Avoidance Behavior of Ovigerous Tanner Crabs *Chionoecetes bairdi* Exposed to Mine Tailings: A Laboratory Study

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Reprinted from the
Alaska Fishery Research Bulletin
Vol. 5 No. 1, Summer 1998

Alaska Fishery Research Bulletin 5(1):39–45. 1998.

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ABSTRACT: Avoidance behavior was examined in ovigerous Tanner crabs *Chionoecetes bairdi* exposed to mine tailings produced in a pilot plant associated with a proposed gold mine near Juneau, Alaska. Individual crabs were placed in a circular tank that was divided into 4 equal sections containing natural marine sediment (control) and tailings in alternate sections. A time-lapse video camera recorded the position of each crab within the tank over 24 h. Crabs spent significantly ($t = 2.43$, $P < 0.02$, df = 24) more time on control sediment (61%) than on tailings (39%). Of 25 test crabs, 19 spent the most time (≥12 h) on control sediment, whereas only 6 crabs spent the most time on tailings. Ovigerous Tanner crabs may avoid areas affected by the submarine disposal of tailings during the life of the mine. Location of potential submarine tailings disposal sites in areas with high natural sedimentation may accelerate recovery of the sea floor by rapid burial of tailings.

INTRODUCTION

Recently, permits were sought to reopen the Alaska Juneau (AJ) Mine adjacent to Juneau, Alaska. Submarine tailings disposal (STD) was one option considered for the mine tailings, which are the finely crushed rock that remains after milling and mineral separation. In the U.S., current regulations prohibit the discharge of flotation-mill wastewater to receiving waters; mill wastewater is unavoidably associated with tailings (Kline 1994). The U.S. Environmental Protection Agency (EPA), however, allowed the developer of the AJ Mine an exemption to consider STD as a possible option for reopening the mine (EPA 1996a). Concern about the environmental consequences of smothering the sea floor with tailings prompted several studies to assess possible effects (EPA 1996b). Knowledge of the possible biological effects of STD from the AJ mine should be applicable to other potential mines in Alaska where 20 other ore bodies have been identified as possible candidates for STD (Coldwell and Gensler 1993).

A major concern was the potential effect of STD on benthic biota, either from altered physical habitat or from possible increased exposure to contaminants such as heavy metals or milling reagents. Taku Inlet, the proposed STD area for the AJ Mine, hosts commercial and recreational fisheries for Tanner crab *Chionoecetes bairdi;* the commercial fishery exvessel value averaged about $225 thousand per annum from 1986 to 1995 (K. Imamura, Alaska Department of Fish and Game, personal communication), so the effects of STD on this resource became an important concern. Because Tanner crabs are intimately associated with benthic sediment, they can be readily affected by an altered sea floor. Ovigerous females are especially suspect because they brood their eggs for up to a year (Hilsinger 1976) while partially buried and often ingest sediment incidentally while feeding (Jewett and Feder 1982). Tanner crabs may be able to avoid mine tailings by fleeing areas affected by disposal. Our objective was to determine whether ovigerous Tanner crabs avoid mine tailings as a substrate and, if so, attempt to identify those sediment characteristics that may be responsible for the avoidance behavior. Information gained from this study should provide resource managers with a better understanding of how Tanner crabs may be affected by STD.

METHODS

We obtained 36 ovigerous female Tanner crabs collected commercially in baited pots in Young Bay near

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Acknowledgments: Dr. Don Heinle, Dr. Stanley Rice, and Ben Kirkpatrick — reviewed earlier drafts of the manuscript. Dr. Tom Shirley — provided the time-lapse video camera. Jack Pasquan of the *F/V Hungry Jack* — collected Tanner crabs.
Project Sponsorship: This study was funded by the Habitat Investigations Program at the Auke Bay Laboratory.

Juneau, Alaska. Crabs were transported to Juneau in the live wells of commercial crab vessels. They were then placed in coolers and moved to a laboratory where they were held in flow-through seawater tanks. All crabs were in good condition (e.g., few or no missing appendages), free of Bitter Crab Disease (Love et al. 1993), and approximately the same size (mean carapace width 104.5 mm, range 93.9–118.0 mm). The circular experimental tank was divided into 4 equal pie-shaped sections, alternating between natural marine sediment (control) and recently produced AJ Mine tailings (Figure 1). The fiberglass tank had a diameter of 1.5 m, a central standpipe, and a circular seawater flow-through design (1.5 $L \cdot min^{-1}$). Sediments in each section were 3 cm deep, and water on top of sediments was 40 cm deep.

Control sediment, taken from tidelands in Auke Bay at approximately mean lower low water, was transported in plastic buckets. Control sediment was frozen at –20°C for 72 h and sieved through a 500-μm screen to approximate the grain-size composition of the tailings and to remove most macrofaunal prey items. Tailings were prepared for Echo Bay Mines, Ltd. by its pilot plant, Lakefield Research in Ontario, Canada, as part of an initial evaluation to determine the effects of STD from the AJ Mine (EPA 1996c). Approximately 10 kg of tailings were sent to Auke Bay Laboratory in a plastic bucket for use in this study. A complete characterization of the tailings (e.g., milling, acid-volatile sulfide normalization) can be found in EPA (1996b,1996c). Particle-size analysis (Shepard 1963) and compressive strength (internal friction) of sediments were determined at the end of the study. Compressive strength was determined by hand-held penetrometer. Metal concentrations of tailing and control sediments were determined in earlier studies (EPA 1996c; Johnson et al. 1998).

Random assignment of treatments (sediments) to each tank section during the individual trials was not practical; therefore, control tests were first conducted

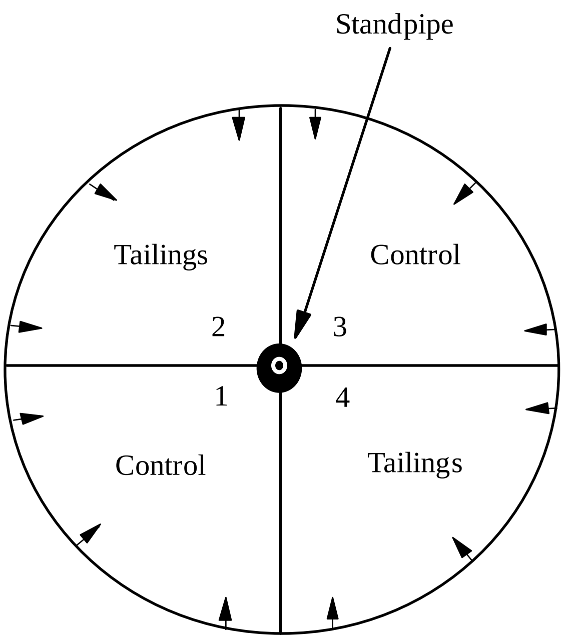

Figure 1. Schematic diagram of circular experimental tank (1.5-m diameter) to test sediment avoidance by ovigerous Tanner crabs. Natural marine sediment (control) was placed in sections 1 and 3, and mine tailings in sections 2 and 4. Small arrows along tank perimeter represent seawater flow (1.5 $L \cdot min^{-1}$) into tank. During each of 11 control and 25 treatment trials, an individual crab was placed on the standpipe and allowed to fall presumably at random into the tank; sediment preference over 24 h was recorded by a time-lapse video camera placed above tank.

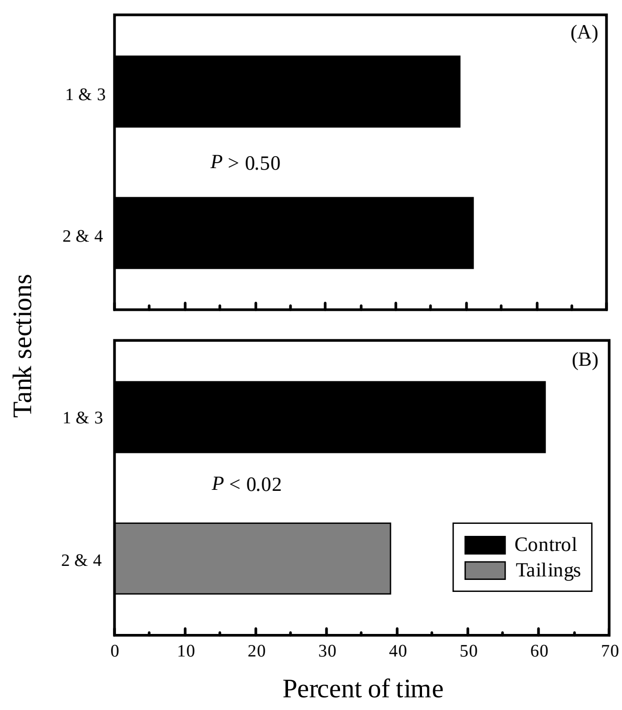

Figure 2. Percentage of time ovigerous Tanner crabs occupied either control or mine tailings sections during a 24-h period. **(A)** Tank effect was examined by individually exposing 11 crabs to control sediment in all tank sections; **(B)** treatment effect was examined by exposing 25 crabs to control sediment in sections 1 and 3 and tailings in sections 2 and 4.

to ensure that all factors (e.g., waterflow, lighting) were equal among tank sections and that the only selective criterion used by crabs was sediment type (i.e., no tank effect). Control sediment was placed in each tank section. Natural lighting was supplemented by overhead fluorescent lights during daylight. Water temperatures ranged from 3.2 to 3.5°C.

Each of the 11 crabs used in the control test was individually tested. A test began with a crab being placed on the standpipe in the center of the tank (Figure 1) and allowed to fall, presumably at random, into the tank. A time-lapse, low-light video camera mounted above the tank recorded the behavior of each crab for 24 h. From those continuous recordings of position (tank section) within the tank, the percentage of time and number of visits per section were determined. String taped to the top of the tank provided a visual boundary for each tank section on video. A white plastic tag (2.5-cm diameter) glued to the center of the carapace on each crab allowed easier viewing of crabs on video. When a crab straddled 2 sections, the section in which the white tag was most visible was counted.

After completion of control tests, control sediment was removed from 2 opposing sections (2 and 4; Figure 1) and replaced with mine tailings to examine crab behavior for treatment effects. Sediment preference of 25 crabs was then determined as described above for the control tests. Crabs were not fed during the 24-h observation period but were fed squid *Loligo* sp. mantle or mussels *Mytilus trossulus* twice a week while held in the laboratory. Crabs were used only once in all tests; each crab represented an independent observation.

Possible tank and treatment effects on crab behavior were analyzed by a randomized paired-comparison design (Box et al. 1978). For each crab, pairs

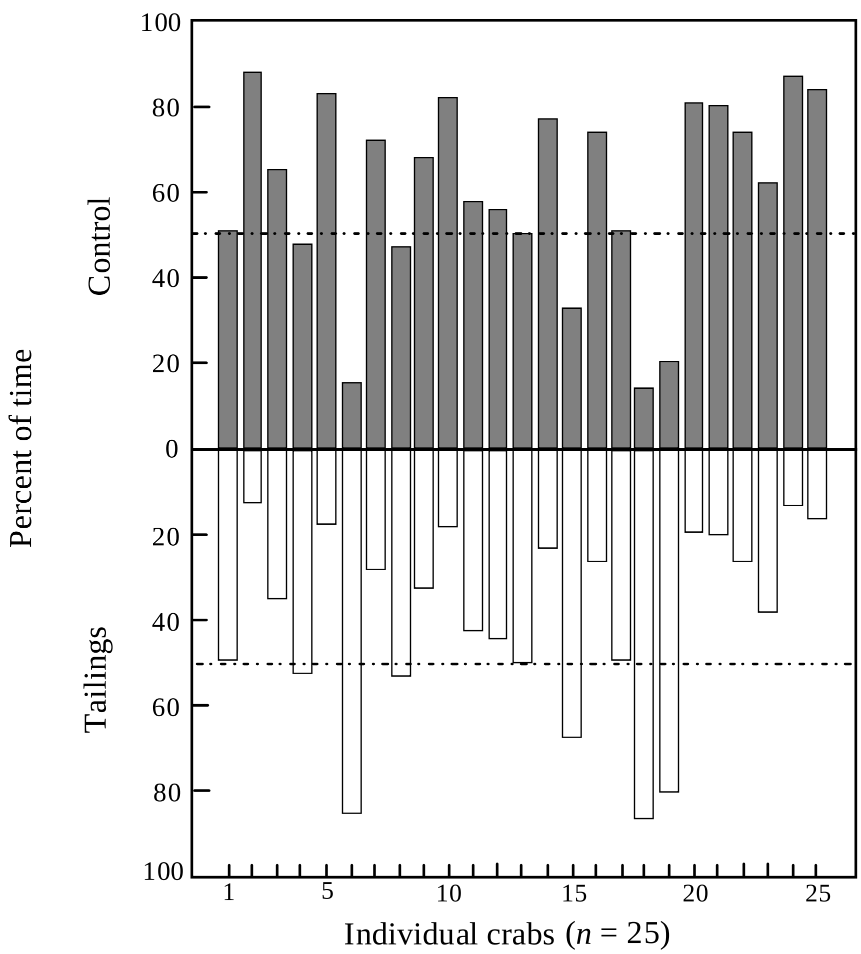

Figure 3. Sediment type that ovigerous Tanner crabs selected for most (≥50%) of the 24-h test period (broken line = 50%). Crabs were exposed to 2 sediment types (control and mine tailings) in a circular experimental tank; sediment preference over 24 h was recorded by a time-lapse video camera placed above the tank.

Table 1. Tank and treatment trial results: mean (and range) number of minutes that ovigerous Tanner crabs occupied each tank section over 24-h periods and mean number of visits to each tank section. Sediments differed between tank and treatment effects (tank effect = control sediment in all 4 tank sections; treatment effect = control sediment in sections 1 and 3 and mine tailings in sections 2 and 4).

		Tank Section							
		1		2		3		4	
Trial	*n*	Time (min)	Visits[a]	Time (min)	Visits[a]	Time (min)	Visits[a]	Time (min)	Visits[a]
Tank effect	11	370 (158–734)	51	419 (86–850)	52	330 (43–648)	47	321 (86–878)	47
Treatment effect	25	389 (14–1152)	46	245 (43–878)	53	489 (86–1238)	50	317 (14–1181)	42

[a] A visit constitutes any movement from one section and entry into an adjacent section.

consisted of the proportion of time spent on control sediment (tank sections 1 and 3 combined) and tailings (tank sections 2 and 4 combined). Because pairing caused observations to be dependent, we used differences between paired observations. Because differences were normally distributed in both the control and the treatment tests, we then used a scaled t distribution with the average difference between paired observations to determine overall significance. Significance for all tests was accepted at $\alpha = 0.05$.

RESULTS

Control tests

With only control sediment in the tank, the 11 crabs in the control trials spent an average of 370 min (26%), 419 min (29%), 330 min (23%), and 321 min (22%) in sections 1, 2, 3, and 4 respectively (Table 1). No tank effect was observed in these trials, selection being similar between tank sections 1 and 3 combined and tank sections 2 and 4 combined (t = 0.391, $P > 0.50$, df = 10; Figure 2).

Treatment tests

A treatment effect was observed after replacing control sediment with tailings in 2 opposing tank sections. Crabs spent significantly more time on control sediment than on tailings (t = 2.43, $P < 0.02$, df = 24; Figure 2). Over the 24-h observation period, the 25 test crabs spent an average of 489 min (34%) in one control section, 389 min (27%) in the other control section, 317 min (22%) in one tailings section, and 245 min (17%) in the other tailings section (Table 1). Of these 25 crabs, 19 spent 50% or more of their time on control sediment, whereas only 6 crabs spent over 50% of their time on the tailings (Figure 3).

Sediment characteristics

Test sediments differed in particle-size composition, compressive strength, and metal concentration (Table 2). Particles <63 μm made up 34% of the tailings and only 5% of the control sediment, whereas particles 125–250 μm made up 40% of the control sediment and only 20% of the tailings. Tailings formed a much more compact (firmer) substrate than the control sediment; compressive strength of the tailings was 4.10 $kg \cdot cm^{-2}$ versus only 0.13 $kg \cdot cm^{-2}$ for the control sediment (Table 2). Except for Cr, all metal concentrations were higher in the tailings than in the control sediment (Table 2). For example, tailings versus control concentrations were 16 versus <1.0 $\mu g \cdot g^{-1}$ for Cd, 164 versus 5 $\mu g \cdot g^{-1}$ for Pb, and 744 versus 60 $\mu g \cdot g^{-1}$ for Zn; the concentration of Cr in the control sediment (309 $\mu g \cdot g^{-1}$) was about twice as great as in the tailings (186 $\mu g \cdot g^{-1}$).

DISCUSSION

Tailings produced in a manner similar to those we examined and deposited on the sea floor may be avoided by ovigerous Tanner crabs. Our ovigerous Tanner crabs spent a greater proportion of time on control sediment (61%) than on tailings (39%); only 6 of 25 crabs spent >50% of the 24-h observation period on the tailings. Male and juvenile Tanner crabs would probably avoid tailings as well because they also partially bury (R. P.

Table 2. Particle-size composition, mean compressive strength (±SE), and metal concentrations in control sediment and mine tailings used in treatment trials with ovigerous Tanner crabs. Compressive strength was determined by hand-held penetrometer. Metal concentrations in control sediment from Johnson et al. (1998) and tailings (pilot plant run PP-7) from EPA (1996c); sediments were subjected to complete HF acid digestion and x-ray fluorescence or atomic absorption.

	% Particle size (μm)					Compressive strength	Metals ($\mu g \cdot g^{-1}$, dry wt.)					
Sediment	<63	63–125	125–250	250–500	>500	$kg \cdot cm^{-2}$	As	Cd	Cr	Cu	Pb	Zn
Control	4.5	20.1	40.1	35.2	0.1	0.13 (0.01)	7	<1	309	18	5	60
Tailings	34.0	21.0	20.0	22.0	3.0	4.10 (0.21)	10	16	186	46	164	744

Stone and S. W. Johnson, unpublished data) and forage in soft sediments (Jewett and Feder 1982).

Preference for control sediment over tailings by ovigerous Tanner crabs may have been partially due to differences in physical characteristics of the sediments. Tailings formed a much more compact substrate (compressive strength, 4.1 $kg \cdot cm^{-2}$) than the control sediment (0.13 $kg \cdot cm^{-2}$), possibly from the greater percentage of fines (<63 μm) in the tailings and the high angularity of the grains (EPA 1996d). The sea floor, when altered from a soft to a more compact substrate by adding tailings, may not support an adequate or appropriate prey population for foraging Tanner crabs. In addition, brooding female Tanner crabs often bury in soft substrates (Stevens et al. 1994). From a submersible, we have observed Tanner crabs partially buried in soft substrates of very fine sand and silt in Taku Inlet; compressive strength of Taku Inlet sediments was <0.10 $kg \cdot cm^{-2}$, and silt made up 65–85% of the sediment (Stone and Johnson, unpublished data). Although we did not observe Tanner crabs buried in our laboratory study, tailings avoidance may have been a tactile response to the comparatively firm substrate formed by tailings. In a similar avoidance study, juvenile yellowfin sole *Pleuronectes asper* consistently avoided tailings from the AJ mine compared to other sediment types (Johnson et al. 1998). Juvenile yellowfin sole also bury in soft sediments of silt or sand (Moles and Norcross 1995) to avoid predators or during overwintering.

Altering the control sediment by removing the coarser particles (≥500 μm) to more closely simulate tailings did not appreciably affect the results. Removal of the coarse particles (about 15% by volume) made the control sediment, if anything, slightly less suitable for Tanner crabs than had these particles been retained. Fine-grained sediments pack together tightly and have poorer water circulation than coarser-grained sediments (Pinto et al. 1984). Removal of the larger particles from the control sediment increased even further the compactness of these sediments; less compact sediments should be more suitable for burial. Thus, the avoidance of tailings by Tanner crabs we observed in the laboratory may be even greater in a natural setting.

Preference of control sediment over tailings by Tanner crabs may also have been due to contaminants in the tailings. Some metal concentrations were more than 10 times higher in the tailings than in the control sediment. Whether Tanner crabs could detect and avoid particular contaminants in the tailings is unknown, as is the consequence of long-term exposure, but Cr, Pb, and Zn do leach from tailings (Johnson et al. 1998) and could have been detected by crabs. Two metal concentrations in the tailings (Cd at 16 $\mu g \cdot g^{-1}$ and Zn at 744 $\mu g \cdot g^{-1}$) exceeded effects-range median (ERM) concentrations, i.e., the concentration of a particular metal in marine sediments above which adverse biological effects frequently occur (Long et al. 1995). In a laboratory study, Macdonald et al. (1988) reported that Cd and Zn were highly toxic to embryos and larvae of the yellow crab *Cancer anthonyi*. Other possible contaminants in the tailings that we did not examine, but that may have been responsible for the avoidance of tailings by Tanner crabs, included several organic milling reagents (e.g., carboxymethyl cellulose) manufactured for the flotation process (EPA 1996c). There are other possible reasons for the avoidance of tailings (e.g., tailings may lack an attractive factor such as a bacterial or organic coating), but these possibilities were outside the scope of this study. Further studies of a matrix of artificial tailings with combinations of sediment particle size and metal concentration would be necessary to definitively determine the cause of the observed avoidance behavior.

Because STD areas are typically large (Caldwell and Welsh 1982), some ovigerous Tanner crabs may be unable to avoid mine tailings. Effects of prolonged exposure to tailings by more sensitive life history stages (e.g., eggs, zoeae) are unknown. In a laboratory study with ovigerous Tanner crabs, survival of adults, eggs, and larvae was not adversely affected by holding crabs on tailings from the AJ Mine for the last 90 d of the brood cycle (Stone and Johnson, unpublished data). Reduced food availability to ovigerous females due to smothering of the sea floor could lead to reduced fecundity and poor larval survival. In addition, sublethal concentrations of contaminants can stress crustaceans (Aiken and Waddy 1986), and stressed Tanner crabs may be more susceptible to Bitter Crab Disease. Regardless of toxicity or physiological stresses, tailings on the sea floor may displace crabs from preferred habitats by creating an unfavorable substrate.

Avoidance of mine tailings as described in this study would probably diminish with time. Tailings deposited intertidally from an ore body adjacent to the AJ Mine and weathered for 75+ years were not avoided by juvenile yellowfin sole in the laboratory (Johnson et al. 1998), and juvenile Tanner crabs held on these same tailings in the laboratory for 500+ d showed no deleterious effects (Stone and Johnson 1997). Thus, tailings deposited on the sea floor may be avoided by Tanner crabs during the life of the mine. After mine closure, however, the sea floor could recover and provide suitable crab habitat, but the time needed for recovery is unknown. At Island Copper Mine in British Columbia, marine life extensively recolonized tailings deposited on the sea floor within 2 years after tailings deposition ceased in a particular area (Pedersen et al. 1993). Similarly, Kline (1998) reported that after 22 months the taxonomic composition, abundance, and biomass of invertebrates that colonized tailings (from the Kensington gold mine near Juneau, Alaska) were similar to those of invertebrates on a reference sediment placed in trays on the sea floor.

The focus of this study was to determine whether ovigerous Tanner crabs avoid mine tailings as a substrate. The ovigerous Tanner crabs in this experiment preferred natural marine sediment over tailings; so, after deposition on the sea floor, tailings may not initially provide suitable habitat for ovigerous Tanner crabs. The sea floor should recover with time, however, especially if the deposit zone receives a heavy load of natural sediment (e.g., near large or glacier-fed river mouths). Recolonization of the benthos and availability of food could also be an important factor in determining the speed of sea-floor recovery. In a study with juvenile yellowfin sole and AJ Mine tailings, avoidance of tailings as a substrate was reduced when tailings were covered with natural marine sediment (Johnson et al. 1998). Tanner crabs would probably return to the zone of deposit as tailings became buried with natural sediment and the benthos recolonized; this may occur quickly in areas with high natural sedimentation rates. Thus, ore sites adjacent to marine areas with high natural sedimentation rates may be the best sites to consider for initial field testing of STD effects on marine life.

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