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Effects of oil on arctic marine organisms: a review of studies conducted by the Arctic Biological Station

by

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Abstract

Studies carried out by the Arctic Biological Station as part of the Beaufort Sea Project are briefly reviewed. Lethal and sublethal effects of northern crude oils on seals, invertebrates, phytoplankton, seaweeds and bacteria, and the petroleum biodegradation potential of the marine microbial flora are discussed.

Résumé

Les études conduites par la Station de Biologie de l'Arctique en rapport avec le Projet de recherche dans la Mer de Beaufort sont brièvement décrites. Les effets lethaux et subléthaux des huiles non raffinées sur les phoques, les invertébrés, le phytoplancton, la flore macroscopique et microscopique, et le potentiel de biodégradation du pétrole par la flore microbienne sont analysés.

Introduction

The discovery of oil at Prudhoe Bay in Alaska stimulated exploratory activities in the nearby Mackenzie Delta region of Canada. Limited, but encouraging, discoveries in the delta led inevitably to exploratory drilling in the adjacent waters of the southern Beaufort Sea. Initial drilling was carried out in shallow water from artificial islands but recently drillships have been active in deeper waters. It became apparent early in these developments that little was known about the biology of the Beaufort Sea. A comparable degree of ignorance was evident in several other branches of marine science.

In the early 1970's the Arctic Biological Station expanded its research programs in the western Arctic to respond to rising demands for environmental information. In 1974 a comprehensive program of marine research called the Beaufort Sea Project was launched, funded jointly by the Federal Government and the Arctic Petroleum Operator's Association. Its dual objectives were to determine the potential impact of the harsh arctic marine environment upon offshore drilling activities, and, conversely, to assess the potential impact of offshore drilling activity upon the marine environment in the southern Beaufort Sea, particularly in the event of a major blowout. Government agencies, private consulting firms and university groups participated in various aspects of this program. The contribution of the Arctic Biological Station assumed two distinct, but complementary forms. A series of survey studies on marine mammals (Sergeant and Hoek, 1974), fish (Galbraith and Fraser, 1974), zooplankton (Grainger, 1975), benthic invertebrates (Wacasey, 1975), phytoplankton and seaweeds (Hsiao, 1976; Hsiao et al., 1977) and bacteria (Knowles, 1975; Bunch and Harland, 1975) were designed to provide a general picture of the present undisturbed Beaufort Sea ecosystem and to pinpoint potentially sensitive areas. A further group of studies focussed upon direct effects of crude oil upon particular components of the ecosystem in order to assess the probable impact of a major oil spill upon the biota. The present review summarizes some of the findings of the latter studies.

Arctic oil spills

Studies of oil spills in temperate waters indicate that major oil spills may not be as ecologically disastrous as once anticipated, and long-term damage has in most cases been minimal. However, the Arctic Ocean differs in several respects from other oceans and some of these differences are such that they would tend to heighten and prolong the adverse effects of an oil spill.

One unique feature of the arctic marine ecosystem is the presence of ecological communities associated with a sea-ice habitat that is particularly vulnerable to severe contamination by oil. A rich algal bloom forms on and within the lower surface of the ice in early spring. This ice flora "forms an important fraction of the total production in the arctic ocean and .... it helps greatly to prolong the productive season beyond that of the water-borne phytoplankton" (Dunbar, 1975). A variety of invertebrates, fish and mammals are associated with the ice-water interface and a simple food chain based upon the ice flora has been postulated. Virtually nothing is known about the general ecology and trophic relationships of the components of this epontic community or about its sensitivity to crude oil.

Effects on seals

Seals and other marine mammals are particularly vulnerable to oil because they may encounter massive quantities in the form of surface slicks in leads, breathing holes and breeding lairs, as oil lenses under the sea ice, and along the shoreline during hauling out. It is clearly important to know how sensitive the animals might be to fouling by oil. Studies were carried out on both adult ringed seals from the Beaufort Sea and on harp seal whitecoat pups from the Gulf of St. Lawrence. Selected clinical, behavioral, hematologic and biochemical factors were examined, following immersion in, and ingestion of fresh crude oil (Smith and Geraci, 1975).

Adult ringed seals swam readily through oil slicks with little evident awareness of the oil. However, with prolonged exposure attempts to avoid the oil became evident. No mortality attributable to the oil occurred among adult animals kept in holding pens near the collection site and exposed to a 1 cm layer of oil for 24 hours. Similarly, harp seal pups liberally coated with oil survived for 3 or 4 days until sacrificed for examination. In marked contrast, adult seals kept in holding tanks at Guelph University died unusually rapidly following exposure to a 1 cm layer of oil. Of three seals exposed, one died in 21 minutes, another in 60 minutes and the third after 71 minutes. The stresses associated with handling, transporting and maintaining the seals in the laboratory rendered them extremely susceptible to further stress from oil. It is probable that under conditions of natural stress, such as during a moult or during a period of poor feeding in severe ice conditions, seals may be particularly sensitive to spilled oil. However, it is highly unlikely that the effects in the natural habitat would be quite as dramatic as suggested by the laboratory study.

Several sublethal effects were considered. Oil on the pelt did not cause any thermoregulatory problems in animals exposed to the cold, and core temperatures remained constant. This was anticipated because blubber rather than hair is the primary insulating material in these animals. A complementary study (Øritsland, 1975) on the effect of oil on the thermal properties of dry seal pelt indicated that solar heating of the skin would be increased in the presence of oil. This effect is largely attributable to increased transmittance by lightly pigmented hairs. Absorbance and reflectance were not significantly altered over the range of wavelengths studied. Such solar heating effects could be of significance during the seals hauling out.

The eyes of the seals were found to be particularly sensitive to the light, highly volatile oil used in the study. Animals swam through oil layers with no apparent attempts to close their eyes or avoid the oil. Within 10 minutes of exposure animals began to lacrimate profusely, followed shortly by evidence of increasingly severe eye irritation. They had great difficulty keeping their eyes open and the conjunctiva became progressively more reddened and inflamed. Following transfer to clean water the eye problems began to diminish within 3 hours, and after 20 hours were undetectable. Given the severity of the initial effects it is probable that prolonged exposure to fresh oil would have resulted in more severe and possibly permanent eye damage.

Behavioral changes were noted in the seals during their encounter with the oil slick. Several animals extended their heads from the water and shook them violently, probably in response to the intense eye irritation. The breathing rate also increased, and on the surface the seals frequently exhaled audibly through their nostrils. During the latter stages of the exposure period many of the seals remained submerged for extended periods as if avoiding the slick and the noxious fumes above it. When they did surface they exhibited an uncharacteristic arching of the back. In seals exposed to oil in laboratory tanks, body quivering began almost immediately and swimming movements soon became uncoordinated. Considerable thrashing about occurred just prior to death.

Oil ingestion studies were conducted on both adults and pups. Adult ringed seals were given 5 ml of encapsulated crude oil per day for 5 consecutive days. Harp seal pups were given either 25 ml or 75 ml of crude oil by means of a stomach tube. No significant short-term changes in health or behavior were noted following such oil ingestion.

No consistent hematologic changes attributable to the oil were detected in either the immersion or ingestion studies. There was evidence of significant changes in concentration of certain plasma enzymes following oil exposure. The results suggest kidney damage with evidence of minor influences upon the liver. Analyses of tissues and body fluids for petroleum hydrocarbons revealed elevated levels in kidney tissues and in urine, indicating perhaps that the kidney damage occurs during attempts to excrete the oil or its metabolites.

These studies clearly demonstrate that crude oil can have a deleterious effect upon seals. The nature and magnitude of this effect may vary considerably depending upon the circumstances of the exposure and the physiological state of the animal. The pronounced effects on eyes and kidneys need to be examined in more detail. Additional studies are also required to determine the effects of chronic exposure to crude oil.

Effects upon lower trophic levels

Seals may be adversely affected by a major oil spill both directly, as described above, or indirectly by a reduction or elimination of food organisms. This trophic effect may be singularly important in arctic seas where food chains are often simple and therefore more susceptible to disruption (Grainger, 1975). Studies were therefore undertaken to examine some of the effects of crude oils upon selected marine invertebrates, phytoplankton, seaweed and the microbial flora.

Invertebrates

Effects of northern crude oils on selected invertebrate species common to the southern Beaufort Sea have been studied by Percy and Mullin, 1975. As expected different species differed markedly in their sensitivity to dispersed oil, and it was possible to distinguish sensitive and resistant species (Fig. 1). Isopods of the Mesidotea complex proved particularly resistant to crude oil. The large copepod Calanus hyperboreas tolerated high concentrations of oil, and even animals trapped in a surface layer survived for at least 96 hours. Amphipods, frequently abundant in both benthic and epontic habitats, generally appear to be sensitive to crude oils. However, even the so-called "sensitive" species required dispersed oil concentrations of 100 ppm or greater for significant mortality to occur during short-term exposure. It is unlikely that such high concentrations will occur in the sea except in very localized areas and in bottom sediments.

Rapid lethality is a poor criterion for evaluating consequences of oil pollution, although it serves as a useful first approximation in predicting pollution impact. A variety of sublethal dysfunctions may occur and either result directly in the death of the organism after prolonged exposure, or more insidiously impair its ability to tolerate normal environmental stresses.

The effects of oil exposure on behavior, locomotory activity and respiratory metabolism have been examined in a number of arctic invertebrates, particularly crustaceans. There is limited, but convincing evidence that low levels of petroleum in the marine environment interfere with the normal behavior of certain species. In view of the markedly heterogeneous distribution of spilled oil in the marine environment it is probable that for many species the behavioral response to the oil may be a factor influencing the degree of exposure of the population to the pollutant. The behavioral responses of several arctic marine crustaceans to crude oil masses, oil contaminated food and oil contaminated sediment have been examined in detail. None of the species examined were attracted by crude oil. Amphipods tended to avoid oil masses; but the avoidance response was significantly diminished if the oil was weathered or if the animals were pre-exposed to dispersed oil (Percy, 1976). In contrast, the isopod Mesidotea entomon appeared to be completely oblivious to the presence of oil.

Both Onisimus and Mesidotea are omnivorous scavengers and could become exposed to high levels of hydrocarbons by consuming fish or other organisms heavily contaminated and killed by oil. The results of food preference tests involving animals presented with oil tainted food alone and in combination with clean food are presented in Figs. 2 and 3. Amphipods clearly rejected the tainted food even when presented alone. In contrast, isopods readily consumed heavily tainted fish and when allowed a choice, showed no particular preference for untainted or tainted food.

Both Onisimus and Mesidotea crawl upon and burrow shallowly in bottom sediments. There is also evidence that Onisimus burrows in the sediment and swims in the water column in a regular cycle that may be associated with the tidal cycle. Oil contamination of the sediment interferes with the normal behavior of this species (Percy, 1977a). The responses of both species, when presented with a choice between clean and tainted sediments, were consistent with those observed earlier for oil masses and contaminated food. Onisimus consistently avoided oiled sediments, while Mesidotea was completely neutral in its response (Figs. 4 and 5). The maximal avoidance response occurred in the amphipod even at the lowest oil concentration tested (0.05 ml of oil/15 gm dry sediment).

Locomotory activity of both the amphipod Onisimus (Fig. 6) and the discomedusa Halitholus (Fig. 7) were significantly impaired by short exposures to dispersions of fresh crude oil (Percy and Mullin, 1977). The reduction in activity occurred at the lowest oil concentrations tested (0.05 ml/liter). The manner in which oil interferes with activity is uncertain. Physical fouling did not appear to be a major factor. Amphipods appeared to have difficulty maintaining the normal upright orientation required for effective swimming. Activity of Halitholus was impaired by a loss of coordination of the bell contraction and in some cases by a total inhibition of the contractile response. It is probable that certain components of the oils interfere with neuromuscular processes in aquatic animals.

The rate of respiratory metabolism is a relatively sensitive indicator of an organism's general physiological state and is frequently used as a measure of environmental stress upon an organism. Results on the effects of exposure to crude oil dispersions upon the respiration of Onisimus suggest that we are dealing with something more complex than the simple unidirectional stimulation or inhibition of metabolism suggested by some studies (Percy, 1977b). All four oils tested evoked a similar pattern of response (Fig. 8). Low concentrations depressed metabolism while at higher concentrations the trend was reversed and metabolism increased. This response may reflect a decrease in activity related metabolism at low oil concentrations and a stimulation of basal metabolism by certain hydrocarbons penetrating into the cell as the concentration in the medium increases.

The precise long-term ecological effects of such interference with behavior, locomotory activity and respiratory metabolism are difficult to ascertain. The problem is complicated by the fact that several interrelated physiological dysfunctions usually occur during exposure to the oil. Depending upon species and circumstance, one or more of these primary effects may assume overwhelming importance in determining the ultimate fate of the population.

Phytoplankton and seaweeds

Animal populations are ultimately dependent upon the primary producers phytoplankton and seaweeds. To fully evaluate the impact of petroleum upon an ecosystem it is necessary, therefore, to know something about the sensitivities of the predominant primary producers. Toxic effects of petroleum upon marine algae have been reported by several investigators, but few studies have dealt with arctic species.

Two complementary experimental approaches have been employed. Effects on primary production were determined *in situ* by means of carbon-14 uptake by natural populations of phytoplankton and seaweed at selected stations in the Beaufort Sea (Hsiao, Kittle and Foy, in press). Effects on growth were measured by direct cell counts in uni-algal cultures in the laboratory (Hsiao, submitted). In the latter study the effects of oil type, oil concentration, exposure time and temperature on growth were examined.

Effects of oil on *in situ* primary production of phytoplankton at a given station depended upon species composition. At a nominal oil concentration of 10 ppm both stimulation and inhibition of production occurred at different stations. At those stations where inhibition occurred the degree of inhibition increased with increasing oil concentration (Fig. 9). The photosynthetic activity of two macrophytes *Laminaria saccharina* and *Phyllophora truncata* was consistently inhibited by all four of the oils tested (Fig. 10).

Laboratory studies on the survival and growth of selected species confirmed the general conclusion reached in the *in situ* study that different species respond differently to petroleum. The green flagellate *Chlamydomonas pulsatilla* was not killed by any of the concentrations of oils tested, while lethal effects among diatoms varied with species, oil type, temperature and exposure time. The growth of diatoms was consistently inhibited by all of the oils at a nominal concentration of 10 ppm and the degree of inhibition increased with increasing oil concentration (Fig. 11). Growth of *Chlamydomonas* was stimulated at low oil concentrations at low temperature. Growth of both diatoms and green flagellates was markedly inhibited by oil concentrations higher than 100 ppm, with the diatoms being most severely affected. These results suggest that a large oil spill would probably result in a change in species composition of the phytoplankton community in the immediate vicinity, with a probable trend towards dominance by flagellates. Diatoms in the epontic community would be exposed to particularly high concentrations of oil and would probably be severely affected.

Microbial flora

There is some uncertainty about the rate of biodegradation of crude oil that might occur in the arctic marine environment. If the biodegradation rate is excessively slow then it is possible that petroleum hydrocarbons could progressively accumulate in certain parts of the ecosystem, and with time reach concentrations at which sublethal behavioral and physiological effects occur, with significant ecological repercussions.

Two basic interrelated questions are involved here. What effect would the spilled oil have on the marine microbial flora and, conversely, what effect would the microbial flora have on the crude oil? With regard to the first question, studies of CO_2 production from labelled glutamate in the presence of oil indicated that fresh and weathered oil did not significantly inhibit mineralization of the glutamate (Bunch, 1975). It appears probable that the activity of heterotrophic bacteria in cycling organic material would not be significantly affected in a major oil spill.

The question of the rate of breakdown of petroleum hydrocarbons at the low temperatures prevalent in the Arctic Ocean is complex. Most of the heterotrophs present in the water column after break-up of the ice are psychrophilic in character growing best at temperatures below 20°C. Oleoclastic bacteria, those capable of utilizing hydrocarbons as an energy source, range from 2.3×10^2 to 9.3×10^4 cells per liter representing 0.001% to 1.63% of the total heterotrophic flora. In enriched cultures these oleoclasts accomplished relatively complete degradation of saturated aliphatic fractions of oil in approximately 4 weeks at 5°C (Fig. 12). All of the oleoclast cultures obtained were capable of degrading petroleum at 5°C and most were capable of slow degradation at 0° or -1°C.

In unenriched cultures, a situation more closely approximating the natural state, a significant loss of the aliphatic fraction could not be detected until four weeks had elapsed (Fig. 13). At 5°C, 11 to 12 weeks were required for degradation of 85-90% of the aliphatic fraction. Nothing is known concerning the fate of the remaining heavier ashphaltene fraction of the oil. It is probable that it would eventually become incorporated into the sediments with unknown long-term consequences.

Both nitrogen and phosphorus are required as nutrients for biodegradation to proceed. Examination of known nitrate and phosphate concentrations in the Beaufort Sea (Grainger, 1975) suggests that nitrogen, but not phosphorus could become limiting at certain times of the year, although further work will be required to verify this.

Inshore bottom sediments possess a significant oleoclastic flora that is capable of a relatively complete breakdown of the aliphatic fractions. In marked contrast, sediments from offshore stations were relatively devoid of oleoclasts. It is suggested that a hydrocarbon substrate for the nearshore flora is provided in the Mackenzie River outflow.

Conclusion

The brevity of the Beaufort Sea Project dictated that studies dealt primarily with short-term biological effects of exposure to high concentrations of petroleum. Effects of chronic exposure to low levels of hydrocarbons have not been investigated. Results obtained thus far are fragmentary and permit few firm generalizations concerning long-term effects of oil spills in arctic waters. They do serve to indicate that the potential for significant ecological damage exists. However, the degree of expression of that potential in the real world is dependent upon a broad range of poorly understood variables that have been discussed in detail by Percy and Mullin (1975). In temperate waters much useful information has been obtained by monitoring accidental spills. Few arctic oil spills have been studied in sufficient detail and for a long enough period to realistically assess the environmental impact of such incidents. Logistic difficulties pose a major problem in attempts to carry out research programs on accidental oil spills in arctic waters. To ensure that the maximum amount of useful scientific information is derived from a blowout in the Beaufort Sea the Canadian government has formulated a detailed contingency research program to be launched in the event of a spill (Ward and Tull, 1977). This program draws upon the expertise of many of the participants of the Beaufort Sea Project for both its formulation and implementation.

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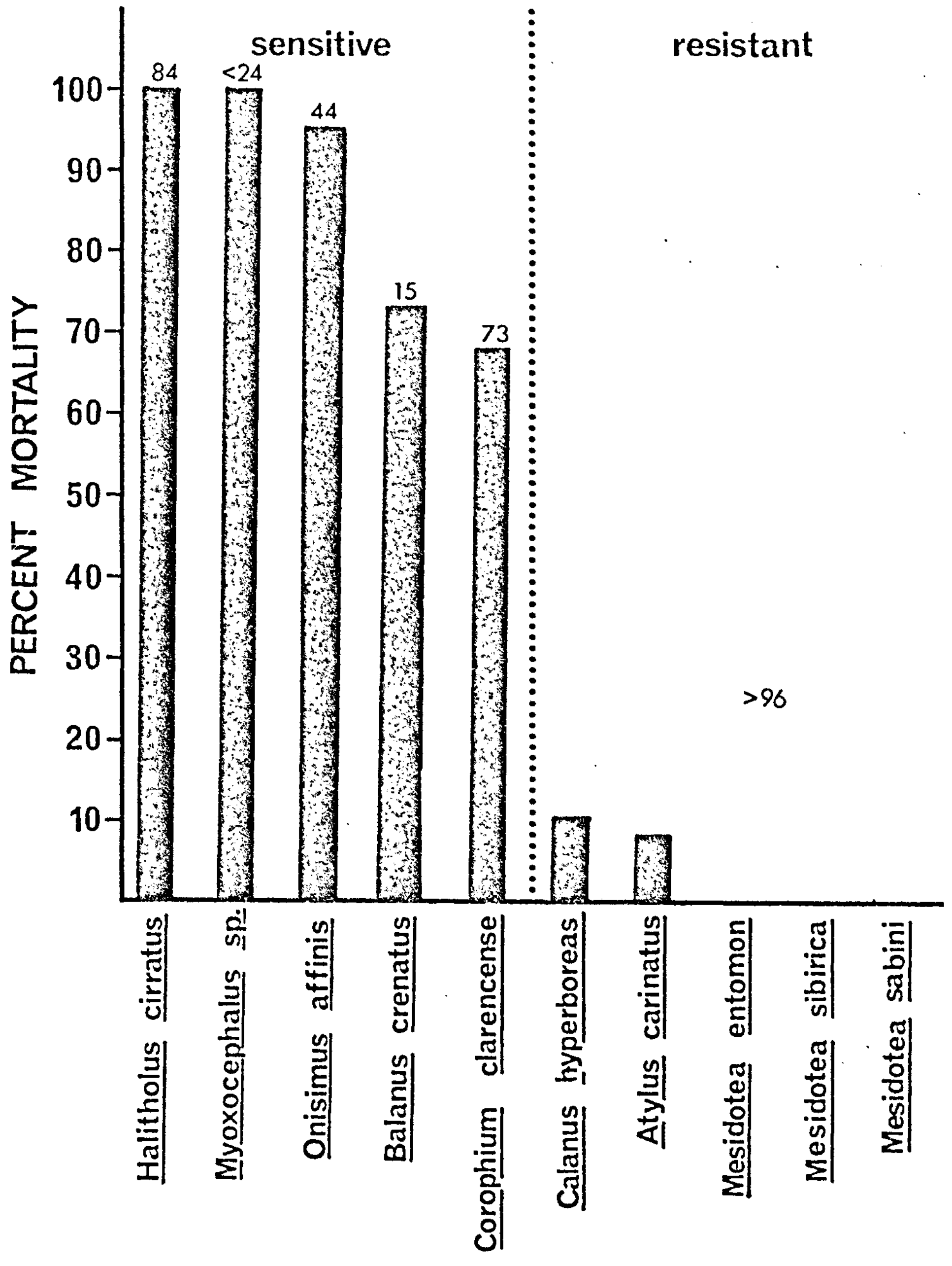

Figure 1. Relative toxicity of dispersions of Norman Wells crude oil (535 ppm as measured by fluorescence spectrometry) to various Arctic marine species. Percent mortality after 96 hours exposure to the oil under standard conditions. Figure above each bar represents estimated time in hours for 50% mortality.

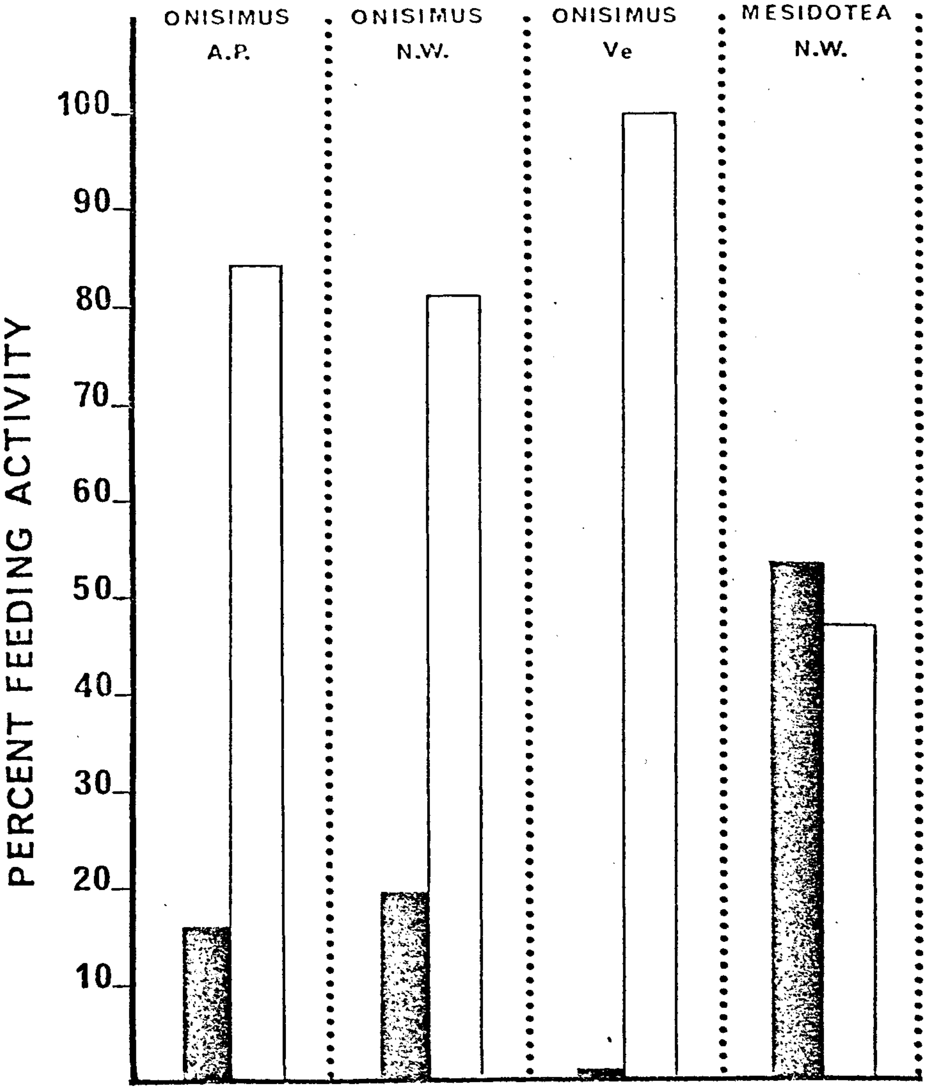

Figure 2. Food preferences of Onisimus affinis and Mesidotea entomon presented with oil contaminated food (black bars) and clean food (white bars) simultaneously. (A.P. = Atkinson Point crude, N.W. = Norman Wells crude, Ve = Venezuela crude.)

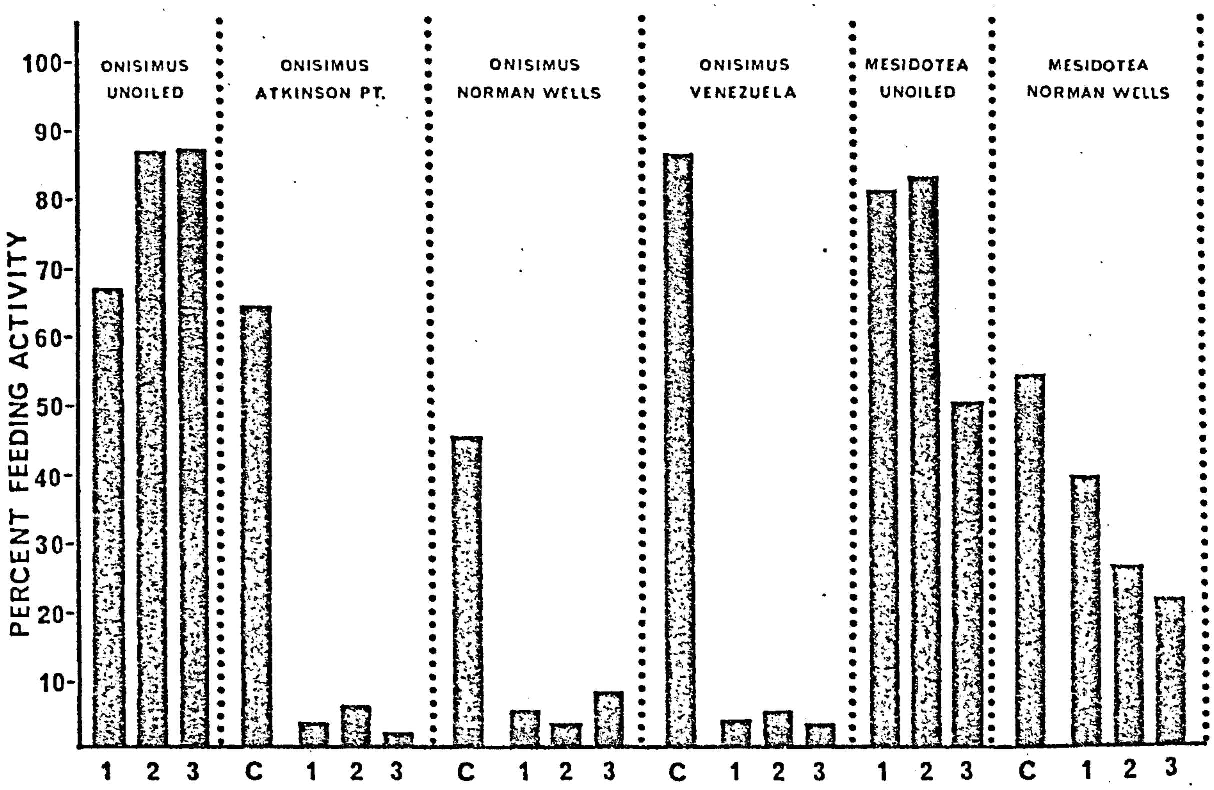

Figure 3. Relative feeding activity (proportion of animals feeding during 30 minute observation period) of Onisimus affinis and Mesidotea entomon presented with either clean food or with food contaminated with crude oil. Control group (c) and three replicates used for each oil type.

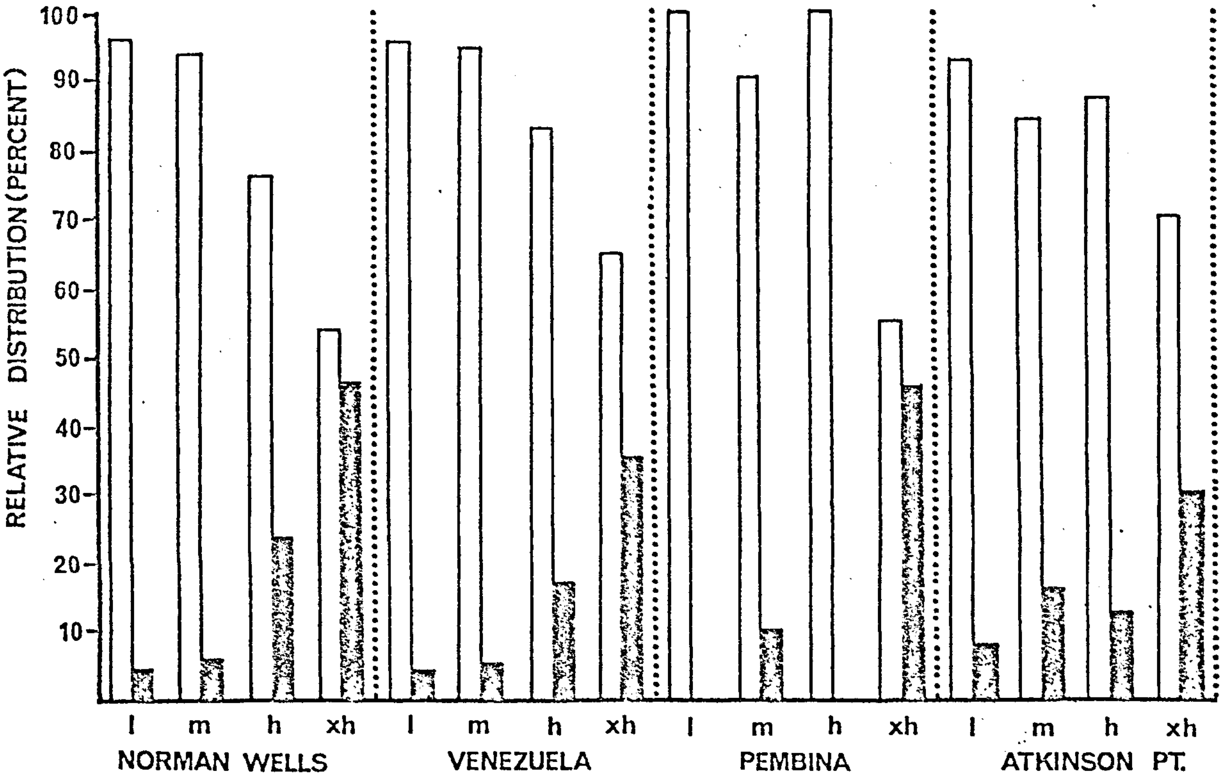

Figure 4. Relative distribution of Onisimus affinis presented with a choice between clean sediment (white bars) and various concentrations of three crude oils. Degree of contamination of sediment indicated as light (l), medium (m), heavy (h) and extra heavy (xh) corresponding to 0.05, 0.5, 1.0 and 2.0 ml of oil per 15 grams of dry sediment.

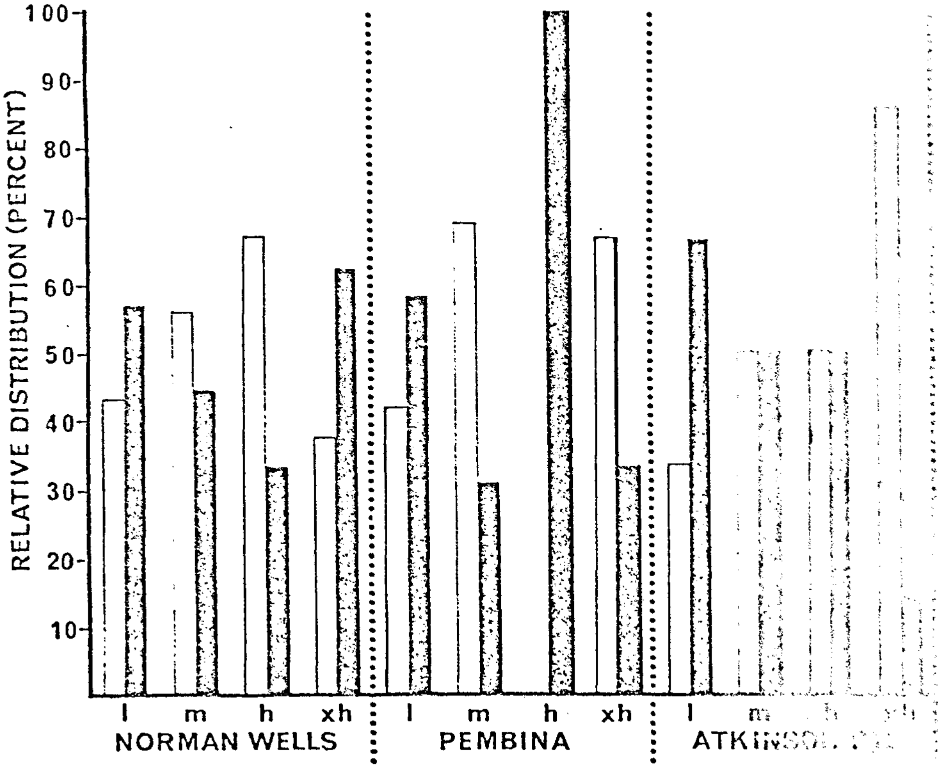

Figure 5. Relative distribution of <u>Mesidotea</u> <u>entomon</u> presented with choice between clean sediment (white bars) and sediment contaminated with various concentrations of crude oil (black bars). Degree of contamination of sediment expressed as in Figure 4.

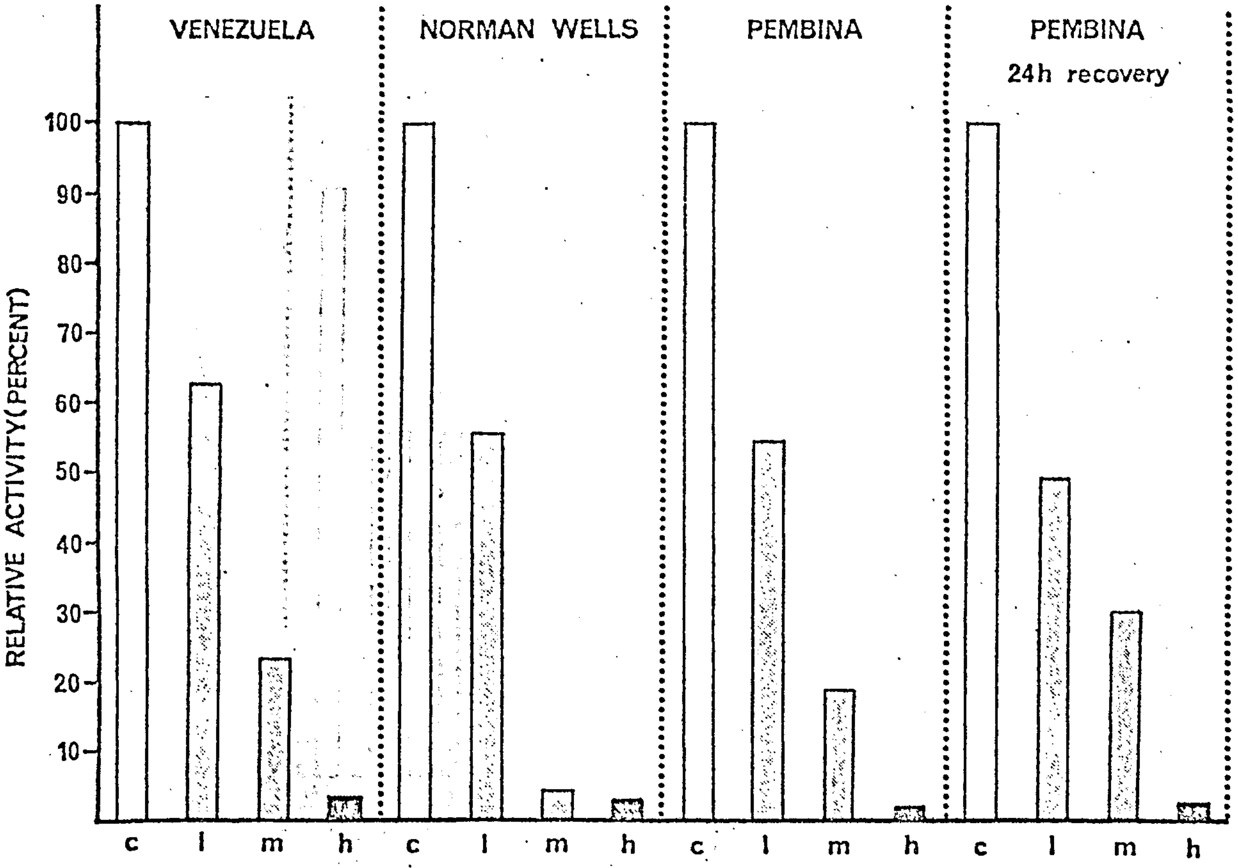

Figure 6. Effect of 24 hours exposure to light, medium and heavy dispersions of crude oils on the locomotory activity of <u>Onisimus affinis</u> (unoiled controls = c). Activity of animals exposed to Pembina crude measured again after 24 hours recovery in clean sea water.

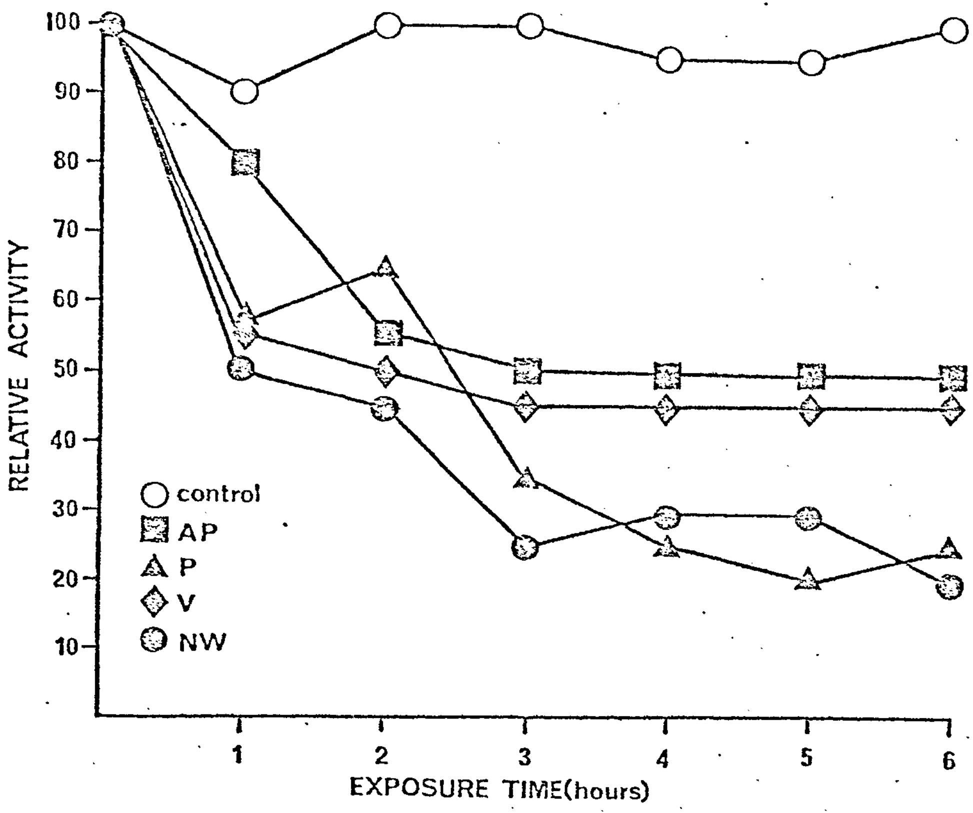

Figure 7. Effect of short-term exposure to dispersions (0.5 ml per liter of seawater) of four crude oils on the activity of the disco medusa Halitholus cirratus.

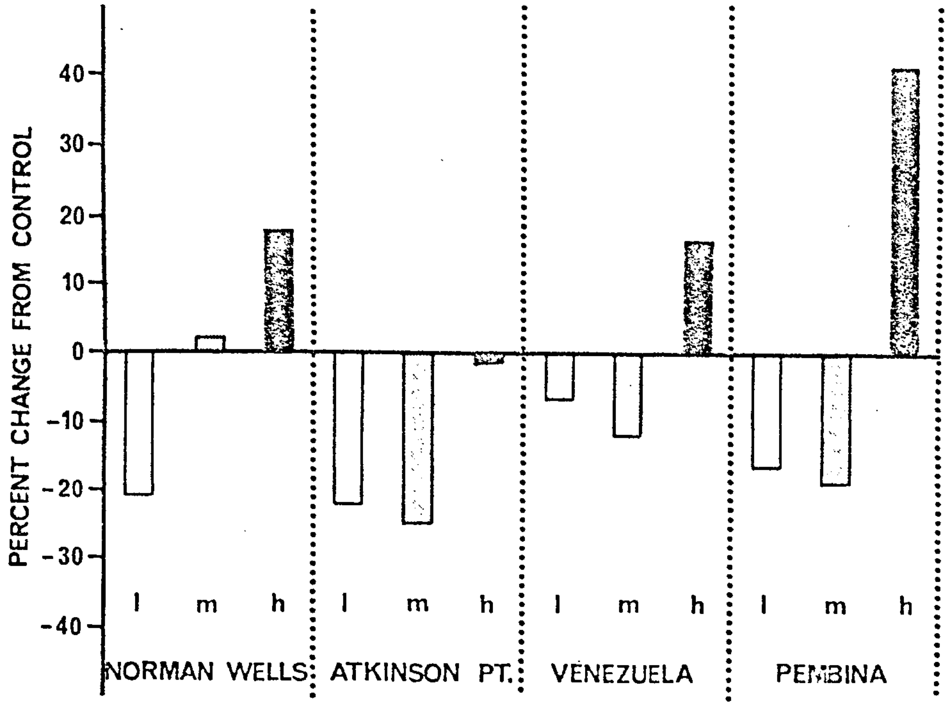

Figure 8. Effect of 24 hours exposure to light, medium and heavy dispersions of crude oils on the respiratory metabolism of the amphipod *Onisimus affinis*.

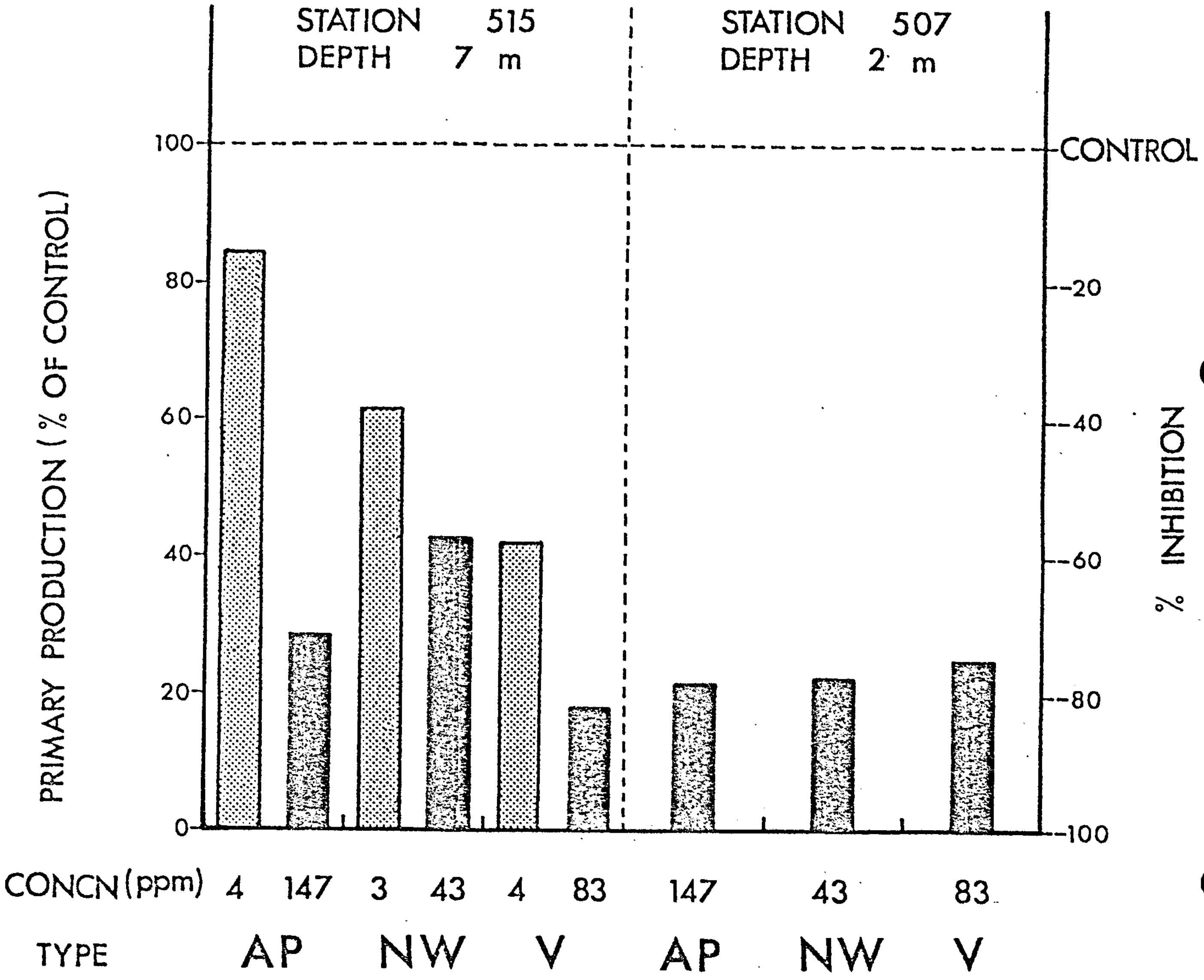

Figure 9. Effect of different concentrations of crude oil-seawater dispersions on primary production of phytoplankton at two different stations. (From Hsiao, Kittle and Foy, in press.)

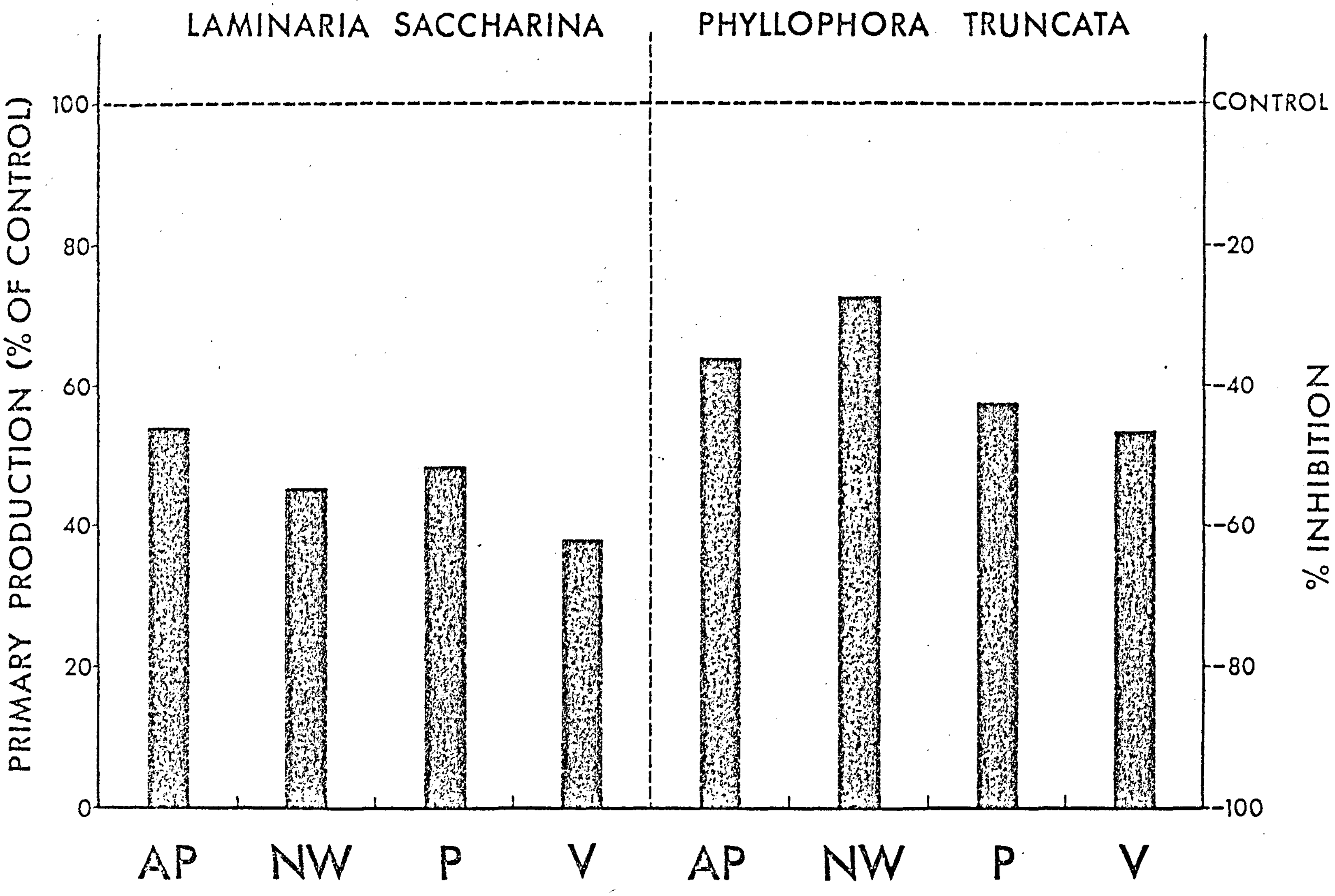

Figure 10. Effects of crude oils (4000 ppm) on primary production of *Laminaria saccharina* and *Phyllophora truncata*. (From Hsiao, Kittle and Foy, in press.)

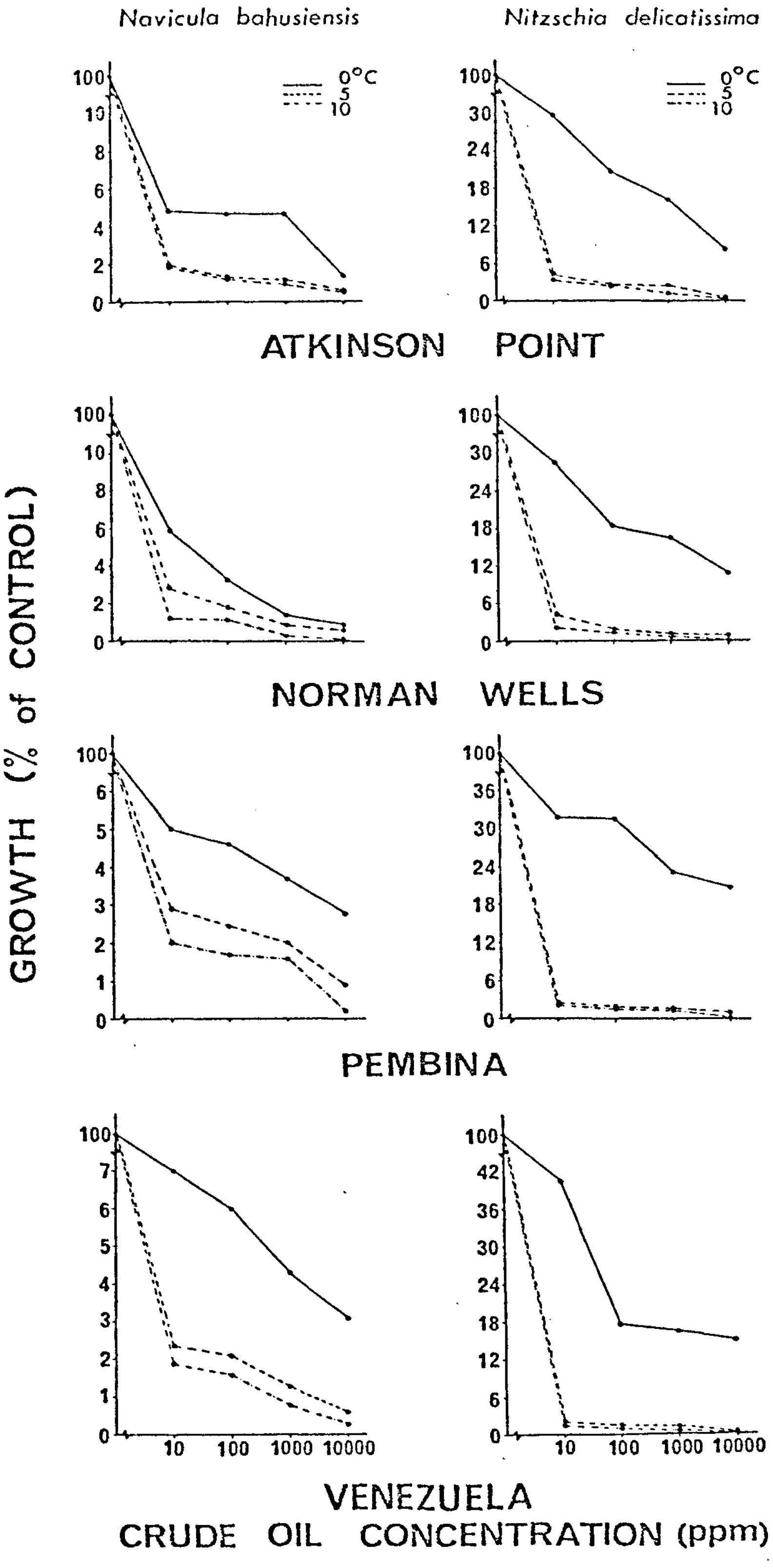

Figure 11. Effects of different types and concentrations of crude oils on the growth of Navicula bahusiensis and Nitzschia delicatissima at different temperatures (10 day exposure). (From Hsiao, submitted.)

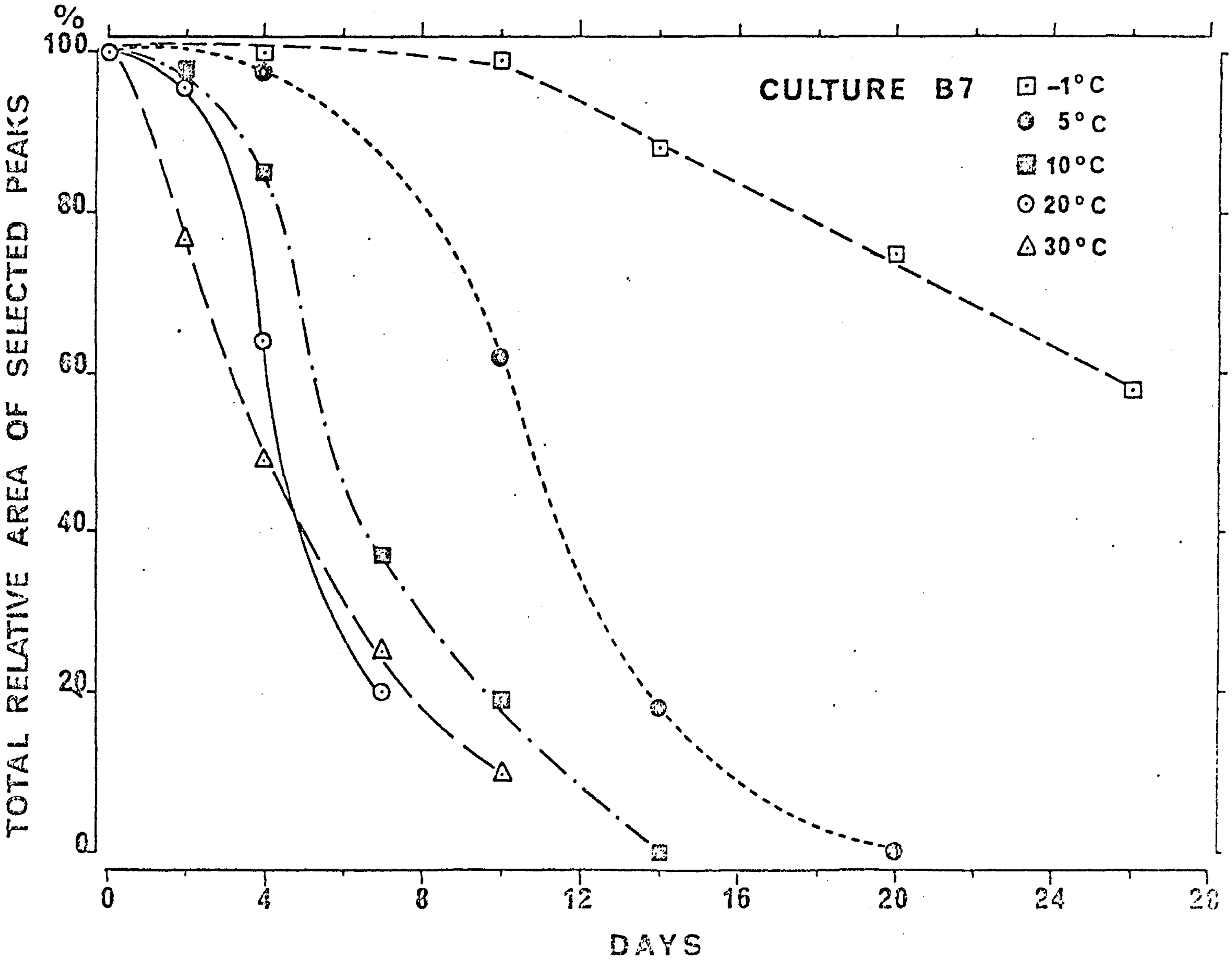

Figure 12. Degradation of weathered Norman Wells crude by culture B7 at defined temperatures. Cultures and oil controls were removed at intervals during incubation and residual petroleum was extracted from each. Summed areas of selected peaks of GC profiles were expressed as percentages of the summed areas of the same peaks in [illegible]degraded controls. (From Bunch and [illegible]arland, 197[illegible].)

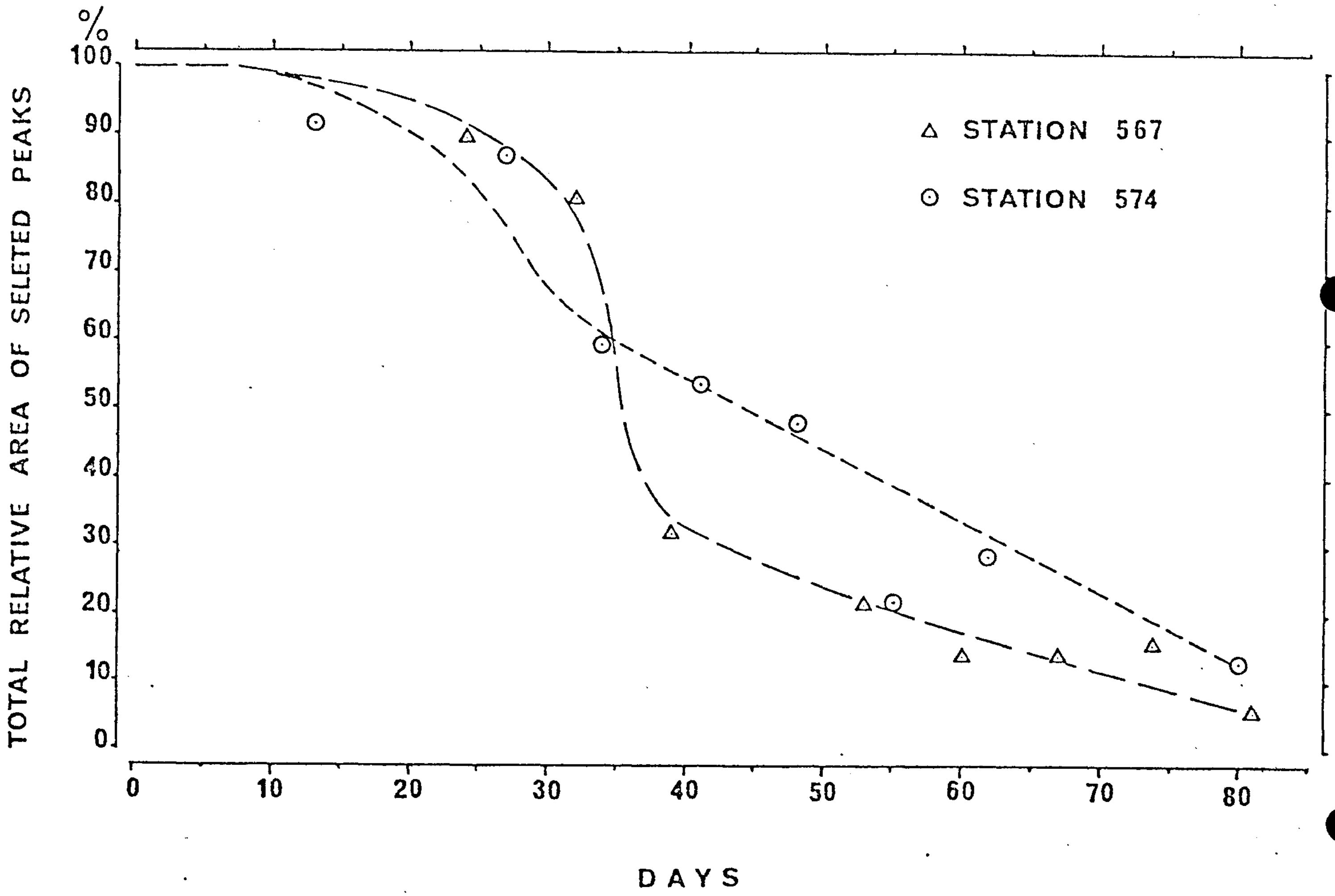

Figure 13. Degradation of weathered Norman Wells crude by the indigenous flora of one metre seawater samples. Replicate samples of 500 ml were supplemented with 500 mg of crude oil and incubated with agitation at 5°C. Summed areas of selected peaks of GC profiles expressed as percentages of the summed areas of the same peaks in undegraded controls. (From Bunch and Harland, 1975.)