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TOXICITY OF OIL-WELL DRILLING MUDS TO ALASKAN LARVAL SHRIMP AND CRABS

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INTRODUCTION

Environmental concerns about oil-industry activities in the marine environment have focused primarily on the effects and clean up of spilled oil. There have been less concern and less research on the potential effects of discharged drilling muds. Drilling muds are used during the well-drilling process and are utilized to bring up rock cuttings, control subsurface pressures, support the walls of the well hole, deliver hydraulic energy on the formation being drilled, aid in the suspension of the drill string and casing, prevent corrosion, and cool and lubricate the bit (IMCO 1980).

There are several common types of muds and hundreds of additives that may be used. The specific constituents and proportions vary considerably, depending on drilling conditions (depth, rock formation, etc. [Tagatiz et al. 1979]). Most drilling muds are water-based. They are complex chemically and may include bactericide, sealants, corrosion inhibitors, emulsifiers, flocculants, lubricants, foaming agents, filtrate reducers, weighing agents, and substances to control the pi-i. Barite (barium sulfate) is added to increase the density of the mud; bentonite (Montmorillinite clay) is commonly added to increase the viscosity. Lignosulfonates, which are derived from the treatment of wood lignin with bisulphite, are widely used viscosity reducers (IMCO 1980; Hrudey 1979). Ferrochrome lignosulfonate (FCL) has trivalent chromium ions chelated with the lignosulfonate complex (McAtee and Smith 1968).

The discharge of drilling muds might not be considered a problem for several reasons: (1) relatively small amounts of drilling muds enter the water during the drilling process (although a large volume may be discharged after drilling at a site has been completed); (2) although drilling muds may contain toxic additives, they are usually in low concentrations, and the bulk of the mud components is relatively inert; (3) mud is dense and rapidly settles out of the water column; (4) any toxic components are quickly dispersed and diluted; (5) bioassays have documented that the toxicity of most muds is low. Nevertheless, there is insufficient information to categorically conclude that drilling muds have no significant effects on marine life.

In 1978, the English Bay Native Corporation brought suit against the U.S. Department of Interior to stop discharging drilling muds into lower Cook Inlet. Many of the members of the corporation are fishermen with concerns about the local fishery resources, particularly shrimp and crab. Although an earlier study in Cook Inlet by Dames and Moore (1978) showed that drilling muds were not very toxic to salmon fry and adult shrimp, there was no information about the effects on larvae of crab and shrimp. Crustacean larvae are sensitive to oil water-soluble fractions (WSF's), particularly when molting (Brodersen et al. 1977; Mecklenburg et al. 1977). Because larvae are small, they equilibrate with toxicants rapidly and may be more sensitive than adults to the physical effects of suspended mud particles.

The purpose of this study was to measure the toxicity of drilling muds to crab and shrimp larvae, to provide a better basis for assessing potential environmental effects of drilling muds.

The study had four major objectives:

(1) To examine the toxicity of drilling muds to crustacean larvae. What proportion of the effect is due to physical stress caused by suspended solids, and what proportion is due to dissolved chemicals? Is the toxicity stable over time? Do toxic effects occur rapidly as they do with oil?

(2) To compare the toxicities of several muds using stage-I larvae of one shrimp and one crab species. Muds vary widely in constituent composition and probably have different toxicities.

(3) To compare the sensitivities of stage-I larvae of several species of shrimp and crab to one relatively toxic mud. Observations included survival and inability to swim after different lengths of exposure.

(4) To determine the effects of several pure mud additives--ferrochrome lignosulfonate, barite, and bentonite. Barite and bentonite make up the bulk of many drilling muds, and ferrochrome lignosulfonate is a common additive for reducing viscosity.

METHODS AND MATERIALS

Several types of tests were conducted to reach the objectives stated. Mud toxicities were compared by exposing larval king crab and coonstripe shrimp to all six muds and water-soluble fractions (WSF's) of muds. (A description of the muds tested during this study is given in table 1.) All six species were compared by exposing them to used Cook Inlet mud (mud B) suspensions (SM) and W. SF's. Additionally, the persistence of toxicity of the mud B WSF was tested with king crab and coonstripe shrimp larvae by repeatedly testing progressively older WSF preparations. The effect of salinity on toxicity was investigated by exposing coonstripe shrimp larvae at various salinities in mud B WSF. The toxicities of three mud components (ferrochrome lignosulfonate [FCL], barite, and bentonite) to Dungeness crab and dock shrimp were also determined.

Six species of crab and shrimp larvae were tested: king crab (*Paralithodes camtschatica*), Tanner crab (*Chionoecetes bairdi*), Dungeness crab (*Cancer magister*), coonstripe shrimp (*Pandalus hypsinotus*), dock shrimp (*Pandalus danae*), and kelp shrimp (*Eualus suckleyi*). Gravid king, Tanner, and Dungeness crabs were collected by divers in Auke Bay and maintained in large flow-through seawater aquaria. The coonstripe and dock shrimp were collected in Auke Bay and Big Port Walter, but the kelp shrimp were collected only in Auke Bay.

Larvae for the bioassays were collected daily from the water column as they were released by the adults. Al I tests were static and were conducted with stage I larvae 3-days old or younger. Larvae were not fed during the 6--day experimental periods, which limited the length of testing and also resulted in some cannibalism. Salinities ranged from 28.4 to 30.9°/00 with a mean of 30.0 ± 0.8°/00 through the course of study. Temperatures gradually increased throughout, at approximately 0.04 °C/day, and ranged from 4.5 to 7.5°C with a mean of 5.6 ±0.8°C.

The muds were stored in 5-gallon buckets with snap-top lids placed in a bath of cold water to keep them as cool as possible. Muds were mixed in the storage buckets with a barrel mixer at 3,450 rpm for a minimum of one-half hour before use to ensure sample homogeneity. All the muds contained ferrochrome lignosulfonate (FCL) except mud A' (Table 1).

In order to measure the mud WSF, salinity, pH, and absorbance, samples were centrifuged until ail, or most of, the particulate matter was removed. The supernatant was then passed through a #5 filter. Salinities were measured with an osmometer, and pH was measured with a combination glass electrode. Samples were diluted with distilled water as necessary for spectrophotometric measurements and scanned from 400 to 190 nm in a Beckman [1] model 25 spectrophotometer.

The chemical stability of FCL was determined by maintaining six replicate samples with an initial concentration of 0.160 g/1 of FCL at four different temperatures (-0.2° ±0.5°C, 5.8° ±0.6°C, 11.9° ±1.5°C, and 18.7° ± 1.7°C) for 24 days. The absorbance peaks at 277 nm were measured six times over this period, at 1, 4, 8, 17, and 24 days. Identical tests were completed with the mud B WSF starting at 0.98% by volume.

Drilling Mud Tests

Suspended Mud Tests

Tests began with the solid fraction of the muds distributed homogeneously through the water. Drilling mud (1-10% by volume) was added by syringe to seawater in 25—mm x 200 mm glass test tubes (final volumes were 50 ml). The tubes were then capped and shaken vigorously 10-20 seconds and the larvae were added immediately by pipette. Death was a difficult parameter to quantify accurately in the SM tests because some of the larvae were buried. Behavioral observations were more accurate: larvae were classified as swimming if they maintained their positions in the water column or were observed swimming up off the surface of the mud.

Except for mud B, the majority of the suspended mud settled out very rapidly (within 1-2 h). Because the suspended particles in mud B prevented direct observation even after 6 days, the testing procedure for this mud was different. Mud B was added by syringe to 400 ml beakers. Concentrations ranged from 0.05% to 10% by volume in 200 ml seawater. The mud was agitated, and larvae confined in glass tubes with screen bottoms (2 cm dia X 15 cm with 210μm plankton net). observations were made by briefly placing the larvae in clean seawater. Death was determined from such visual clues as body posture, color, and opacity. Larvae that swam horizontally or upward after the tubes were mildly agitated with an up-and-down motion were classified as swimmers.

WS F Tests

To prepare mud WSF's, equal volumes of mud and seawater were added to an Erlenmeyer flask and agitated vigorously for 2 min. This mixture was then centrifuged in 30 ml tubes at 10,000 rpm for 10 rein, then aspirated through GF/C or #5 filters. Mud B (only) was centrifuged a second time at 21,500 rpm for 10 min to remove remaining particles. The supernatant salinity was measured, then adjusted to match the daily salinity of Auke Bay seawater by adding a brine solution. The WSF's were then diluted to the desired test concentrations.

Larvae were placed by pipette into glass tubes with screen bottoms in clean seawater. These tubes were then transferred to glass beakers containing 200 ml of the WSF to begin testing. Fresh WSF's were prepared at the beginning of each experiment. If the highest concentrations of WSF were too opaque for observation, larvae in all concentrations (including controls) were placed briefly in clean seawater for observation. Observational criteria were the same as for mud B suspended-mud experiments:

Coonstripe shrimp larval assays were conducted at different salinities with mud B WSF to determine whether the additional stress would increase the toxicity of the WSF. Salinities ranged from 30.58 $^{0}/_{00}$ to 12.01 $^{0}/_{00}$.

Tests designed to determine the stability of the toxic effect required repeated assays with the same WSF preparation. Beakers containing the concentration series remained in the water bath between tests. The WSF preparation ranged from fresh to that aged for 4 weeks.

Component Tests

Ferrochrome lignosulfonate powder was dissolved in seawater with the aid of a magnetic stirrer. Testing procedures were analogous to the WSF testing techniques. Test concentrations ranged from 0.07 to 16.67 g/1 of FCL.

Barite (barium sulfate) and bentonite samples were weighed and added to 25 X 200-mm glass test tubes containing 50 ml of seawater. Experimentation proceeded as with the suspended-mud tests. Barite concentrations ranged from 0.004 to 0.200 g/ml, and bentonite concentrations ranged from 0.004 to 0.100 g/ml.

Analytical Methods

The LC50's and EC50's were determined from the bioassay data by logit analysis (Finney 1?371). (EC50's are those concentrations that caused 50% of the larvae to cease swimming.) Abbott's correction was applied as necessary (Finney 1977). However, replicates with a control mortality greater than 20% were disregarded. The LC50's and EC50's were further analyzed with analysis-of-variance techniques (ANOVA) followed by the Scheffe' a posteriori multiple comparison test. Ail Scheffé comparisons were made at the 95% confidence level. if ail comparisons were significant, a ">" was used; if some of the comparisons were significant, "≥" was used to define the relationship, and nonsignificant differences were represented with a "-."

Average mud LC50's and EC50's were converted to equivalent FCL concentrations with the use of a standard curve and correlated with mud LC50's by computing the product-moment correlation coefficient (Sokal and Rohlf 1969). Negative correlations were expected since LC50's and EC50's and chemical toxicity are inversely proportional--that is, the greater the FCL concentration, the smaller the LC - or EC50 should be.

RESULTS

The Nature of Drilling-Mud Toxicity

The rates of response (changes in swimming behavior and mortality) to mud B suspensions (SM) and water-soluble fractions (WSF's) were slow.

Measurable mortality (LC50's) began at 48-72 h, decreased at variable rates, and stabilized between 96 and 144 h. Measurable changes in swimming ability (EC50's) began between 4 and 24 h, and approached stability between 72 and 120 h (Figure 1). Comparisons between mud toxicities or species sensitivity at 144 h were, therefore, independent of the larval response rate because EC50 and LC50 curves became asymptotic before 144 h.

Although mud B was the most toxic mud tested, depressed swimming was not noted until approximately 24 h, and no recovery was observed. In some cases, particularly with the Dungeness crab larvae, mud accumulated in the gut of the larvae. This did not result in immediate death but inhibited swimming activity.

The sensitivity variation between species was measured by exposing each species to mud B SM's and WSF's. Species sensitivity to mud B suspensions (LC50's) ranged from 0.05% (dock shrimp) to 0.94% (Tanner crab), and the EC50's ranged from 0.05% (dock shrimp) to 0.28% (king crab) (Figure 2). Mud B WSF LC50's ranged from 0.30% (dock shrimp) to 3.34% (king crab), and the EC50's ranged from 0.21% (dock shrimp) to 2.58% (king crab) (Figure 2, Table 2).

Coonstripe and dock shrimp larvae were relatively sensitive in both the mud suspensions and WSF's. In contrast, larval tanner crab and kelp shrimp appeared to be relatively more sensitive than the other larvae in the WSF but more tolerant in the suspensions. The species sensitivities were as follows:

Decreasing Tolerance →

(1) Suspended mud B: Tanner > kelp ≧ king > Dungeness ~ coonstripe ~ dock.

(2) Mud B WSF: king ≧ Dungeness ≧ tanner ~ coonstripe ~ kelp ~ dock.

In tests involving the remaining muds, king crab larvae were generally more tolerant than larval coonstripe shrimp.

The variation in mud toxicities, which was considerable, was measured by exposing king crab and coonstripe shrimp larvae to each of the six muds. In the suspended-mud tests, EC50's varied from 0.28% (mud B) to 1.53% (mud D) fur king crab larvae, and from ≦0.2% (mud B) to 2.98% (mud D) for larval coonstripe shrimp. (Only EC50's were computed for the SM's because some larvae were buried in the settlings, which made it difficult to assess mortality accurately.) In the WSF tests, the EC50's for king crab larvae varied from 2.58% (mud B) to 18.05% (mud D), and from 0.65% (mud B) to 26.79% (mud D) for larval coonstripe shrimp. The WSF LC50's for king crab larvae ranged from 2.33% (mud A') to 30.08% (mud D), and from 0.90% (mud B) to 37.62% (mud D) for coonstripe shrimp larvae. Larval coonstripe shrimp were generally more sensitive than king crab larvae (Figure 3, Table 3).

Mud B was generally the most toxic mud, whereas mud- D was generally the least toxic. The comparative toxicities were as follows:

Decreasing Toxicity →

(3) Suspended-mud tests: B > A ~ C ~ C'.

(4) Mud WSF tests: A' ~ B ≧ C' ~ C ≧ A ≧ D, where

A ≡ used Prudhoe Bay mud (2926 m)

A' ≡ unused Prudhoe Bay mud

B ≡ used Cook Inlet mud (3382 m)

C ≡ Homer 'spud' mud

C' ≡ unused Homer "spud" mud

D ≡ used Homer mud (442 m)

The toxicity of the suspended mud was much greater than the WSF toxicity. Comparison of mud WSF's and the suspended muds $1 - \frac{\text{WSF LC50}}{\text{SM LC50}}$ indicates that the particulate matter in the whole muds accounted for 81% ±

16% of the toxicity. Cessation of swimming indicated that the particulate matter contributed 80% ± 10% of the observed response.

The stability of the mud B WSF toxicity was tested with king crab and coonstripe shrimp larvae. The toxicity in mud B WSF EC- and LC50's increased gradually over time (Table 4). These increases were not significant for king crab larvae in .21 days but were significant for coonstripe crab larvae in 28 days. The decrease in toxicity (indicated by increased sensitivity) was due to dilutions of the toxicant caused primarily by water condensation.

Coonstripe shrimp larvae were also tested in mud B WSF at several different salinities. Their sensitivity to mud B WSF was unaffected by salinities ranging from 30.58°/00 to 15.07°/00. A salinity of 12°/00 without toxicant was lethal within 96 h. The median lethal salinity, without acclimation, was 15.51°/00 (13.09-17.93°/00) at 96 h. Evidently, coonstripe shrimp larvae are euryhaline because salinities in controls as low as 18.14°/00 caused no death or behavioral changes. Salinity differences apparently did not alter the chemical configuration of the toxicant sufficiently to change its toxicity.

Mud-Component Toxicities

Dock shrimp and Dungeness crab larvae were tested in ferrochrome lignosulfonate (FCL) solutions. The LC50's were 0.12 g/1 (dock shrimp) and 0.21 g/1 (Dungeness crab), and the EC50's were 0.05 g/1 (dock shrimp) and 0.15 g/1 (Dungeness crab) (Table 5). Dock shrimp larvae were also more sensitive than Dungeness crab larvae in the suspended-mud and WSF tests.

The FCL concentrations in a given mud could be calculated from the mud absorbance data (Table 1) and a FCL standard curve. Mud B, for example, contained 28.5 g/1 FCL according to data supplied by IMCO (Table 6), and

66% of this was detected in the WSF. The actual FCL concentrations (FCL 'equivalents') at the LC50 (or EC50) were then calculated for each mud, and compared with the observed mud LC - and EC50's. Negative correlations were anticipated because greater FCL concentrations should yield smaller mud LC - and EC50's. FCL LC50 equivalents ranged from 0.04 to 0.63 g/l (king crab) and from 0.04 to 0.17 g/1 (coonstripe shrimp). Equivalent FCL EC50's ranged from 0.04 to 0.48 g/1 (king crab) and from 0.02 to 0.12 g/1 in the coonstripe tests. Moderate-to-strong negative correlations (-0. 31 and -0. 95) between FCL and mud WSF L. C50's and between FCL and mud WSF EC50's (-0.49 and -0.89) were obtained in the king crab experiments. However, FCL and mud WSF LC50's correlations from the coonstripe shrimp experiments were negligible to moderate (-0.09 and -O. 64), and no correlation between FCL and EC50's (0.06 and 0.03) was found. Further analysis revealed the regression coefficients (slopes) were not significantly different from zero and implied that other factors also contributed significantly to the mud WSF toxicity.

The rate of response to FCL was very similar to the mud B WSF rate. Measurable LC50's began at 48 h and approached stability by 120 h. Measurable EC50's began at 4 h and were stable by 72 h (Figure 4).

Barite and bentonite were not particularly toxic. The EC50's were first measurable after 24 h and did not decrease with time, thereafter. The EC50's for Dungeness crab larvae ranged from 3.88 g/1 to 4.28 g/1 with bentonite and was 3.57 g/1 (2.22-5.75 g/1) with barite. Dock shrimp larvae were more sensitive: the bentonite EC50's ranged from 0.69 to 1.73 g/1, and the barite EC50's 0.27 to 2.52 g/1 (Table 4).

In toxic mud B suspensions, bentonite was present at 1% to 3% of its toxic level, and barite was present in more significant quantities (12% to 63% of its toxic level). The quantities of barite and bentonite in mud B were calculated from the data in table 2. The bentonite concentrations were 0.02 g/1 (dock shrimp) and 0.1 g/1 (Dungeness crab); barite concentrations were 0.3 g/1 (dock shrimp) and 1.4 g/1 for Dungeness crab.

DISCUSSION

The toxicities of the drilling muds we tested are similar to the toxicities to crustacean larvae reported in other drilling-mud studies. Gilfillan et al. (1980) observed a 96-h WSF LC50 of 1.7% for Stage I pink shrimp (Pandalus borealis) larvae, and 0.5% for stage V American lobster (Homarus americanus) larvae. Carr et al. (1980) observed a 96-h WSF LC50 of 2.7% in l-day-old Mysidopsis almyra juveniles. Neff et al. (1980) observed a 96-h WSF range of 1. 17-2.75% for stage I grass shrimp (Palaemonetes pugio) larvae. All of these values fall within the 96-h range observed in this study. -

Dames and Moore (1978) reported that coonstripe shrimp adults had a 96-h LC50 range between approximately 3.2% and 15%. Comparison with coonstripe shrimp larvae findings in this study suggest the larvae may be approximately an order of magnitude more sensitive than the adults. N eff et al. (1980) observed adult and larval grass shrimp sensitivities varied by a factor of approximately 3-4.

Cessation of swimming responses were more sensitive indicators of the larval response to the toxicants than mortality responses. Compared to mortality, swimming stopped relatively early in the exposures and at lower exposure levels. The EC50'S for cessation of swimming and LC50's eventually did approach convergence, however; since dead animals cannot swim, the number of nonswimming larvae is dependent on mortality. At the extreme, 100% mortality and 100% nonswimming must occur together. The mean EC50: LC50 ratio at 96 h, 0.51 (0.45-0,58), was significantly less than at 144 h, 0.66 (0.60-0.71).

Chemical compositions and toxicities between drilling muds vary widely, as is evident from this study. Hrudey (1979) found that surface muds were the most toxic, and midhole muds were the least toxic. Data in our study tend to follow this pattern. Other studies have demonstrated increasing mud toxicity with drilling depth (Tornberg et al. 1979). With multiple mud and formation combinations possible, it is probable that consistent trends do not occur. Mud B was comparatively toxic for two reasons: (1) it stayed in suspension; therefore, the larvae were subjected to continual physical stress; and (2) mud B contained a much higher concentration of FCL than the other muds.

The effect of the suspended muds on larval swimming ability was not very rapid. The rate at which swimming ceased was the same as the rate of cessation in the controls but occurred earlier with increasing mud concentrations (Figure 5). This suggests the toxicity mechanism is physical, rather than chemical, by requiring extra energy expenditure to cope with suspended particles. Because none of the larvae were fed during the testing periods, experimental larvae, which probably expended more energy, would run out of energy and stop swimming before the controls, but this rate of decline would be the same (Figure 1). In contrast, acute chemical toxicity would be expected to cause a more rapid decline, because the larvae probably take up chemical toxicants quickly.

The particulate matter in the drilling muds, which was composed primarily of barite and bentonite, caused roughly 80% ± 16% of the observed toxicity. This agrees reasonably well with work by Logan et al. (1973) who determined barite and bentonite accounted for approximately 45--60% of the total theoretical mud toxicity (Land 1974). Logan et al. (1973) point out that the contribution of solids is strongly dependent on the actual mud composition. Several authors (Beckett et al. 1975; Dames and Moore 1978; Sprague and Logan 1979; Gilfillan et al. 1980) have suggested that suspended solids may cause mortalities through abrasion, erosion, or the clogging of respirator y surfaces. Robison (1957) suggested the toxic effect of Montmoril lonite (bentonite) may be related to its absorptive capacity as suspended solids are passed through the gut. All these effects, including swimming in a more viscous mud, would consume more of the larva's energy.

The fact that barite and bentonite had an initial effect, followed by no change in the component tests, suggests that the detrimental effects were caused by particles in suspension and that after these had settled out of the water column, no further interaction took place. Others (Daugherty 1951; Logan et al. 1973; Sprague and Logan 1979) have found very low bentonite and barite toxicities. Sprague and Logan (1979) found. 96-h LC50's for rainbow trout (Salmo Gairdneri) were 76 g/1 for barite and 19 g/1 for bentonite. Our experiments indicate that crustacean larvae are approximately an order of magnitude more sensitive than trout, and perhaps more, because no attempt was made to keep these materials in suspension in our larval tests.

Water-soluble fractions accounted for about 20% of the toxicity of drilling muds. Apparently, the chemical compounds in the WSF also increased the rates of larval energy expenditure. Carr et al. (1980) found Mysidopsis almyra juveniles increased fo od COnSUmptiOn and initial respiration rates but their growth was retarded when exposed to sublethal mud WSF's. Respiration rates eventual l y returned to normal, but dose-dependent growth retardation became more pronounced. He concluded that the shunting of energy into homeostatic mechanisms reduced the amount of energy available for growth.

The FCL content of the muds (see the WSF absorbance data, Table 1) suggested that B >> C' > C > D > A. This hypothesis was largely substantiated (Comparison 4) and implies that FCL is a major factor in the WSF toxicity. The FCL concentration correlated well with the observed toxicity in the king crab experiments.

Absorbance data indicated that FCL did not volatilize or degrade in seawater but changes in concentration were caused by water evaporation and condensation. The bioassays also indicated that FCL was essential l y stable under the given test conditions. The concentration of the mud WSF slowly decreased over time due to two factors: (1) the principal concentration decrease was due to dilution caused by water condensation, and (2) water introduced with each new batch of larvae caused slight progressive dilutions. This dilution explains the observed drift in toxicities over the course of a month.

The chromium associated with the lignosulfonates may be one of the toxic factors in mud toxicity, The toxicity of chrome varies widely for different aquatic organisms and also depends on its valence (Hrudey 1979). Chromium exhibits its greatest bioavailability in pure solution, is less available in FCL solutions, and is least available in mud WSF's (Page et al. 1980). This decreasing bioavailability is due to (1) chelation of Cr with the lignosulfonate molecule, and (2) the ion-exchange capacity of bentonite. FCL is absorbed along the edge of the clay platelets and may also be absorbed on barite (Monaghan et al. 1976; Sprague and Logan 1979; Ray and Meek 1980).

Other heavy metals also occur in drilling muds and may contribute to its toxicity. Only a small fraction of these metals appear in the aqueous phase. Natural-formation drill solids may be the major source of most trace elements. Lead may originate from drill-string lubricant (Ayers et al. 1980; Page et al. 1980; Ray and Meek 1980).

Although petroleum hydrocarbons and drilling muds are the two main pollutants from well-drilling activities, they are very different chemically and toxicologically. In oil WSF's, crustacean larvae are unable to swim within minutes of exposure although it may take several days before they die. Low concentrations of aromatic hydrocarbons in the oil WSF are toxic and are taken up quickly. In contrast, the effects of relatively high drilling-mud concentrations are slow, and the principal toxic factor is physical. EC50 hydrocarbon WSF concentrations for king crab, coonstripe shrimp, Dungeness crab, and kelp shrimp larvae range from 0.8 ppm to 2.1 ppm (Rice et al. 1981). This range is roughly 3-5 orders of magnitude below the mud WSF EC50 range. A difference of two orders of magnitude occurs between FCL toxicity and hydrocarbon WSF toxicity.

The fate of drilling muds in the natural environment. is more complex than in the laboratory. The same currents that bring larvae into contact with a plume of discharged drilling muds also dilute the plume and carry larvae downstream. After a relatively brief exposure, the mud WSF probably will virtually "disappear" through water dilution. Ray and Meek (1980) observed dilutions of 500:1 to nearly 1,000:1 within 3 m of a platform discharge pipe; within 200 m of the discharge, total suspended solids were approaching background levels.

Our toxicity studies indicate that larvae are not damaged quickly because both the chemical and physical toxicity of drilling muds is low. Because the length of time they are exposed to significant drilling-mud concentrations is very short, discharges of drilling muds are not particularly harmful to crustacean larvae even though they are probably an order of magnitude more sensitive than salmon fry and adult shrimp.

SUMMARY

Drilling muds were toxic to crustacean larvae, with the level of toxicity dependent on the mud composition, species, and the type of test (suspended mud or WSF). All comparisons between toxicities or sensititivities were made at 144 h because the larval response had stabilized by that time.

1. The suspended muds were more toxic to crustacean larvae than mud water-soluble fractions were. For used Cook inlet mud (mud B), the 144 h LC50 range for several species was 0.05 -0.94% by volume for suspended mud, and O. 30-=3.34% for the water-soluble fraction.

2. The particulate fraction of the muds caused approximately 80% of the observed toxicity, and the water-soluble fraction accounted for the remaining 20%.

3. Variation between mud toxicities was greater than variations between species sensitivity. The 144-h mud WSF LC50 range was 0.90 -3'7.62 for king crab and coonstripe shrimp larvae. The WSF toxicity from the most toxic to least toxic mud was: A' ~ B ≥ C' ~ C ≥ A ≥ D,

   where A ≡ used Prudhoe Bay mud ('2926 m)

   A' ≡ unused Prudhoe Bay mud

   B ≡ used Cook Inlet mud (3382 m)

   C ≡ Homer 'spud' mud

   C' ≡ unused Homer mud

   D ≡ used Homer mud (442 m).

4. Mud-component tests with dock shrimp and Dungeness crab larvae indicated that barite and bentonite EC50's ranged from 0.3 to 4.3 g/1. At 144 h, average ferrochrome lignosulfonate LC50's were 0.250.1 g/1.

5. Ferrochrome lignosulfonate concentrations in the mud B WSF correlated well with the toxicity and swimming cessation in the king crab larval tests. Chromium may be a significant factor in FCL toxicity.

6. Some variation in relative species sensitivity occurred between the suspended mud and the water-soluble-fraction (WSF) tests. Larval tanner crab and kelp shrimp were relatively tolerant in the suspended muds, but were more sensitive in the WSF. However, coonstripe and dock shrimp larvae were sensitive in both test types, and larval king and Dungeness crab were generally tolerant.

7. The cessation of larval swimming was a more sensitive indicator of the mud toxicity than mortality was. EC50's, measured by nonswimming, were measurable earlier (4-24 h) than LC50's, measured by death, (48-72 h) and occurred at lower exposure concentrations (66% of the LC50 at 144 h).

8. Variations in salinity over the range 30.58-15.07°/00 did not affect the water-soluble fraction toxicity of the used Cook Inlet mud (mud B).

CONCLUSIONS

1. The toxic nature of drilling muds is very different from the toxic nature of crude oil. Drilling muds affect larval crustacean swimming ability and survival slowly, whereas the effects. of oil are very rapid. The water-soluble fractions of drilling muds are stable in solution, but oil WSF's are not. However, the particulate fraction of the mud generally settles out of the water quickly.

2. The slow nature of the drilling-mud toxicity suggests the toxic components are not very active as chemical poisons, but cause extra larval energy expenditure to maintain homeostasis. Accelerated energy depletion results in early death.

3. Crustacean larvae are more sensitive to drilling muds than adult crustaceans and fish by approximately an order of magnitude. However, drilling muds are not particularly toxic, for toxic concentrations ranged from approximately 4 to 40 parts per thousand. .

4. Water-column concentrations of drilling muds capable of causing toxicity are probably brief and limited to distances less than 3 m from the point of platform discharge. Under most conditions, drilling mud discharge probably has no measurable impact on planktonic and nectonic communities in the natural marine environment.

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FOOTNOTE

[1] Reference to trade names does not imply endorsement by the National Marine Fisheries Service, NOAA.

TABLE 1

Description of Drilling Muds Used in Bioassays

Mud identity	Location	Condition	Depth (m)	Density ($kg \cdot l^{-1}$)	100% WSF pH	100% WSF Salinity (‰)	100% WSF Color	100% WSF Absorbance[a]
A	Prudhoe Bay	used	2,926	1.122	8.9±0.0	1.8±0.1	yellow	2.68
A'	Prudhoe Bay	new	0	1.183	13.2*0.0	3.1±0.0	clear	b
B	Cook Inlet	used	3,382	1.655	8.6±0.0	17.5±0.1	red/orange	173.77
C	Homer	used "spud"	--	1.168	9.9±0.0	5.2±0.1	yellow	5.26
C'	Homer	new	0	1.174	9.9±0.0	5.2±0.1	yellow	5.46
D	Homer	used	442	1.067	12.2±0.0	4.0±0.1	yellow	4.19

a--Calculated 100% values at 277 nm.

b--No absorbance peak at 277 nm.

Table 2. Sensitivity of shrimp and crab larvae to used Cook inlet mud (mud B). Sensitivities were measured by mortality (LC50's) and the cessation of swimming (EC50's). Tests were conducted with whole mud suspensions and with mud water-soluble fractions. The 144-h means and the 95% confidence intervals are listed as percent mud by volume.

	LC50		EC50	
Species	SM	WS F	SM	WS F
King crab	0.48 0.35-0.61	3.34 1.12-5.56	0.28 0.00"0.57	2.58 1.62-3.54
Coonstripe shrimp	*	0.90 0.54"1.27	≦0.20	0.65 0.46-0.83
Tanner crab	0.94 0.00-6.25	1.65 0.40-2.90	NC	0.56 0.35"0.77
Kelp shrimp	0.44 0.36-0.53	0.47 0.24-0.69	<0.50	NC
Dungeness crab	0.20 0.16-0.23	1.41 0.00-3.85	NC	NC
Dock shrimp	0.05 0.05-0.05	0.30 0.00-1.53	0.05 0.02-0.08	0.21 0.16-0.29

NC. Not calculable.
* Not tested.

Table 3. Comparative mud toxicities, using larval king crab and coonstripe shrimp as indicator species. See table 2 for the mud B data. Tests measured mortality (LC50's) and the inability to swim (EC50's). The 144-h means and 95% confidence intervals are in percent mud by volume. See table 1 for description of mud types.

Species	A	A'	C	C'	D
		A--WSF LC50			
King crab	*	2.33 0.00-9.96	9.45 7.67-11.22	7.17 7.09-7.24	30.08 17.68-42.48
Coon stripe shrimp	15.31 4.29-26.34	3.23 0.46-5.99	*	<5	37.62 27.72-47.53
		B--WSF EC50			
King crab	*	NC	6.60 4.61-8.58	6.18 4.13-8.24	18.05 11.87-24.24
Coonstripe shrimp	9.07 6.17-11.97	2.42 (0.00-5.38)	*	<5	26.79 16.47-37.11
		C-SM EC50			
King crab	*	<1	NC	<1	1.53 0.86-2.71
Coonstripe shrimp	*	<1	*	NC	2.98 1.18-7.51

NC. Not calculable.

* Not tested.

Table 4. Toxicity of aged Cook Inlet mud (mud B) water-soluble fractions with king crab and coonstripe shrimp larvae as indicator species. The tests measured mortality (LC50's) and the swimming cessation (EC50's). The 144-h means and 95% confidence intervals are listed as percent mud by volume.

	AGED WSF LC50			
Species	7	14	21	28
King crab	3.91 2.60-5.21	6.03 1.16-10.89	5.63 4.22-7.51	*
Coonstripe shrimp	1.47 0.88-2.06	4.08 1.44-6.72	5.83 1.47-10.19	4.19 2.90-5.49

	Aged WSF EC50			
Species	7	14	21	28
King crab	2.41 1.37-4.23	3.63 0.00-10.89	NC.	*
Coonstripe shrimp	0.92 0.79-1.05	.2.49 0.00-5.82	2.87 0.00 -19.31	3.82 1.51-6. 13

NC. Not calculable.
* Not tested.

Table 5. Mud-component toxicities. Sensitivities of larval Dungeness crab and dock shrimp to ferrochrome lignosulfonate (FCL), bentonite, and barite were measured by mortality (LC50's) and the loss of swimming ability (EC50's). Means and 95% confidence intervals are in grams per liter.

FERROCHROME LIGNOSULFONATE

Species	LC50	EC50
Dungeness crab	0.21 0.18-0.24	0.15 0.09-0.24
Dock shrimp	0.12 0.00-0.48	0.05 0.02-0.16

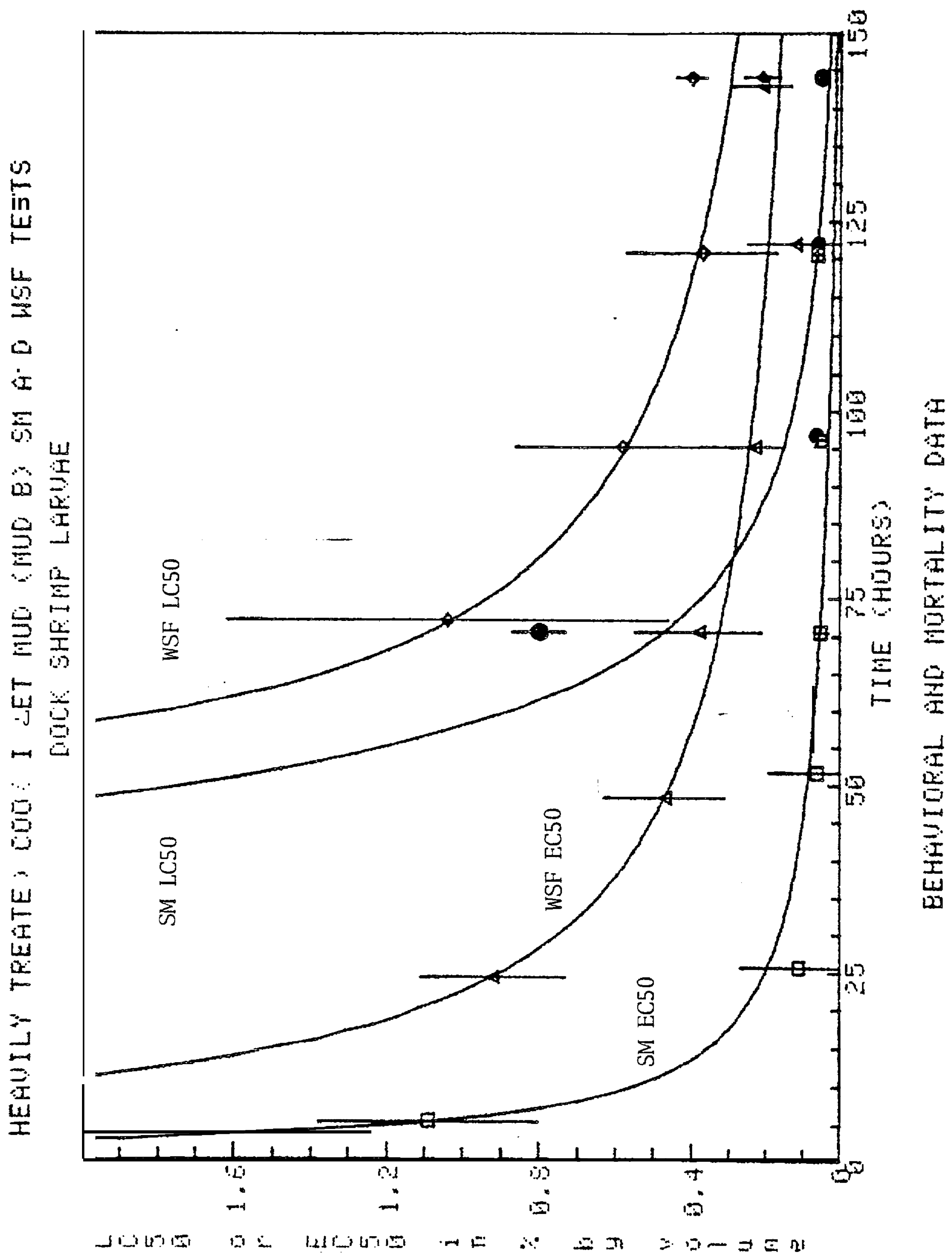
Species	24.1 h	42.8 h	71.1 h	119.0 h
BENTONITE				
Dungeness crab	NC	3.88 2.06-7.31	4.28 3.05-6.02	NC
Dock shrimp	0.99 0.45-2.17	NC	0.97 0.00-4.48	1.53 0.28-8.29
BARITE				
Dungeness crab	NC	NC	3.57 2.21-5.75	NC
Dock shrimp	0.40 0.00-2.72	NC	NC	2.52 0.41-15.64

NC. Not calculable.

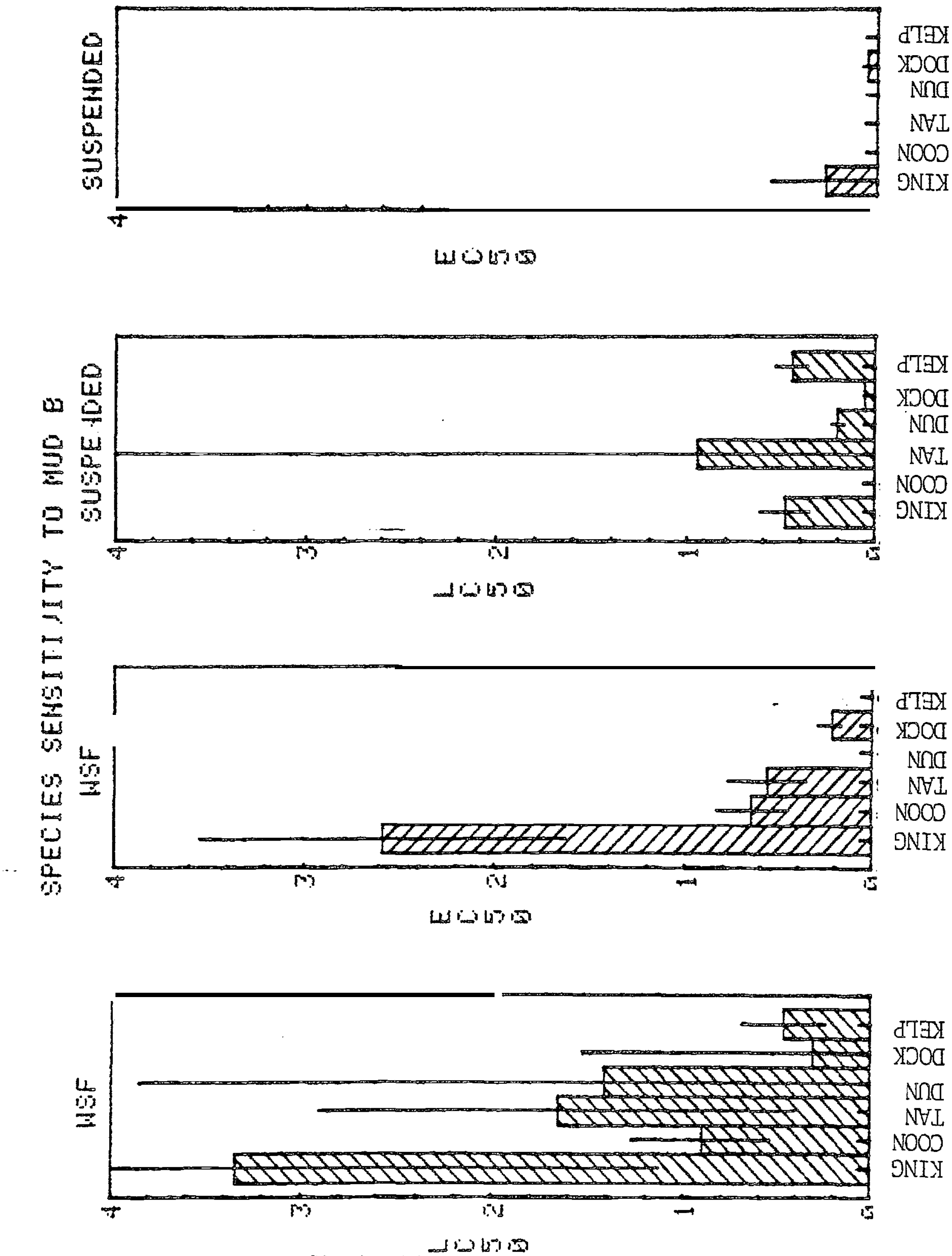
Table 6. Composition of mud B*

Component name	Composition	Quantity (g/l)
IMCO Bar	Barite ($BaSO_4$)	570.0
IMCO Gel	Bentonite (Montmorillinite clay)	42.8
IMCO VC-10	Ferrochrome lignosulfonate	28.5
Soltex	Sulfonated asphaltene	17.1
Drispac Super Lo	Polyanionic cellulosic polymer	5.7
IMCO Poly Rx	Ferrochrome lignosulfonate, lignite, sodium carbonate, sodium nitrilotriacetic acid	2.9
Desco	Sulfonated quebracho containing tannins of the condensed type	2.9
IMCO caustic soda	Sodium hydroxide (NaOH)	2.9
Water	(% by volume)	75%
Solids	(% by volume)	25%

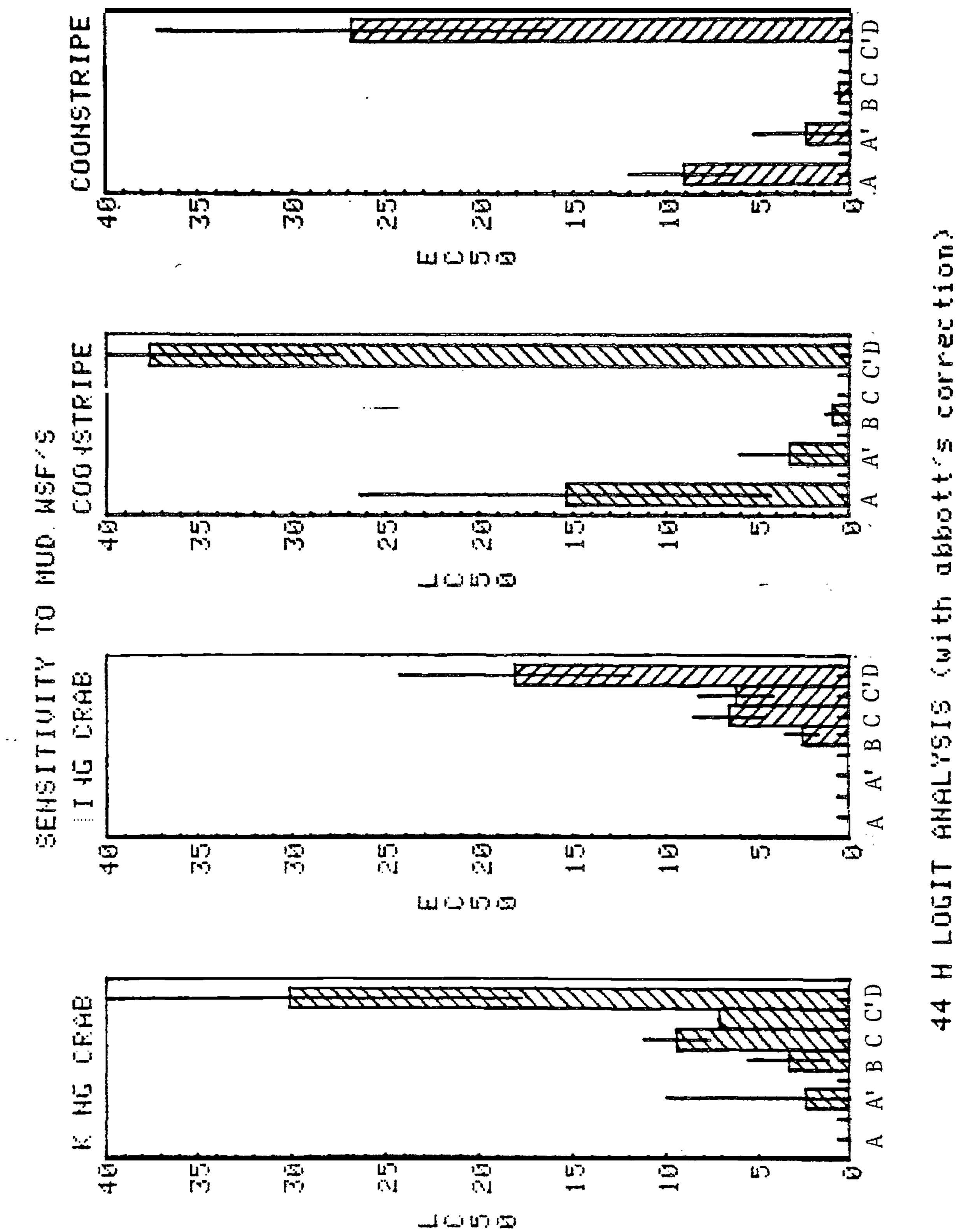
* Data supplied by IMCO Services, the supplier of mud B.



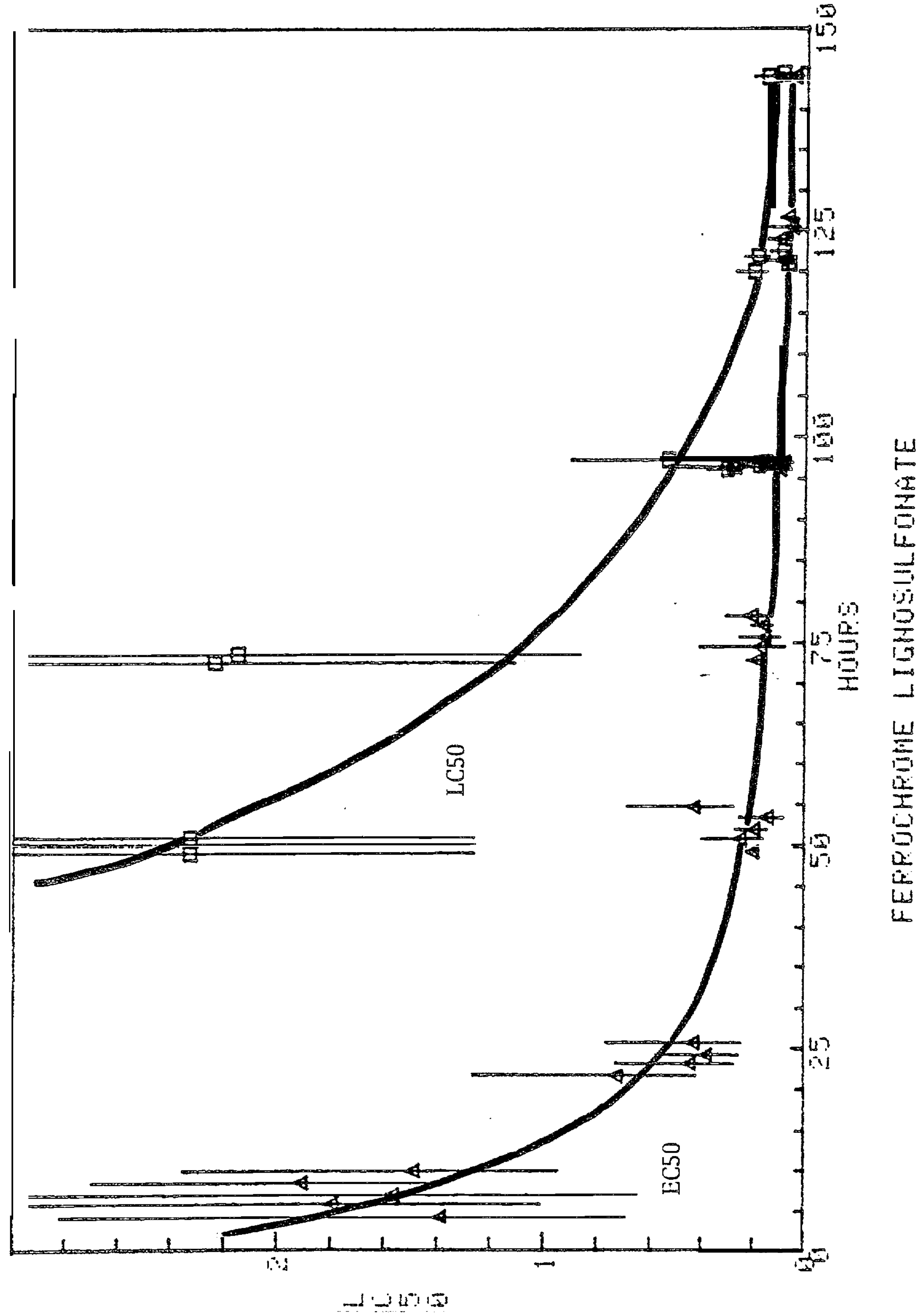
1. **Comparison of average mud B suspension and WSF rates of effect on dock shrimp larvae. The effect in the suspensions occurred prior to the WS F effect, and resultant EC- and LC50's were smaller. Cessation of swimming (EC50's) occurred well before mortality (LC50's) began. Vertical bars indicate the 95% confidence interval .**



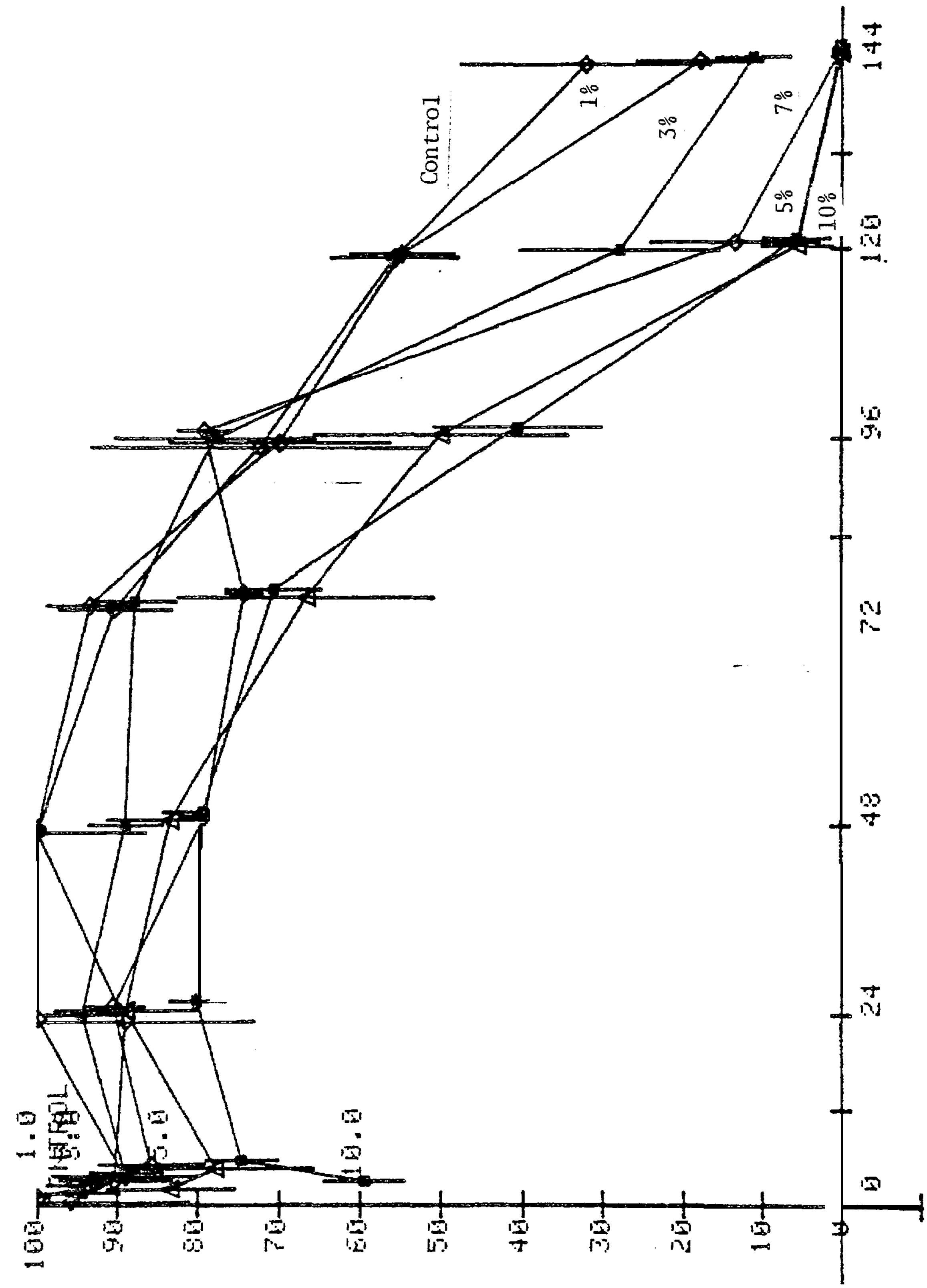
2. Comparison of sensitivity of six species of larval shrimp and crabs to **both the water-soluble fraction** (WSF) **and suspension** (SM) **of a heavily treated Cook Inlet drilling mud (mud El).** The responses measured were mortality (LC50) and **the inability to swim** (EC50). Vertical **bars indicate the** 95% **confidence interval.**



3. **Comparison of mud** WSF toxicities (LC50's) **and concentrations causing swimming cessation** (EC50's) **with king crab and** coonstripe **shrimp larvae as indicator as species. See table 1 for description of mud types.**



4. **Rate** of **e f f e c t** of ferrochrome lignosulfonate (FCL) **o n** dock shrimp **larvae. Changes** in **swimming** (EC50) **occurred** before **mortality** (LC50) **began. Rate patterns for** FCL **and mud** B WSF **(Figure** 1) **were quite similar.**



5. **Effect of used Homer mud (mud D) suspension on swimming ability of larval king crab. After the initial effect, some recovery was observed. Note that swimming declines tended to mirror the control pattern.**

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