fritz Cove. Sediments were collected at 21.6 m below MLLW and graded using Wentworth scale

Sediment type	Size (μm)	Weight (g)	Composition (%)
Pebble	>4000	0.0	0.0
Granule	4000–2000	0.0	0.0
Very coarse sand	2000–1000	1.7 ^a	0.5
Coarse sand	1000–500	0.5	0.1
Medium sand	500–250	16.5	4.9
Fine sand	250–125	168.1	49.8
Very fine sand	125–63	76.1	22.5
Silt	<63	74.7	22.2

^aConsisted of approx. 67% bivalve shell fragments

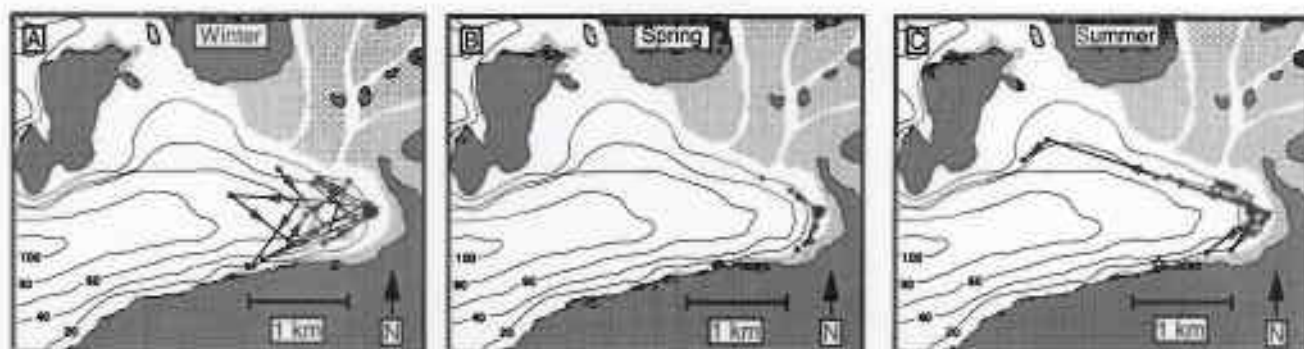


Fig. 3. *Cancer magister*. Areas of distribution and movement patterns of females fitted with ultrasonic transmitters. Arrows indicate large-scale movement. (A) Distribution from November 1989 to mid-April 1990; (B) distribution from late April through early June 1990; (C) distribution from mid-June through August 1990. Star symbols ($n = 5$) show where female crabs molted. Depth contours are in meters

males had home ranges between 1.14 and 10.5 km² ($\bar{x} = 3.75$ km²) (Table 1). Female crabs moved between 0.38 and 4.23 km from the head of the bay where they were tagged, and none left the bay (Fig. 3). Male crabs migrated between 2.13 and 7.24 km from the head of the bay but all either molted near the entrance of the bay or returned to the bay in spring (Fig. 4).

The mean depth occupied by females was shallower than that occupied by males during each month, except when both groups occupied shallow water during June and July (Fig. 5A). Female crabs occupied depths from -0.5 to -61.3 m, whereas male depths ranged from +0.1 to -89.0 m.

Both female and male crabs had low activity rates during winter (through March), but activity rate increased sharply in spring when crabs moved into shallow water (Figs. 2 & 5B). Female crabs were relatively inactive during the period of larval hatch, but activity

increased again during summer when females presumably foraged at greater depths (Fig. 5B). Male crabs had maximum activity in early April when they moved into shallow water, followed by a relatively quiescent period while in shallow water through June (Fig. 5B). Males were very active between July and October (Figs. 2 & 5B).

Because the oceanographic variables measured during this study varied with depth, and both female and male crabs had similar patterns of depth distribution (Fig. 5A), these variables did not differ greatly for the 2 groups (Fig. 6). Mean water temperature of areas occupied by females ranged from 3.1°C during early March to 10.0°C during late August (Fig. 6A). Males occupied areas with mean water temperatures ranging from 3.0°C during early March to 9.5°C in July (Fig. 6A). Individual crabs occupied water temperatures between 2.7 and 12.2°C.



Fig. 4. *Cancer magister*. Areas of distribution and movements of males fitted with ultrasonic transmitters. Arrows indicate large-scale movement. (A) Distribution from November 1989 through March 1990; (B) distribution from April through late July 1990; (C) distribution from late July through October 1990. Star symbols ($n = 2$) show where male crabs molted. Depth contours are in meters

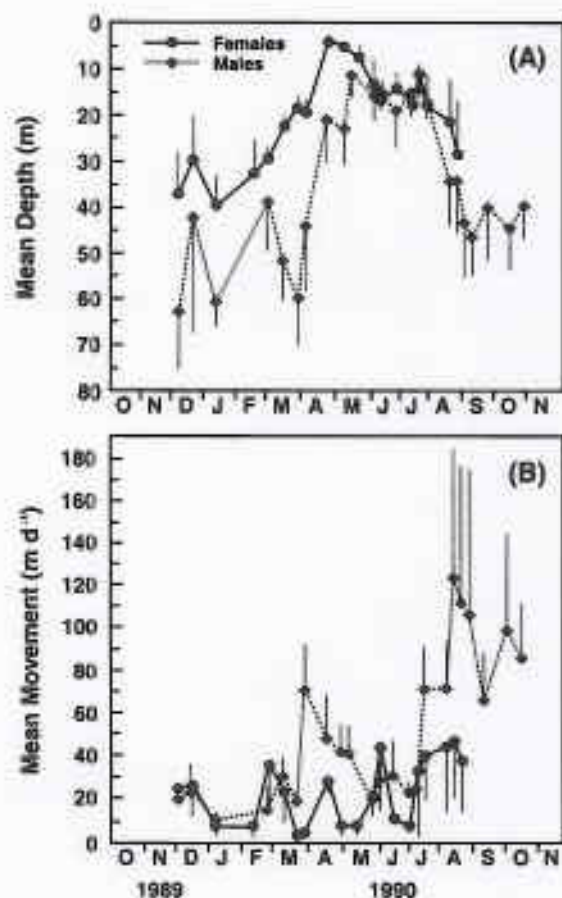


Fig. 5. *Cancer magister*. (A) Mean depth and (B) activity rate (mean movement per day, $m d^{-1}$) for females (-1 standard error of the mean, SEM) and males ($+1$ SEM) fitted with ultrasonic transmitters between November 1989 and 1990

The mean salinity of areas occupied by females ranged from 26.5 to 31.3 compared with 24.8 to 31.5 in areas occupied by males (Fig. 6B). Crabs were exposed to the lowest salinity in July, when they occupied shallow water inundated with fresh water from streams, and were exposed to the highest salinity in late March before they moved into shallow water. Individual female crabs occupied areas where salinity was 21.0 to 31.8, whereas males occupied areas where salinity was 18.3 to 31.9.

Both groups of crabs occupied areas of fairly well-oxygenated water throughout the year (Fig. 6C). In general, shallow water had higher dissolved oxygen (DO) concentrations, and this was especially evident beginning in April during the spring phytoplankton bloom, when both groups of crabs moved into shallow-water areas. Larvae began to hatch during this period, as evidenced by *in situ* observations of females with matted pleopodal setae and observations on collected

crabs held in the laboratory. We suspect that the sharp drop in DO in early June (Fig. 6C) was due to the rapid settlement of senescent phytoplankton from shallow water. Mean DO concentrations of areas occupied by female crabs ranged from $5.1 ml l^{-1}$ (69% saturation) in December to $7.8 ml l^{-1}$ (118% saturation) in July (Fig. 6C). Individuals occupied areas ranging from 4.4 (62% saturation) to $8.7 ml l^{-1}$ (131% saturation) DO. Males occupied areas with mean DO concentrations ranging from $4.3 ml l^{-1}$ (61% saturation) in December to $8.2 ml l^{-1}$ (124% saturation) in July. Individual crabs occupied areas with DO ranging from 3.5 to $9.0 ml l^{-1}$ (50 to 135% saturation).

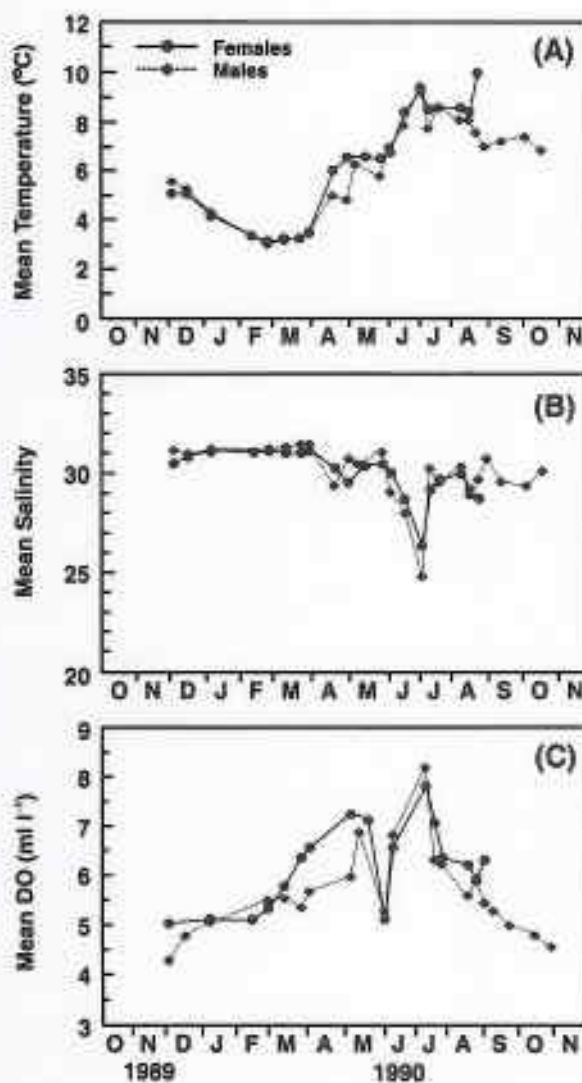


Fig. 6. (A) Mean bottom water temperature, (B) salinity, and (C) dissolved oxygen of areas occupied by female and male *Cancer magister* fitted with ultrasonic transmitters between November 1989 and 1990

DISCUSSION

Despite the existence of important *Cancer magister* fisheries in Alaska (e.g., Alaskan harvests account for almost 50% of the total US harvest in some years; Alaska Department of Fish and Game 1990), information on movements and the timing of critical life history events of Dungeness crabs in Alaska is incomplete. Although we do not intend the data collected in this study to be comprehensive, we believe the movement and life history patterns that we infer from relatively short tracking periods (73 to 555 d) are indicative for this species in southeastern Alaska.

Research on the movements and distribution of Dungeness crabs in inland waters of southeastern Alaska has been limited. Lehman & Osborn (1970) tagged both female and male crabs in a fjord-type estuary and concluded from tag recoveries that post-larval crabs probably do not undertake extensive migrations. They attribute the limited movements to the discontinuity of appropriate habitat. Results from that study on movement and depth distribution patterns for males and females were similar to our study, except they did not observe movement by females into shallow water in spring.

Results from this study substantiate previous work on short-term movements (up to 10 d) of Dungeness crabs in southeastern Alaska, which indicated that ovigerous female crabs were less active, moved shorter distances, and used fewer of the available habitats than male crabs (O'Clair et al. 1990). Furthermore, we were able to confirm that ovigerous crabs use a very restricted area for much of the egg-brooding period. The restriction of egg-brooding to a small proportion (<10%) of the total habitat at the head of Fritz Cove is strong evidence for habitat selection by ovigerous female crabs. We suspect this habitat has specific characteristics which are optimal for brooding eggs.

Compared to adult Dungeness crab populations outside southeastern Alaska, Fritz Cove crabs had very limited movements and restricted distribution. Merritt (1985) briefly summarized data from a mark and recapture program conducted on Dungeness crabs in Lower Cook Inlet, Alaska, which indicated that movement of crabs differed with geographical area. Crabs inhabiting bays appeared to have more restricted and localized movements than crabs which occupied coastal areas. Although described as localized movements, crabs in Lower Cook Inlet had estimated home ranges (52 to 667 km²) much larger than those we estimated for crabs in Fritz Cove.

Smith & Jamieson (1991) studied the movement of adult Dungeness crabs in southern British Columbia, and although they described movements as non-migratory and limited, they estimated movement rates much

greater than those observed in this study. They estimated rates of 419 m d⁻¹ for females and 288 m d⁻¹ for males compared to our measurements of 23 and 51 m d⁻¹, respectively, for females and males. They monitored the movements of crabs from August through February, whereas we monitored crab movements from November through August for females and for 1 full year for males. They used beam trawling, mark and recapture, and acoustic tagging methods to infer that females moved more than males, a result that differs from that of the present study. Smith & Jamieson (1991) found that both females and males were less active during winter, and that males retreated to deeper water in fall and winter and returned to shallow water in spring and summer, these results agree with those of the present study.

The movements of male Dungeness crabs (≥ 155 mm CW) along coastal Washington were studied as part of mark and recapture study by Cleaver (1949). Males made considerable along-shore migrations averaging 18.5 to 22 km after 6 mo. Although most crabs moved less than 37 km, 1 crab moved over 148 km in just 6 mo. Smaller crabs (≤ 169 mm CW) tended to migrate more than larger crabs.

Movements of Dungeness crabs were also studied in northern California (Gotshall 1978, Diamond & Hankin 1985). Gotshall analyzed mark and recapture data from a multi-year study of male crabs. Movements were described as limited and crabs as resident to areas, despite moving at rates up to 740 m d⁻¹ and straight-line distances of 60 km or more in a fishing season (1 crab moved 29 km in 39 d). Extensive along-shore movements were made in some areas and prevailing currents were suspected as factors governing those movements. The farthest straight-line distance moved by a male in our study was 7.2 km. Gotshall (1978) also observed the seasonal deep to shallow-water movement of males observed in our study and that of Smith & Jamieson (1991).

Diamond & Hankin (1985) studied the movements of adult (≥ 90 mm CW) female Dungeness crabs in northern California using mark and recapture methods. Of the females recovered that were at large for 1 full year, 37% were recovered within 2 km of their release site. The authors suggest that this degree of site-fidelity implies that adult females constitute highly localized stocks there. Over 40% of the females moved more than 5 km, however, and several moved over 60 km. They did not indicate the reproductive status (i.e., ovigerous or non-ovigerous) of the females in their study; ovigerous females tend to be less active than non-ovigerous crabs (O'Clair et al. 1990). Diamond & Hankin (1985) found no difference in female movements in relation to body size. In general, females moved inshore in spring for molting, mating, and egg extrusion, and then moved offshore in the fall to release larvae.

Table 3. Peak timing of life history events of adult Dungeness crabs from locations throughout its range

Location	Female ecdysis	Male ecdysis	Mating	Oviposition	Ecdysis	Source
California			Mar to Jun	Late Sep to Nov		Wild (1980), no data provided
Central California				Oct	Late Dec to Early Feb	Wild (1980), no data provided
N. California				Oct	Jan to early Mar	Wild (1980), no data provided.
N. California			Apr & May			Gotshall (1978)
N. California					Late fall	Diamond & Hankin (1985)
N. California	Mid-Feb to Mid-May ^a	Late Jul to Late Aug ^a			Mid-Dec to Late Feb	Hankin et al. (1997)
Coastal Washington	May & Jun	Early Nov	May & Jun ^c	Early Nov	Jan to Mar	Cleaver (1949)
Washington					Mid-Feb	Sulkin & McKeen (1996)
Washington	May & Jun	Jul to Oct	May & Jun			Orensanz & Gallucci (1988)
British Columbia				Sep to Feb		Butler (1956)
SE Alaska				Oct & Nov		Shirley et al. (1987)
SE Alaska	Jul to Sep	May to Aug	Aug & Sep			Shirley & Shirley (1988), no data provided
SE Alaska		Feb to May ^b		Sep & Oct	Apr	Lehman & Osborn (1970)
SE Alaska	Jun & Jul	Dec to Mar	Jun to Sep ^c	Aug to Oct	Apr to Jul	This study

^aPeaks in late August
^bPeaks in early April
^cObserved every month except January

^aObserved soft-shelled crabs every month except January
^bObserved every month except February

Compared to the above studies on movements of Dungeness crabs, the adult population in Fritz Cove showed very localized movements. None of the female crabs moved further than 4.2 km from the head of the cove, and although several males moved outside the cove, those which did not molt and which we were able to continue monitoring, returned to the shallow-water areas of the cove in the spring. No tagged crabs moved close to the nearest established population of Dungeness crabs 9.6 km distant. Because of the disjunct distribution of crab populations in southeastern Alaska, and based on results of this study, limited movement of adult crabs in populations in southeastern Alaska may be more the rule than the exception. Given the limited movements and small home ranges of adult Dungeness crabs in southeastern Alaska populations, they may be a good candidate species for studying the effectiveness of marine reserves designed to protect populations from overexploitation and human disturbance.

The timing of life history events for crabs in this study occurred later in the year than in southern populations (Table 3). One notable exception was that we observed mating (i.e., crabs in a pro-copulatory embrace) pairs of Dungeness crabs *in situ* every month except February in northern southeastern Alaska (Stone & O'Clair pers. obs.). Mating in Dungeness crabs is not strictly seasonal or synchronous in southeastern Alaska, although a peak in mating occurs in late summer and early fall. The timing of mating may differ between

female reproductive classes. We observed pubescent females (i.e., females about to undergo their molt to maturity, <118 mm CW) mating between August and April, while larger females (>118 mm CW) were observed mating between May and December. A similar size-dependent timing for mating in female crabs was observed in northern California (Hankin et al. 1997). Our observations of mating pairs were rare, however. We have observed only 65 pairs in shallow water (intertidal to -25 m) during any time of year. One explanation for this is that mating may be more common deeper than -25 m. Although we did find 1 mating pair which was completely buried in sand-silt substrate, we do not know if this is common behavior. Cleaver (1949) observed mating pairs in all months except January in coastal Washington. Another difference we found in the timing of life history events was that females in Fritz Cove oviposit at about the same time of year or earlier than those in southern areas and they brood eggs for a much longer time (up to 9 mo). Embryonic development in the colder water (3 to 7°C) of southeastern Alaska should be slower than in warmer southern waters (Shirley et al. 1987).

Although *Cancer magister* is a weak hyperosmotic regulator and is able to tolerate lower salinity than other *Cancer* species (Mantel & Farmer 1983), only 4 tagged crabs (on 6 separate occasions) were tracked into the intertidal region where salinity was often greatly reduced (21.2 in this study). Crabs moved to

deeper water in late June, when shallow-water areas became brackish, but crabs were not inhibited from moving into shallow-water areas by the strong thermocline and halocline that developed there in spring. Movements of female red king crabs appear to be constrained by these strong clines (Stone et al. 1992). Crabs in the present study occupied areas where salinity ranged from 18.3 to 31.9. *In situ* salinity ranges for adult Dungeness crabs have not been published, so we cannot compare the range observed in our study with that in other areas. Crabs in this study occupied areas with a relatively narrow range of temperatures (2.7 to 12.2°C). Water temperatures in Fritz Cove never dropped to 1°C, at which temperature adult female crabs held in the laboratory suffer 100% mortality after 35 d (Shirley et al. 1987).

The Fritz Cove population may be representative of most adult Dungeness crab populations inhabiting shallow embayments of the coastal fjord system of southeastern Alaska. These populations may also be geographically discrete and very localized. If such populations are dependent on larval recruitment from within to maintain the population, they may be more susceptible to local disturbances such as over-fishing, mass mortality from sea otter predation, pollution, and development. Genetic studies indicate little stock separation over much of the species' range (Soulé & Tasto 1983), however, probably due to extensive dispersal of the larvae, which are planktonic for up to 5 mo. Genetic studies have not been conducted on discrete populations in southeastern Alaska. Until larval transport dynamics and recruitment and genetic studies are conducted, populations of adult crabs in southeastern Alaska should be managed as though they are spatially discrete.

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**Mass Molting of Tanner Crabs *Chionoecetes bairdi*
in a Southeast Alaska Estuary**

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Mass Molting of Tanner Crabs *Chionoecetes bairdi* in a Southeast Alaska Estuary

Robert P. Stone

ABSTRACT: A spring migration of Tanner crabs *Chionoecetes bairdi* into a shallow, glacially-influenced cove to molt en masse was studied in 1992 and 1993. An estimated 11,500 crabs molted in a 0.034 km² area of shallow (+0.6 m to -17.4 m) water in 1992. Over 2,400 carapaces from intact exuviae were collected by scuba divers in a 100×70 m section of the molting area. Molting in both years was restricted to a small area of the cove even though oceanographic conditions and habitat were similar throughout the cove. Crabs were 97% males and had probably molted within the previous year. Approximately 30% of the crabs would have recruited to the commercial fishery after this molt. Chelae measured from exuviae in spring 1993 indicated the migration consisted almost entirely of small-clawed crabs.

INTRODUCTION

The Tanner crab *Chionoecetes bairdi* on the North America coast ranges from Oregon (Hosie and Gaumer 1974) to the southeastern Bering Sea where it co-occurs and hybridizes (Karinen and Hoopes 1971) with the snow crab *Chionoecetes opilio* (Hart 1982). In Alaska, the Tanner crab currently supports a commercial fishery in Southeast Alaska only, but until recently it supported large-scale commercial fisheries throughout the Gulf of Alaska and the southeastern Bering Sea. Although much of the life history of this genus has been extensively studied, information is scarce on the timing, habitat requirements, and environmental factors influencing ecdysis in Tanner crabs.

Ecdysis is a critical stage for crustaceans. Growth, reproduction, and susceptibility to predation depend on the periodicity and timing of the molt cycle in crabs. Pubescent females (i.e., females about to undergo their molt to maturity) must molt before mating for the first time (Adams and Paul 1983). In the laboratory, male crabs are incapable of mating for at least 90 d after ecdysis (Paul et al. 1995). The molt cycle may also be an important factor in the dynamics of disease transmission and infection (Meyers et al. 1990).

Female *Chionoecetes* have determinate growth and become anecydial when sexual maturity is attained

(Hartnoll 1969; Hilsinger 1976). Male *Chionoecetes* are thought to exhibit indeterminate growth, but their growth pattern is subject to debate (Conan and Comeau 1986; Ennis et al. 1988; Donaldson and Johnson 1988; Conan et al. 1990; Dawe et al. 1991). A significant change in allometric growth occurs for some adult males; the chelae become disproportionately enlarged (Hartnoll 1963). Males that have attained differentiated chelae are referred to as large-clawed and may have competitive advantages over small-clawed crabs in mating and intraspecific agonistic interactions (Hooper 1986; Lee and Seed 1992; Stevens et al. 1993). Claw differentiation for male Tanner crabs occurs over a range of several size classes.

Only male Tanner crabs with a carapace width (CW) ≥140 mm including carapace spines (138 mm CW excluding spines) are commercially harvested in Southeast Alaska. Because male size at 50% sexual maturity is estimated at 113 mm CW (Brown and Powell 1972), a size limit of 138 mm would allow most male crabs to breed before harvest, thus preserving the stock's reproductive potential (Donaldson and Donaldson 1992). Crabs are not harvested during the molting period to minimize fishing mortality and maximize meat yield and market value. Colgate (1982) suggested that May is the peak molting period for male crabs in the western Gulf of Alaska, whereas Meyers

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et al. (1990) stated that Southeast Alaska Tanner crabs begin molting in mid March with peak activity occurring in April.

Tanner crabs were first observed molting en masse at the head of Fritz Cove on 6 April 1990, when numerous, large piles of exuviae were observed along and just above the slope at -1.8 m. Approximately 100 soft-shelled and actively-molting crabs were also found scattered in the area. All crabs and exuviae examined were males and comprised several size classes. Similar observations were made during the first week of April 1991. Field work during 1990 and 1991 were lim-

ited to these qualitative observations. The objective of this study was to quantitatively examine annual mass migration of Tanner crabs into shallow water to molt and to relate this event to the life history of the species.

METHODS

Spring migration, molting and reproduction of Tanner crabs were studied in Fritz Cove approximately 11 km northwest of Juneau, Alaska (Figure 1). Fritz Cove is

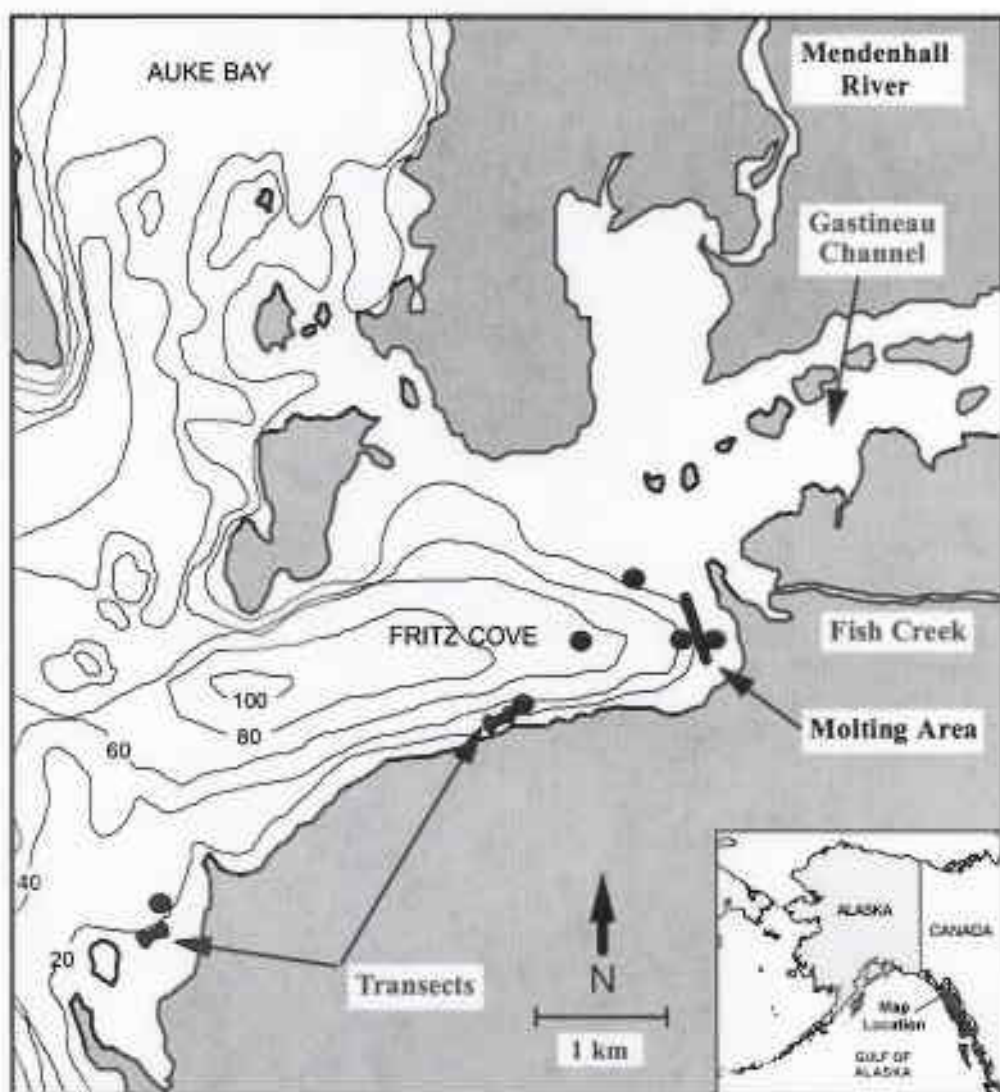


Figure 1. Study area at Fritz Cove near Juneau, Alaska where Tanner crabs were observed molting. Two additional 100-m transects were monitored weekly for the presence of molting crabs. Water temperature and salinity profiles were collected each week at locations denoted by solid circles. Depth contours are in meters.

a small estuary located off a system of large fjords. The cove is strongly influenced by freshwater from both the large, glacial Mendenhall River and the clearwater Fish Creek. Several watersheds empty into Gastineau Channel, a saltwater tidal slough that flows into Fritz Cove. Most of the subtidal area deeper than

-5 m mean lower low water (MLLW) is covered with glacial silt.

A 100 × 70 m section (hereafter referred to as collection area) was delineated within the entire molting area; collections were initially made there and counts during the first week of collection indicated that exu-

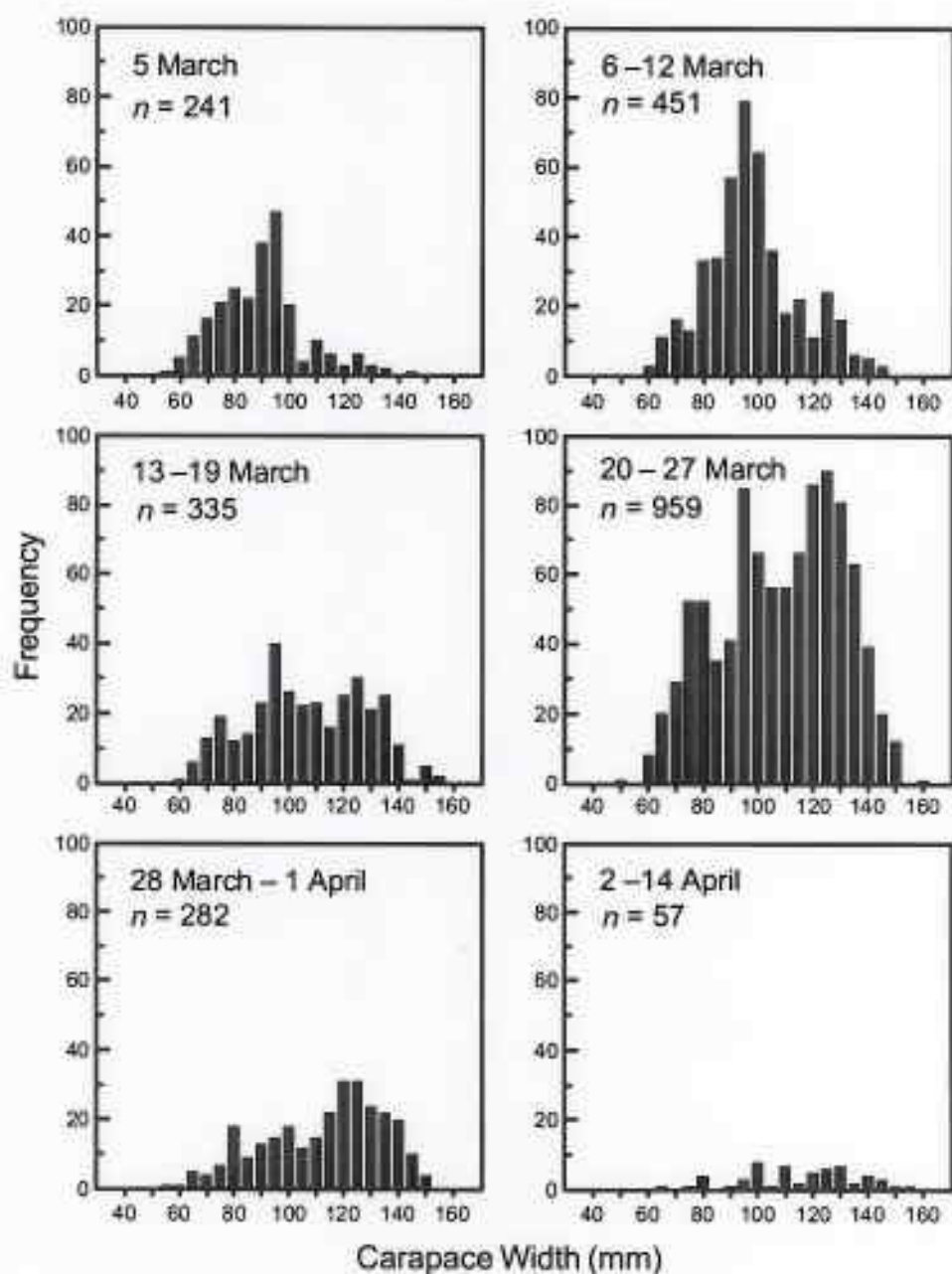


Figure 2. Carapace width frequencies of male Tanner crab exuviae collected during 6 time intervals between 5 March and 14 April 1992. Width intervals are 5 mm. No exuviae were found in the study area after 14 April.

viae were equally distributed in the molting area. The molting area consisted of 3 distinct homogeneous zones: (1) a low-gradient (2–7%), coarse sand flat extending from +0.6 m to a prominent shelf break at -1.8 m; (2) a mid-gradient (18–33%), fine sand slope from -1.8 m to -6.7 m; and (3) a high gradient (33–41%), fine sand and silt slope from -6.7 m to -17.4 m (all depths are reported relative to MLLW). All zones were devoid of boulder patches and associated macrophytes. All observations and collections were made by scuba divers. Depth was measured with a Suunto SME-ML¹ dive computer. Dive observations were made at least once per month in 1992 and 1993. Supporting observations made during several hundred scuba dives in and near the study area between 1990 and 1999 are incorporated into the discussion.

Carapaces of all exuviae ($n = 2,407$) within the collection area were collected every week during March and April 1992. Exuviae were collected on 18 different dates during this period. Dives were made each week to -30 m. Divers swam systematically throughout the collection area until all carapaces from exuviae had been collected. Gender of each exuvium was determined underwater, and carapaces were segregated by sex. Carapace width (i.e., straight line distance

across the widest part of the carapace, excluding spines) of each exuvium was measured to the nearest 0.1 mm. Exoskeleton condition (EC), a subjective measure of exoskeleton age and approximate time since last molt, was recorded for each exuvium using the following criteria: (1) soft, brick red, pliable exoskeleton indicative of a recent molt, (2) hard, clean exoskeleton with limited epifauna and scratches indicative of a molt within one year, and (3) hard, worn exoskeleton with epifauna, discoloration and scratches indicating no molting within the past year. Excessive wear and epifauna on an exoskeleton would indicate several years had elapsed since the last molt.

On 10, 16, 26 March and 1 and 7 April 1993, intact exuviae were collected from the molting area. Exuviae of male crabs ≥ 85 mm CW ($n = 189$) were randomly collected, and CW, chelae height (CH), and EC were recorded for each exuvium. Chelae height was measured at the widest section of the propodus (spines excluded). Because Tanner crabs are homochelous, heights of both chelae were averaged if they differed by less than 1 mm, to exclude from analysis regenerated or damaged chelae. If they differed by more than 1 mm, the larger chela measurement was recorded as CH.

In 1993, 37 old-shell crabs (EC > 2) were collected in or near Fritz Cove and held in flow-through aquaria in the laboratory throughout spring to determine if they

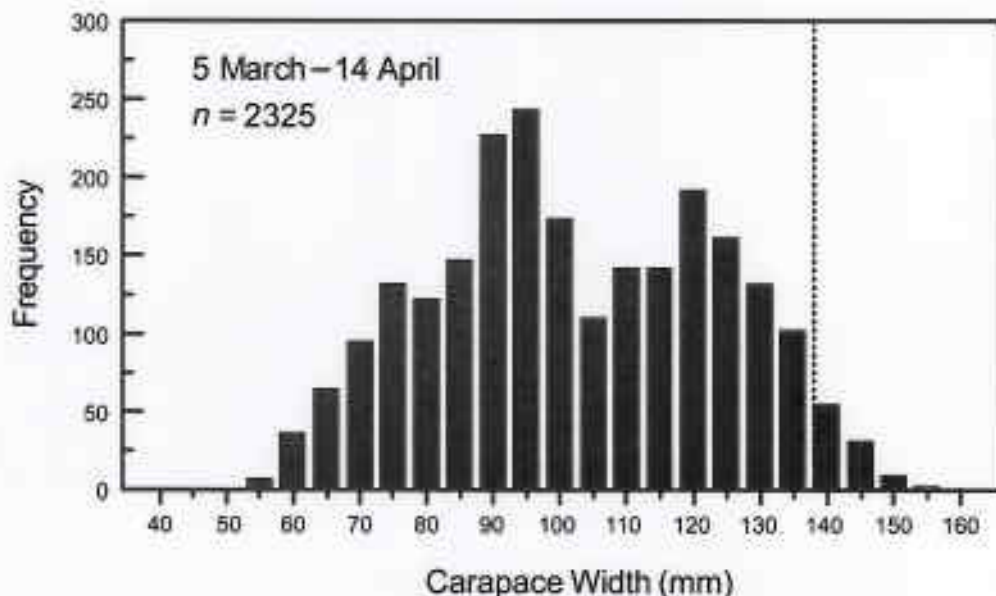


Figure 3. Carapace width frequencies of male Tanner crab exuviae collected between 5 March and 14 April 1992 in Fritz Cove, Alaska. Intervals are 5 mm. The dashed line at 138 mm indicates the minimum legal size for commercial harvest of Tanner crabs in Southeast Alaska.

¹ Use of trade names does not imply endorsement by the National Marine Fisheries Service.

molted. During both years, pre-mating pairs ($n = 61$) found within and near the study area were captured and held in the laboratory until molting or mating occurred. Aquaria were maintained at ambient (~ 30 m depth) temperature and salinity, and crabs were fed a mixed diet of blue mussels and squid twice weekly.

The relationship between chela height and carapace width was compared for non-molting crabs and exuviae collected in 1993. A linear regression line was fit to the natural-log transformed data for each group. The two fitted lines were then tested to determine if they were significantly different from each other (Neter and Wasserman 1977).

Profiles of water temperature and salinity were collected weekly in 1992 at 5 locations in Fritz Cove with a Seabird Electronics Seacat Profiler (Figure 1). Two additional transects (approximately 100×70 m) within the same depth range were established 1.5 km and 5.0 km from the molting area (Figure 1), and were monitored each week for molting activity.

RESULTS

Crabs moved into shallow water near the head of Fritz Cove to molt in early March 1992. Crabs molted within a 0.034 km^2 area ($480 \text{ m} \times 70 \text{ m}$) at depths between $+0.6$ m and -17.4 m. A total of 2,407 Tanner crab exuviae were collected within the collection area between 5 March and 14 April. If exuviae were equally distrib-

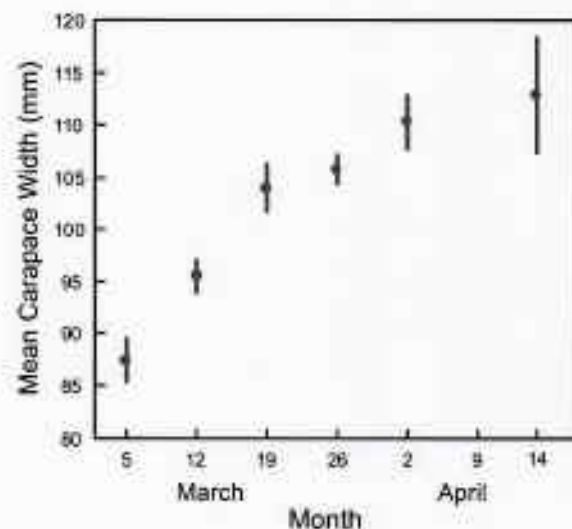


Figure 4. Mean carapace width ($\pm 95\%$ confidence limits) of male Tanner crab exuviae collected during 6 intervals between 5 March and 14 April 1992.

uted throughout the entire molting area as initial observations indicated, an estimated 11,500 crabs at a density of 0.34 crabs per m^2 migrated to the head of Fritz Cove to molt. No exuviae were observed below -17.4 m.

Molting peaked between 20 and 27 March 1992 ($n = 959$, Figure 2). Only 57 exuviae were collected after 1 April, and none were collected after 14 April. An initial peak in molting occurred between 6 and 12 March when 451 crabs molted. Crabs migrating to the head of Fritz Cove to molt were mostly males (96.6%). Male exuviae ranged from 47.8 to 155.2 mm CW and comprised many size classes with modes at 95 and 120 mm CW (Figure 3). Crabs at 95 mm CW would require 2 molts and crabs at 120 mm CW would require 1 molt to reach legal size (Donaldson et al. 1981). Only 84 male exuviae (3.6%) were larger than the minimum legal size of 138 mm CW. Using the growth equation

$$\text{post-molt CW} = 1.07(\text{pre-molt CW}) + 15.75$$

derived for Kodiak Island area male crabs (Donaldson et al. 1981), crabs >114.3 mm CW before molting (698 crabs or 30%) would have recruited to the fishery. Larger males tended to molt later in spring than smaller males (Figure 4).

Exuviae from females and small juveniles were uncommon in Fritz Cove in 1992. Only 81 female exuviae were found in the collection area between 5 March and 1 April (Figure 5); none were found after 1 April. Only one small juvenile exuvium (30 mm CW) of indeterminate sex was collected.

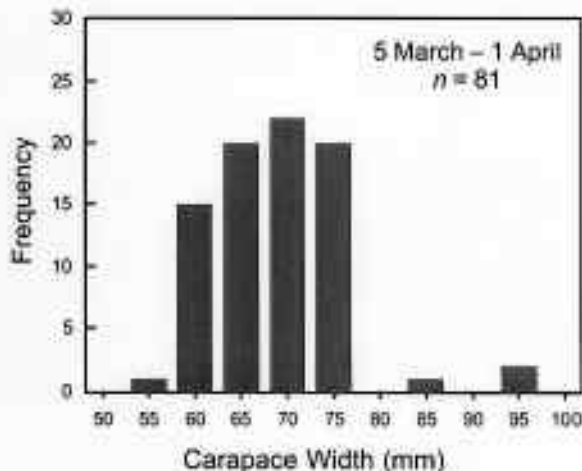


Figure 5. Carapace width frequencies of female Tanner crab exuviae collected between 5 March and 1 April 1992 in Fritz Cove, Alaska. Intervals are 5 mm. No female exuviae were found in the study area after 1 April.

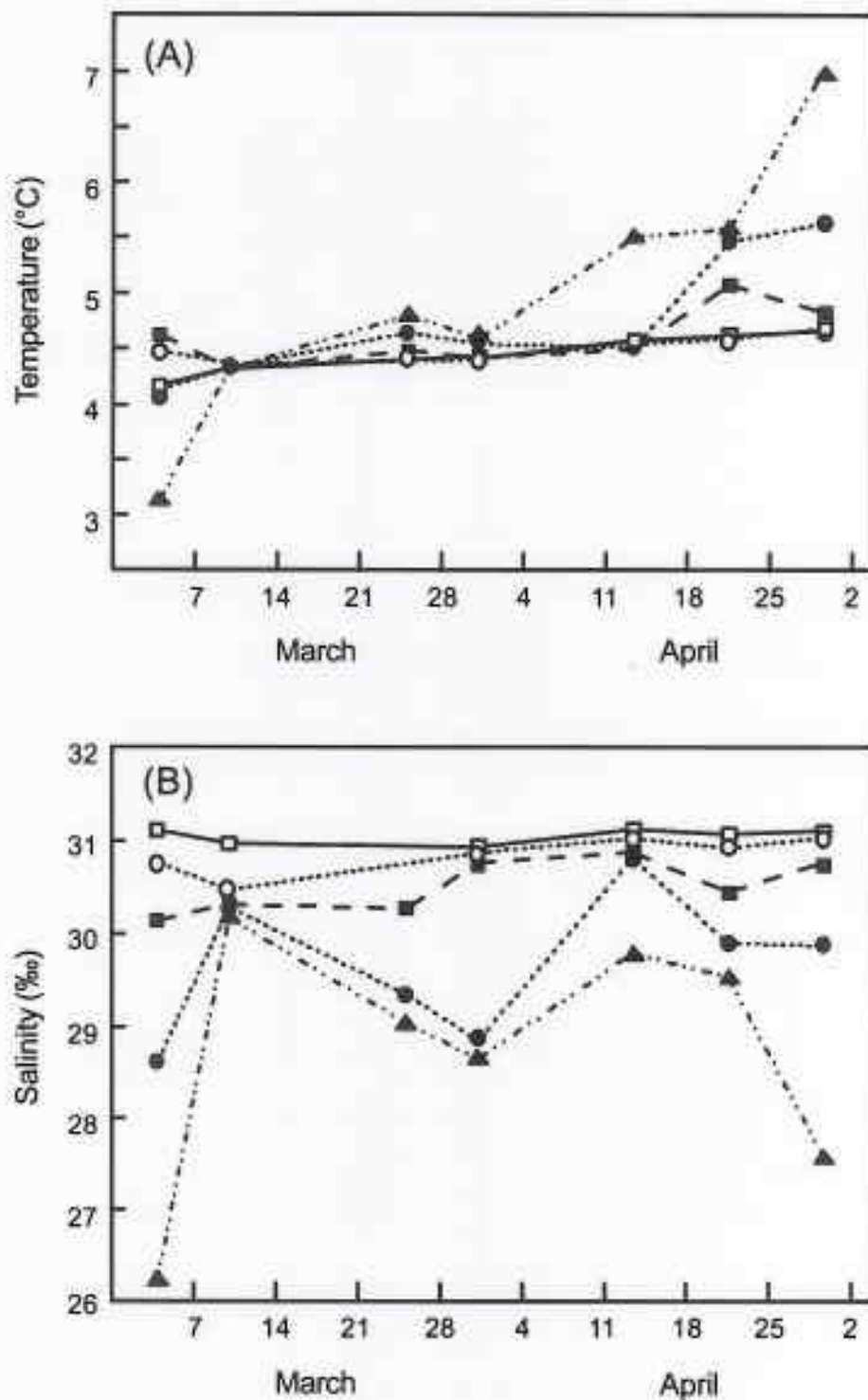


Figure 6: (A) Water temperature and (B) salinity at 0 m (solid triangles), 10 m (solid circles), 20 m (solid squares), 40 m (open circles), and 60 m (open squares) within the study area in Fritz Cove. The measurements at 40 m and 60 m were made at locations directly west of the molting area. Depths are relative to MLLW and measurements were made near the sediment-water interface.

Table 1. Means and ranges of morphometrics of female *Chionoecetes bairdi* from 61 mating pairs collected in shallow water in northern Southeast Alaska between 1992 and 1993. Growth = mean (\pm 1 SE).

Maturity Status	n	Pre-molt (mm)	Post-molt (mm)	Growth (mm)
Pubescent ^a	49	85.3 (72.9–98.3)	102.2 (87.2–115.9)	16.9 (0.3)
Multiparous ^b	12		95.4 (82.3–108.6)	

^a Pubescent females were collected between 24 December and 17 June at depths between -4.3 and -19.2 m MLLW.

^b Multiparous females were collected between 19 March and 23 April at depths between +0.3 and -7.6 m MLLW.

The water column was well-mixed with respect to temperature in Fritz Cove during the study period (5 March to 14 April), and ranged between 3.1°C and 5.5°C (Figure 6A). By late April, surface waters began to warm rapidly and a strong thermocline developed to about 30 m. Salinity was stable between 30.1‰ and 31.1‰ below 20 m during the study period (Figure 6B). Salinity at depths <20 m, however, was lower (26.2‰ to 30.9‰) and more variable (Figure 6B).

Only one exuvium and a few old-shelled males were observed in the 2 additional 100-m transects which were monitored weekly (Figure 1). Although the environmental conditions measured there and the habitat were similar at all sites, molting was restricted to the head of the cove.

Carapaces of all exuviae collected in this study in 1992 and 1993 were EC 2. The relationship between chela height and carapace width differed between non-

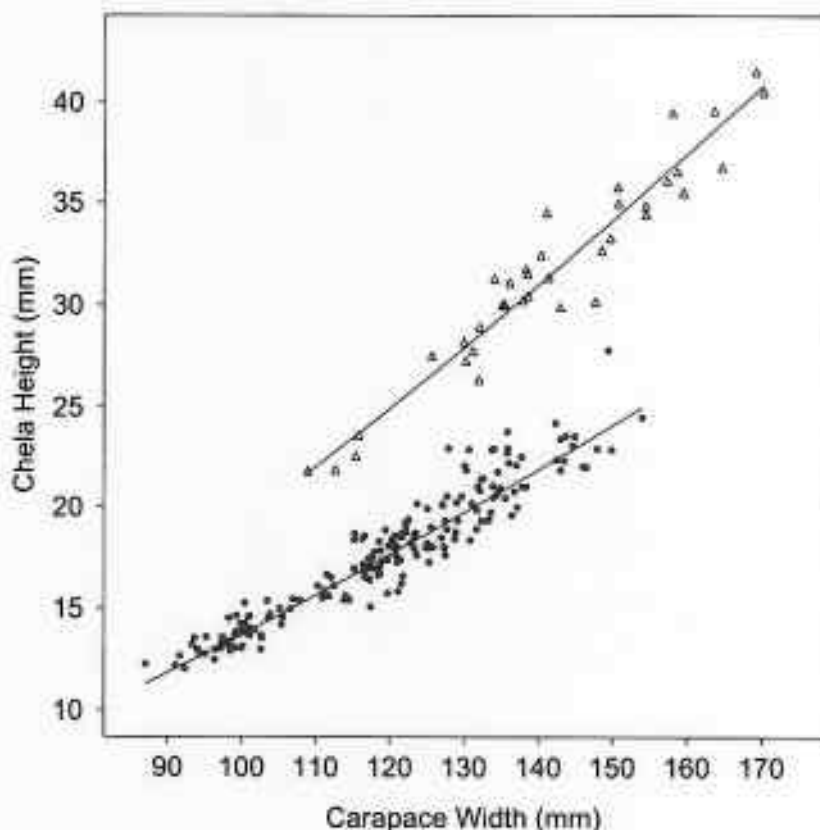


Figure 7. Allometric relationship between chela height and carapace width for non-molting male Tanner crabs ($n = 37$, open triangles) and exuviae ($n = 189$, solid circles) collected in 1993 in Fritz Cove, Alaska. A linear regression line was fit to the natural-log transformed data for each group. The 2 fitted lines are significantly different ($P < 0.001$). Non-molting male Tanner crabs had EC ≥ 3 .

molting crabs and the exuviae collected in 1993 (Figure 7). The 2 fitted lines were significantly different ($P < 0.001$). Non-molting crabs had CH: CW ≥ 0.20 , whereas all but 2 exuviae had CH: CW ≤ 17 . Using the criteria developed by Stevens et al. (1993) for Kodiak Island area crabs, all non-molting crabs could be classified as large-clawed, and all but 2 exuviae could be classified as small-clawed.

DISCUSSION

Spring migration of Tanner crabs into shallow water to molt was noted by scuba divers during several consecutive years in the 1970s (John Karinen, National Marine Fisheries Service, Auke Bay Laboratory, Juneau, Alaska, personal communication). Mixed groups of males and females (< 115 mm CW) and one group of exclusively large males were observed molting at 4 different locations in Auke Bay in March and April. These concentrations of crabs were estimated to number in the hundreds. Although I have observed small aggregations (< 100 crabs) of molting male Tanner crabs at only 2 other locations in Southeast Alaska (8 and 21 km from Fritz Cove), mass molting of Tanner crabs is probably not unique to Fritz Cove. Numerous male Tanner crabs have been observed molting in the same area of Fritz Cove each spring between 1990 and 1999.

No other crab species has been reported to utilize the same area annually to molt en masse. Pubescent females and some male Tanner crabs migrate into shallow water to mate in spring (Stevens et al. 1993), but mass molting has not been reported. Spring breeding migrations of the snow crab *C. opilio* into shallow water have been reported along the eastern shore of Canada (Taylor et al. 1985; Hooper 1986). Predominantly small, but functionally mature male *C. opilio* (i.e., capable of successfully mating in situ in the presence of competition from larger males) may migrate into shallow water in the spring to molt (Sainte-Marie et al. 1988; Sainte-Marie and Hazel 1992).

The molt cycle of Tanner crabs is inextricably related to reproduction. All males that molted at Fritz Cove during 1992 may have been sexually mature; males as small as 45 mm CW produce spermatophores (Paul 1992), and males as small as 68 mm CW can successfully mate in the laboratory (Adams 1982). Males as small as 75 mm CW have been found in pre-mating pairs with pubescent females in situ at Kodiak Island (Paul et al. 1983). The smallest male found in a pre-mating pair with a pubescent female in my study was 92.7 mm CW. Most males (64%) examined in my study were larger than 92.7 mm CW and could have

mated before molting. I observed pubescent females in pre-mating pairs in shallow water between late December and June (Table 1), with peak activity occurring in mid February. Over 90% of the pre-mating pubescent female pairs were collected before 1 April. These observations are consistent with those made near Kodiak Island (Donaldson 1975; Stevens et al. 1993). Multiparous females mate in deepwater aggregations during April and May (Stevens et al. 1993; Stevens et al. 1994) and to a lesser extent in shallow-water areas near mating pubescent females (Donaldson 1975; Stevens et al. 1993; Table 1). Size-related molt timing (Figure 4) may allow larger males to mate with more pubescent females before molting, but would probably preclude them from mating during most of the multiparous female mating period later in spring. Although in situ data are lacking, Paul et al. (1995) reported that recently molted males which were held in the laboratory for extended periods (up to 262 d) did not copulate with multiparous females up to 99 d after molting.

The relative absence of females during this annual migration into shallow water is puzzling. Only 81 female exuviae were collected in the study area. Twenty-two exuviae (27.2%) were larger than the smallest (72.9 mm CW) pubescent female collected from pre-mating pairs (Table 1). These may have been exuviae from pubescent females molting to maturity. Their presence probably was incidental to the molting event, because females mate only with males in the hard-shell condition (Hartnoll 1969). In contrast, 211 male exuviae (8.8% of total) with CW ≤ 72.9 mm were collected.

The frequency of ecdysis for small-clawed males is unknown. Donaldson et al. (1981) statistically predicted an intermolt period of 18 months for legal-size males. Donaldson (1980) tagged and released mature males ≥ 110 mm CW off Kodiak Island, Alaska, and concluded from recovery data that the intermolt period may exceed 3 years. However, chela morphometry was not measured by Donaldson (1980), so tag recoveries may have been large-clawed crabs which molt infrequently or were in terminal ecdysis. Zheng et al. (1997) analyzed historic trawl survey data from Bristol Bay and estimated molting probabilities which varied with time, possibly on a decadal scale. Intermolt periods exceeding 2 years have been recorded for mature males (both small- and large-clawed) held in the laboratory (Paul and Paul 1995). The synchronous nature of the molting event observed in this study indicated a one-year intermolt period for small-clawed males in situ. The absence of molting activity during any other time of year in shallow water at this site, and the consistent classification of exuviae as EC 2 support this

hypothesis. No evidence exists in the literature that mature male Tanner crabs molt at depths greater than those observed in this study during any time of year. An *in situ* study designed to periodically observe crabs throughout an entire year is necessary to confirm the intermolt period for small-clawed male crabs.

Intensity and duration of light, temperature, and possibly salinity may affect molt initiation in crustaceans (Passano 1960). Rapid increases in light intensity and duration during early spring may initiate molting behavior in Tanner crabs. Differences in water temperature between 60 m and shallow water were small, and probably did not serve as cues to migratory behavior. Salinity was reduced at depths shallower than 20 m, however, and Tanner crabs might gain an osmotic advantage by molting in lower salinity water. *Callinectes sapidus* had greater incremental growth when molting in brackish water as a result of the favorable osmotic gradient (deFur et al. 1988). Previous measurements collected in the molting area in March and April 1990 showed increased levels of dissolved oxygen in shal-

low water (<20 m). Because oxygen uptake increases just before exuviation (Passano 1960), molting crabs may move into oxygen-rich waters to meet the high oxygen demands of molting.

Why Tanner crabs molt en masse in shallow water is unclear. Tanner crabs might migrate into shallow water to avoid predators. These shallow-water areas are practically devoid of predators; the only observed predation on a soft-shelled Tanner crab was by a hard-shelled Tanner crab and an adult female red king crab *Paralithodes camtschaticus*. By migrating to shallow water, crabs could separate themselves during ecdysis from deepwater predators such as large groundfish, other crab species, and the non-molting population of Tanner crabs.

Because large numbers of Tanner crabs use the same discrete area each year to accomplish an important life history requirement, the area should be considered essential habitat. Annual monitoring of extensive molting areas may be useful in predicting future recruitment trends.

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Prolonged Exposure to Mine Tailings and Survival and Reproductive Success of Ovigerous Tanner Crabs (*Chionoecetes bairdi*)

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Recently, plans to reopen the Alaska-Juneau (AJ) gold mine near Juneau, Alaska included submarine tailings disposal (STD) as an option for disposal of the finely crushed rock that remains after milling and mineral separation. Because information is scarce on the effects of STD on marine life, numerous studies were initiated to assess the potential biological consequences of STD (Johnson et al. 1998, US EPA 1996a). In addition to smothering the sea floor, STD may introduce elevated metal concentrations to the benthic environment and pose a toxicological hazard to marine life because non-target metals would remain as part of the tailings. Tanner crabs (*Chionoecetes bairdi*), a commercially important resource in Alaska, are intimately associated with benthic sediment; females completely or partially bury in sediment while brooding eggs up to one year and may need to oviposit in a soft substratum to allow for complete cementation of the eggs to the setae (Wickham 1979). Sublethal effects of exposure to heavy metals on crustacean embryos or larvae include inhibition of egg sac development, prolonged larval development, inhibition of larval molting, and reduced growth (D'Agostino and Finney 1974, Mortimer and Miller 1994). Tanner crabs may initially avoid areas affected by STD (Johnson et al. in press) but later recolonize the altered sea floor and incorporate harmful levels of contaminants into their tissues.

Objectives of this study were to determine 1) effect of prolonged exposure to mine tailings on survival and reproductive success (e.g., egg and larval survival) of ovigerous Tanner crabs, and 2) bioavailability of heavy metals to adult crabs. The study was conducted in a laboratory using tailings from the proposed AJ mine. Although plans to reopen the AJ mine were canceled in January 1997, STD remains a future option for some coastal mines in Alaska (Coldwell and Gensler 1993). Results from this study will provide resource managers with valuable information on the potential effects of STD on a dominant benthic invertebrate which supports important commercial and recreational fisheries.

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MATERIALS AND METHODS

Ovigerous Tanner crabs were collected with baited commercial pots on 30 January 1997 in Young Bay near Juneau, Alaska. Sixty-three multiparous females (i.e., have previously reproduced and are anecdysial) with no missing appendages and free of Bitter Crab Disease (Love et al. 1993) were selected for use. Mean carapace width (CW) was 103.7 mm (range 91.0 to 116.7 mm) and all had full egg clutches.

The experimental design consisted of three aquaria containing natural marine sediment (control) and three aquaria containing mine tailings. Sixty crabs were randomly assigned among the six aquaria (148 X 55 cm); the remaining three crabs were frozen whole at -20°C for determination of background metal levels. Tailings were prepared for Echo Bay Mines, Ltd., by Lakeland Research in Ontario, Canada, as part of an evaluation to determine the effects of STD from the AJ mine; a complete characterization of the tailings is provided in US EPA (1996b). Prior to the present study, tailings were aged about 100 d in flow-through seawater tanks. Control sediment was collected with plastic utensils just below mean lower low water from a relatively pristine area near Juneau, frozen at -20°C for 72 hr, and sieved through a $500\ \mu\text{m}$ screen to approximate the grain-size composition of the tailings and to remove macrofaunal prey items. Depth of sediment in each aquarium was 3 cm and water on top of sediments was 35 cm. Seawater (30-32‰) flow rate was maintained at 3L/m and water temperature ranged from 3.2°C to 4.2°C during adult exposure. Particle size analysis, compressive strength (internal friction), and metal concentration of test sediments were determined at the end of the study. Compressive strength was determined by hand-held penetrometer. Triplicate sediment samples were collected from each treatment (control and tailings) for metal analyses.

The study was initiated on 31 January 1997. Crabs were monitored daily for mortality and larval hatch. Crabs were fed 60 g of chopped squid mantle and blue mussels (*Mytilus trossulus*) twice a week. Unconsumed food and feces were removed daily with a glass pipette. A sample of 300+ eggs was collected from each crab at the beginning of the study (0 d), near the mid-point (50 d), and at the end of the study (90 d). Eggs were collected from the anterior margin of the outer-most left pleopod and preserved in Stockard's solution. All samples were collected from the same location within the clutch to eliminate possible error due to differential mortality within the egg mass. Preserved egg samples were observed under light microscopy at 12 or 25 X; setae were placed on a petri dish and the first 300 eggs examined for mortality and presence of symbionts. Mortality estimates were made without knowledge of treatment and expressed as percent dead eggs in the sample. Dead eggs included discolored eggs, and partially empty or empty egg cases with intact funiculi attached to the setae. At 90 d, empty egg cases due to hatching were not included; these eggs could be distinguished from dead eggs by the relatively straight membrane rupture and the

lack of sediment or microbial fouling of the egg case.

After 90 d, three females began hatching larvae; at that time isolated treatment groups were transferred to sterile aquaria without sediment. Eclosion occurred over a 13 d period. As each crab began hatching larvae, they were placed in 4-L plastic containers until several hundred prezoaeae were present. Three replicates of 20 prezoaeae were haphazardly collected and then transferred to 1-L glass containers with a large-bore glass pipette. Only actively swimming larvae near the surface of the container were selected. Larvae were held for 72 hr and monitored daily for mortality. Jars were kept in aquaria surrounded by flowing seawater. Determination of mortality was facilitated by the positive phototactic response of zoeae. Water was changed every 24 hr and larvae were not fed.

Sediment and tissue samples were analyzed for As, Cd, Cr, Cu, Ni, Pb, and Zn. The extraction procedure for sediments included total hydrofluoric acid digestion and analysis by inductively-coupled plasma mass spectrophotometry (ICP-MS). After all crabs extruded new clutches, fresh ova were resected from six randomly selected crabs from each treatment. Periopod muscle was similarly sampled. Tissue analysis of metals followed the methods of the NOAA National Status and Trends Program (Stone and Johnson 1997). The extraction procedure for tissues included digestion in nitric acid and analysis with ICP-MS. A standard reference material (SRM) for sediment and tissue was analyzed for quality control and mean detection limits were determined using three times the SD of the blanks. The concentrations of metals in the procedural blank were near or below the detection limits. The results for the SRMs were within acceptable limits (US EPA 1989).

Differences in egg mortality among treatments were examined by multiple regression; a backward elimination procedure was used to test the relevance of other potential sources of egg mortality. Treatment effect on larval survival was examined with Chi-Square analysis. After 90 d, difference in tissue burdens of metals among treatments was analyzed by Student's t-test or by Mann-Whitney Rank Sum test if normality or equal variance tests failed. All proportion data were arcsine transformed before analysis. An experiment-wise value of $P < 0.05$ was considered significant.

RESULTS AND DISCUSSION

Tailings produced in a manner similar to those we examined may not be toxicologically hazardous to ovigerous Tanner crabs or their progeny if deposited on the sea floor. In our study, survival of adults was 100% after 90-d exposure to tailings and all females extruded a full clutch of ova within 36 h of complete zoeae hatch. In addition, no crabs exhibited any external signs of stress or disease (e.g., loss of limbs, lethargy). In a similar study, survival of juvenile yellowfin sole (*Pleuronectes asper*) was also not adversely affected after 60-d exposure to

"fresh" (aged 0 d) AJ mine tailings (Johnson et al. 1998). Although submarine disposal of these tailings may not pose a toxicological hazard to Tanner crabs, smothering of the sea floor could reduce food availability or displace crabs from essential habitats and indirectly affect growth and survival.

Egg mortality within treatments was highly variable at 0, 50, and 90 d (range 0.3 to 50%). Mean egg mortality ranged from 4.8% to 7.8% for crabs held on control sediment and from 5.1% to 12.1% for crabs held on tailings. Egg mortality increased between 0 and 50 d, but remained relatively constant between 50 and 90 d (Fig. 1). Although crab egg mortality data are scarce, Kon (1974) estimated egg loss (mortality) from oviposition to eclosion as high as 50% for *C. opilio*.

Egg mortality among treatments was similar at 0 and 50 d but was significantly ($P = 0.026$) greater for crabs held on tailings than on control sediment after 90 d (Fig. 1). The difference at 90 d was attributable to the high egg mortality of two crabs (39% and 50%) held on tailings (Fig. 1); removal of these outliers (egg mortality was nearly twice as high as any other crab held on tailings) resulted in no significant difference among treatments. Other potential sources of egg mortality considered were the presence of 1) the nemertean *Carcinonemertes* spp. and its eggs, a known predator of crab eggs, 2) nematodes, whose role in mortality is unknown, and 3) tank effects within treatment. Symbiotic turbellarians, although present as adults or eggs in about 17% of the samples we examined, were not included in the analysis since they are non-predaceous on crab eggs (Kuris 1991). Although Hilsinger (1976) detected a significant increase in egg mortality with an increase in female size (CW), we detected no linear relationship between these two variables for either treatment at 0, 50, or 90 d. In addition, *Carcinonemertes* spp. or their egg clusters were found in only 5 egg samples (3%), while nematodes were found in 43% of all samples. These sources of mortality (including tank effect) were insignificant through backward elimination however, and treatment could be considered the sole source of mortality.

Because larvae are generally more susceptible to toxic heavy metals than adults of the same species (Connor 1972), knowledge of tolerance levels for these life history stages need to be considered when developing pollution control guidelines. Larval mortality in our study was low during the 72 hr survival tests. Only 20 of 3600 larvae held for 72 hr died (0.6%) and there was no significant difference in larval mortality among females reared on control sediment and tailings ($\chi^2 = 0.74$; $df = 1$, $P = 0.39$). Of the 20 mortalities, 35% were failures to successfully molt from prezoa to zoea stage I.

Most metal concentrations in muscle and ova were similar among treatments after 90 d (Table 1), Pb was the only metal that was significantly greater in tissues of crabs held on tailings than on control sediment ($P = 0.002$ for muscle, $P = 0.009$ for ova) (Table 1).



Figure 1. Boxplots of egg mortality from female Tanner crabs held on control sediments and mine tailings for 90 d. Egg samples were taken at 0, 50, and 90 d. Plots show percent mortality. The dark box shows limits of the middle half of the data (interquartile range), the center line represents the median. The whiskers are drawn to a point 1.5 X the interquartile range; data points beyond that are outliers.

Although Pb concentrations were at least eight times greater in muscle ($0.57 \mu\text{g g}^{-1}$) and ova ($0.12 \mu\text{g g}^{-1}$) of crabs held on tailings, concentrations were similar to those values reported for *C. bairdi* from other areas in Alaska (muscle, $0.36\text{--}0.48 \mu\text{g g}^{-1}$; Hall et al. 1978). Similar concentrations of most metals in ova between treatments indicated that prolonged exposure to tailings produced no adverse effects on early development. Lead (Pb) may have been available to Tanner crabs after leaching from tailings into the water and crossing body surfaces (e.g., gills). Sediment concentrations of Cr, Pb, and Zn declined by only 10% to 14% from AJ mine tailings aged 60 d in seawater (Johnson et al. 1998). Ingestion of sediment while feeding is also a likely route of Pb uptake, of 55 Tanner crab stomachs collected near Juneau for diet analysis, 54% contained sediment (R. P. Stone, unpublished data).

Background concentrations of Cd, Cr, Cu, and Ni were significantly higher in muscle from crabs at the beginning of the study than observed in control crabs after 90 d (Table 1). These differences may have resulted from the controlled diet crabs were fed in the laboratory or from high natural concentrations in sediment where crabs were initially collected. Most background metal concentrations of adult crabs in this study were similar, however, to those values reported from juvenile Tanner crabs collected near Juneau (Stone and Johnson 1997).

With the exception of mercury, trace metal concentration guidelines for the safe

Table 2. Metal concentrations ($\mu\text{g g}^{-1}$ dry weight) of control sediment and mine tailings used in a 90 d exposure study of ovigerous Tanner crabs; values are means (± 1 SE), $n=3$. Effects range - median (ERM) values define the concentration of a particular contaminant in sediment above which adverse biological effects were frequently or always observed (Long et al. 1995).

Metal	Control	Tailings	ERM Value
As	4.70 (0.13)	21.52 (1.78)	70.0
Cd	0.54 (0.03)	12.17 (1.09)	9.60
Cr	103.0 (6.57)	97.9 (0.90)	370
Cu	11.75 (0.18)	79.07 (2.66)	270
Ni	47.30 (1.23)	37.47 (0.83)	51.6
Pb	5.54 (0.15)	134.46 (3.26)	218
Zn	54.36 (1.77)	516.86 (41.70)	410

during our study. From a submersible in the proposed discharge area for the AJ mine (Taku Inlet), we have observed ovigerous Tanner crabs partially buried in soft substrates of silt and very fine sand; compressive strength of these sediments was $<0.10 \text{ kg cm}^{-2}$ and silt made up 65-85% of the sediment (*R. P. Stone, unpublished data*). Although grain-size composition of control sediment and tailings was similar for both treatments ($<250\mu\text{m}$, control sediment 63%, tailings 75%), tailings formed a much more compact substrate than the control sediment (compressive strength, 4.1 kg cm^{-2} vs 0.13 kg cm^{-2}) possibly due to the high angularity of the grains (US EPA 1996c). In a laboratory study, ovigerous Tanner crabs avoided AJ mine tailings when given a choice, possibly due to the inability to bury in the substrate (Johnson et al. in press). The inability of females to bury in the substrate may promote unsuccessful oviposition and egg brooding, while increasing their risk to predation. In addition, an altered sea floor may not support an adequate prey population for foraging Tanner crabs.

We have shown that tailings similar to those that may be produced from a gold mine-mill complex and aged about 100 d in seawater were not deleterious to ovigerous Tanner crabs. Most mining operations, however, would probably not age tailings prior to STD. We believe the results of our study would have been the same had we used "fresh" tailings because leaching of metals from these tailings was minimal after 60 d.

We found no significant differences in survival of adult crabs, eggs, or larvae after exposure to tailings and control sediment for the last 90 d of the brood cycle. Tissue burdens of metals were also similar between treatments in this study and within safe consumption guidelines implemented in Europe. Although STD may not be a toxicological hazard to Tanner crabs, protection of essential habitat

Table 1. Metal concentrations ($\mu\text{g g}^{-1}$ dry weight) in muscle and new ova of ovigerous Tanner crabs. Tissues were collected after crabs were held on clean marine sediment (control) and mine tailings for 90 d; values are means (± 1 SE). * = $P < 0.01$, t-test. Baseline samples were taken at 0 d.

Metal	Muscle			New ova	
	Baseline n = 3	Control n = 6	Tailings n = 6	Control n = 6	Tailings n = 6
As	80.77 (8.30)	80.22 (6.44)	68.82 (6.52)	19.87 (1.79)	16.25 (1.75)
Cd	0.74 (0.24)	0.27 (0.03)	0.31 (0.03)	0.20 (0.02)	0.23 (0.03)
Cr	0.60 (0.04)	0.35 (0.01)	0.38 (0.01)	0.34 (<0.01)	0.36 (<0.01)
Cu	76.60 (4.86)	30.55 (1.64)	33.42 (3.80)	76.83 (3.46)	77.65 (3.57)
Ni	0.60 (0.21)	0.16 (<0.01)	0.18 (0.02)	0.47 (0.12)	0.45 (0.08)
Pb	0.06 (<0.01)	0.07 (<0.01)	0.57* (0.05)	0.01 (<0.01)	0.12* (0.02)
Zn	103.67 (2.03)	106.73 (2.73)	106.50 (0.72)	85.60 (3.11)	83.28 (0.99)

consumption of fish and shellfish have yet to be developed in the United States. Concentrations of Cd, Cu, Pb and Zn from crab muscle tissue in this study, however, were within safe guidelines developed in Europe (Brown and Balls 1997).

Metal concentrations ranged from 4 times greater (As) to 24 times greater (Pb) in tailings than in control sediment (Table 2). Only Cd and Zn, however, exceeded the effects range - median (ERM) value; that concentration of a contaminant in marine sediment above which adverse biological effects were frequently or always observed (Long et al. 1995). Similar tissue burdens of Cd and Zn in crabs held on tailings and control sediment for 90 d (Table 2) indicates either low bioavailability of these metals from tailings or, if they were bioavailable, that crabs were able to effectively depurate or store them during normal physiological processes.

Crabs were seldom observed buried in control sediment and never in tailings

remains a priority. Location of STD sites in areas of low productivity and high natural sedimentation rates (e.g., large glacial river mouths) would have the least effect on this commercial resource; high natural sedimentation would accelerate recovery of the sea floor.

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Survival, Growth, and Bioaccumulation of Heavy Metals by Juvenile Tanner Crabs (*Chionoecetes bairdi*) Held on Weathered Mine Tailings

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Between 1891 and 1944, over 80 million metric tons of tailings from three gold mines (Alaska-Gastineau, Alaska-Juneau, and Treadwell) were deposited in Gastineau Channel near Juneau, Alaska (Stone and Stone 1980). Tailings are rock materials that have been subjected to some form of milling and mineral separation process. After at least 50 years of weathering (e.g., rain, tidal flushing) or continuous submergence in seawater, elevated levels of some metals have been found in these tailings (Ecology and Environment, Inc. 1988), but their present availability to biota are unknown. With renewed interest to reopen one of these mines and marine disposal of tailings a possible option, examination of the impact historic tailings have on the environment may reflect future environmental conditions. Thus, further study is needed to document and identify metal concentrations in these weathered tailings and to determine availability and possible impacts to marine life.

Tanner crabs (*Chionoecetes bairdi*) are seasonally abundant in nearshore waters of southeast Alaska to a depth of about 500 m and are harvested by commercial and personal use fisheries. We have observed juvenile crabs on submerged mine tailings in Gastineau Channel. Tanner crabs often bury in and frequently ingest sediment while feeding. The routes of metal absorption in decapod crustaceans are from food in the digestive tract and across the permeable gill membranes (Rainbow 1988).

Objectives of this study were to determine the bioavailability of heavy metals to juvenile Tanner crabs held for 500+ days on weathered mine tailings and to examine possible effects on survival, growth, and health of the animals. In addition, baseline information is scarce on metal concentrations in juvenile Tanner crabs.

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MATERIALS AND METHODS

Tailings were collected from a large disposal area (20 ha) near the mouth of Sheep Creek in Gastineau Channel where the Alaska-Gastineau Mine deposited 10 million metric tons of tailings between 1912 and 1920 (Ecology and Environment, Inc. 1988). A transect was established perpendicular to the shoreline from mean high water to mean lower low water (MLLW). Approximately 2 kg of sediment was collected from the upper 3 cm every 10 m along the transect. Sediment was collected during low tide with plastic buckets and composited in 125-L plastic containers. Control sediment was collected similarly from a relatively pristine area, approximately 35 km north of Juneau. Tailings and control sediment were homogenized thoroughly and placed in three 500-L flow-through aquaria (2 control, 1 tailings) to a depth of 5 cm. A sediment sample was collected from each aquarium at the beginning of the study for particle size and metal analyses.

Juvenile Tanner crabs were collected between 19 and 21 May 1993 at Amalga Harbor, approximately 31 km north of Juneau. Crabs were collected with SCUBA at depths between -10 and -21 m MLLW. Crabs were allowed to depurate in sand-filtered seawater for 1 wk prior to the start of the study. Twenty-four crabs were sacrificed and frozen whole at -20°C for determination of background metal levels. Forty crabs were randomly assigned to each aquarium and placed in separate 15 by 17 cm compartments to prevent cannibalization during ecdysis. Because all crabs were immature, gender was not considered a factor in metal uptake. Carapace width (CW) was measured for each crab. All crabs were approximately the same size (33.8-47.6 mm CW) and in good health (i.e., no missing appendages or gross evidence of disease).

The study was initiated on 26 May 1993. Crabs were monitored daily for molting and mortality. Growth was calculated by subtracting pre-molt CW from post-molt CW. Post-molt CW was measured a minimum of 21 d after ecdysis to allow for complete calcification and hardening (i.e., growth). Mortalities were removed within 24 hr. Each crab was fed a diet of squid mantle rinsed in seawater as follows; 1) day 0-23, 1 g once per wk, 2) day 24-250, 1 g twice per wk, and 3) after day 250, 3 g twice per wk. Unconsumed food was removed after 24 hr. Sand-filtered seawater was maintained at a flow rate of 6 L/min. Water temperature was monitored daily and ranged from 2.9-9.0°C. Salinity ranged from 30.0 to 32.1‰ during the study.

Our initial goal was to terminate the experiment after each crab molted twice. The study was terminated after 502 d at which time all crabs but one had molted at least twice (two crabs molted 3 times). Crabs were starved during the last three days of the study to allow for complete gut evacuation and transferred to aquaria with no sediment to depurate for 48 hr. Three replicates of 10 crabs were randomly selected from each treatment (tailings and both controls) for metal

analysis. Gill and muscle tissue from the merus of the first 3 pereopods were resected from each crab. Tissues were resected with corrosion-resistant stainless steel instruments and composited by tissue and treatment into certified metal-free 118-g glass jars. Samples were kept frozen at -20°C for about one wk before metal analyses.

Sediment and tissue samples were analyzed for As, Cd, Cr, Cu, Ni, Pb, and Zn. The extraction procedure for sediments included multi-acid digestion ($\text{HF-HNO}_3\text{-HClO}_4\text{-HCl}$) and analysis by atomic absorption (Bondar-Clegg, 130 Pemberton Ave., N. Vancouver, B.C., V7P 2R5). Tissue analysis of metals followed the methods of the NOAA National Status and Trends Program (Creclius et al. 1993). The extraction procedure for tissues included digestion in nitric acid and analysis with inductively-coupled plasma mass spectrophotometry. For tissue samples, a NIST certified reference sample (oyster tissue) was analyzed for quality control and mean detection limits were determined using three times the standard deviation of the blanks. Mean detection limits ranged from $0.02\ \mu\text{g/g}$ for Pb and Cd to $0.3\ \mu\text{g/g}$ for Cr and Zn. Percent recoveries were 88 to 115% at a $5\ \mu\text{g/g}$ matrix spike (one outlier - As at 137%) and 88 to 108% at a $25\ \mu\text{g/g}$ matrix spike for all metals.

Survival, growth, disease, condition index, and branchial histopathological changes were examined at the end of the study to determine health of the crabs. Differences in survival between treatments was tested with Chi-Square analysis. Total growth and growth at each molt (2 per crab) were compared between treatments using a one-way ANOVA. Intermolt period (the number of days between molts) was calculated for each crab and differences tested with a one-way ANOVA. Hemolymph was examined from each crab sampled for the presence of the parasitic dinoflagellate which causes Bitter Crab Disease (Love et al. 1993) and infection rate was calculated as no. infected/n. Incidence of Bitter Crab Disease between treatments was tested with Chi-Square analysis. One gill from 10 crabs of each treatment was dissected and prepared on a microscope slide using standard histological techniques and analyzed for histopathological abnormalities.

We hypothesized that stressed crabs would have atrophied muscles and developed a condition index to test this. For each crab sampled, the merus of the third pereopod was broken at the autotomy plane and sliced with a scalpel at the joint between the merus and carpus. Each merus was dried to a constant weight at 65°C for 72 hr. The ratio of muscle dry weight of the merus versus carapace weight for each sample was analyzed with one-way ANOVA. Because of potential stress associated with limb loss, crabs with missing appendages were excluded from analysis. Crabs which had molted within 60 d of final sampling were also excluded from analysis because of incomplete muscle regeneration. Significance for all tests was accepted at $P \leq 0.05$.

RESULTS AND DISCUSSION

Survival was high for both treatments during the 502 d study. Only 12 crabs (11.3%) died, and there was no significant difference in survival between treatments ($\chi^2 = 0.814$; $df = 1$, $P = 0.367$). Although not necropsied, no mortalities showed any obvious signs of disease.

Growth of crabs did not differ significantly between treatments for the first growth period (day 0 to first molt; $P = 0.19$) or the second growth period (first to second molt; $P = 0.07$) (Table 1). The average growth increment to first molt was about 12 mm, whereas growth between the first and second molt was about 15 mm. Intermolt period between the first and second molt did not differ significantly ($P = 0.97$) between control ($\bar{x} = 275.4$ d, range = 165-376 d, $n = 62$) and tailings crabs ($\bar{x} = 275.7$ d, range = 178-351 d, $n = 35$).

Table 1. Mean carapace width (CW) ± 1 S.D. at day 0 and mean growth increment ± 1 S.D. at two subsequent molts of juvenile Tanner crabs held on control and tailings sediment for 502 d. All measurements are in mm.

CW	Control	Tailings	ANOVA
Day 0	41.2 \pm 3.2 (n = 80)	41.1 \pm 2.8 (n = 40)	P = 0.88
Molt 1	11.9 \pm 1.1 (n = 68)	11.6 \pm 1.0 (n = 39)	P = 0.19
Molt 2	14.8 \pm 1.5 (n = 61)	15.5 \pm 1.8 (n = 35)	P = 0.07

Crabs in this study showed no external signs of stress; condition indices were also similar ($P = 0.60$) between treatments. Sublethal concentrations of contaminants can stress crustaceans (Aiken and Waddy 1986). Stressed Tanner crabs are more susceptible to Bitter Crab Disease. A significantly ($\chi^2 = 4.80$; $df = 1$, $P = 0.029$) greater number of crabs held on tailings were infected with Bitter Crab Disease. Whether this difference was due to stress from exposure to tailings is unclear, because the mechanism of infection and source of parasitism are unknown.

Histologic examination of crab gills revealed no tissue alteration due to tailings exposure. An increased prevalence of *Hematodinium*, the causative organism for Bitter Crab Disease, in gills of crabs held on tailings supported our hemolymph observations. There was an increased incidence of leucocytic infiltration in gill sections of some crabs exposed to mine tailings. Exposure to Cd and Cu can cause gill alterations with both acute and chronic effects in crustaceans (Gardner 1993).

Percent particle size distribution was similar for both treatments and consisted mostly of several gradations of sand (63-2000 μm ; control = 99.5%, tailings =

97.3%). The clay-silt fraction (<63 μm) was very small for each treatment (control = 0.3%, tailings = 0.7%), possibly due to regular flushing by tides.

Metal concentrations were 1.5 (Cr) to 12 times (As) greater in the tailings than in the control sediment at day 0 (Table 2). Only Cr, Pb, and Zn in the tailings exceeded the effects-range low (ER-L) concentration; the concentration of a particular contaminant in sediment above which adverse biological effects are thought to occur (Long and Morgan 1990). The tailings originated from sulphide ores which contain As, Ni, Pb, and Zn (Ecology and Environment, Inc. 1988). No metals in the control sediment exceeded ER-L concentrations.

Table 2. Metal concentrations ($\mu\text{g/g}$ dry weight) of control sediment and tailings ($n=2$) at the beginning of the study. Effects Range-Low (ER-L) values are provided for comparison (Long and Morgan 1990).

Metal	Control	Tailings	ER-L Value
As	2.1, 2.9	27.9, 31.4	33.0
Cd	<0.20, <0.20	1.10, 1.30	5.00
Cr	60.0, 61.0	92.0, 94.0	80.0
Cu	13.0, 14.0	32.0, 33.0	70.0
Ni	12.0, 14.0	21.0, 21.0	30.0
Pb	10.0, 10.0	60.0, 62.0	35.0
Zn	67.0, 67.0	196.0, 210.0	120.0

Some metals (Cu and Zn) are essential for normal growth and development in crustaceans, whereas others (Cd and Pb) are non-essential. Non-essential metals may be regulated, detoxified and stored in an inert form, or may accumulate and cause toxic effects (Rainbow 1988). Most baseline metal levels in muscle tissue of Tanner crabs in this study (Table 3) were below or comparable to levels measured for Tanner crabs at five other sites in Alaska (Hall et al. 1978). Only Cr was notably higher in our crab muscle samples than the above study, possibly due to the mineralogical composition of local sediments.

For each tissue type, metal concentrations were similar between treatments at the end of the study (Table 3). A major exception was Cr; for unknown reasons, the concentration of Cr was about six times greater in the muscle of control crabs than in tailings crabs. The overall similarity in tissue burdens of metals between treatments may indicate either low bioavailability of metals from tailings or, if metals were bioavailable, that crabs were able to effectively depurate metals.

through normal physiological processes or store them in other tissues (i.e., hepatopancreas). Red king crab (*Paralithodes camtschaticus*) may purge Ni through the exoskeleton during ecdysis (Rusanowski et al. 1989).

Table 3. Metal concentrations ($\mu\text{g/g}$ dry weight) in gill and muscle tissue of juvenile Tanner crabs. Baseline samples ($n=2$) were composites of 12 crabs each. Tissues for treatment samples were collected after crabs were held on control and tailings sediment for 502 d; values are means (± 1 SE). Treatment samples were composites of 10 crabs each ($n=3$).

Metal	Gill			Muscle		
	Baseline	Control	Tailings	Baseline	Control	Tailings
As	17.70	9.79 (0.29)	8.95 (0.60)	18.90	8.90 (0.43)	8.13 (0.17)
Cd	2.39	9.09 (0.07)	8.60 (0.80)	0.87	0.23 (0.02)	0.24 (0.02)
Cr	3.96	28.30 (2.10)	22.30 (1.67)	5.44	6.09 (0.33)	1.28 (0.09)
Cu	144.00	220 (2.60)	209 (10.7)	63.55	37.5 (2.35)	48.6 (4.10)
Ni	2.93	2.31 (0.17)	2.55 (0.16)	1.40	0.20 (0.03)	0.25 (0.06)
Pb	0.16	2.37 (0.32)	3.42 (0.37)	0.03	0.04 (0.003)	0.05 (0.004)
Zn	101.75	72.80 (1.08)	72.50 (2.63)	93.10	97.8 (2.83)	91.6 (1.49)

Regardless of treatment, the concentrations of most metals (Cd, Cr, Cu, Ni, and Pb) were greater in gill than in muscle (Table 3). Studies with other crustaceans have also reported similar results (Anderson and Brower 1978). The only metal that was greater in muscle than in gill was Zn. Arsenic concentrations were about equal in gill and muscle (Table 3).

In both treatments, most metal concentrations changed over the course of the

study. For example, arsenic concentrations decreased by about 50% in tissues of study crabs compared to background concentrations (Table 3). This may have resulted from the strict diet of squid mantle crabs were fed. Low concentrations of arsenic have been measured in squid mantle (Hall et al. 1978). These changes also could have been due to differences in sediment chemistry; arsenic levels may have been naturally high where crabs were initially captured.

After decades of weathering, tailings deposited into Gastineau Channel from the Alaska-Gastineau Mine do not appear to be deleterious to juvenile Tanner crab. We found no significant differences in survival and growth of crabs held on tailings and control sediment for 500+ days and through two molts. Tissue burdens of metals were also similar between treatments. Whether or not there was some leaching and increased bioavailability of metals the first few years after tailings disposal ceased is unknown. Some leaching may have occurred, especially in intertidal deposits exposed to air, tides, and storms. Waste rock deposited intertidally from a lead-zinc mine in Greenland resulted in severe pollution of surface seawater and marine organisms (Asmund 1992). With renewed interest to reopen one of the mines adjacent to Gastineau Channel and submarine tailings disposal a preferred option, future studies should focus on metal leaching and potential impacts to biota that may occur within the first few years after tailings are deposited on the sea floor.

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