EFFECTS OF ORE DUST POLLUTION ON THE PHYSICAL AND CHEMICAL FEATURES, AND ON THE MEIOFAUNA AND MICROFAUNA, OF A SANDY BEACH

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ABSTRACT

Effects of wind-blown iron and manganese ore dust on the upper part of a sandy beach have been investigated. The fine ore dust was found to reduce the porosity and permeability of the sand by clogging the interstices. The presence of ore dust also greatly increased the rate of heating and cooling of beach sand. Further, ore dust, although of negligible solubility, was found to inhibit the action of aerobic bacteria. This is thought to be due to iron and manganese forming oxidation-reduction combinations in the sand. Ore dust appeared, however, to have no effects on the meiofauna.

INTRODUCTION

The construction of iron and manganese ore-loading facilities at Saldanha Bay and the proposed construction of similar facilities on St. Croix Island, Algoa Bay, raise the question of what effects quantities of ore dust will have on adjacent environments. It would be of great value to be able to predict the effects beforehand in order to facilitate management advice. Preliminary research on ore dust pollution was possible in the vicinity of Port Elizabeth harbour, where ore-loading facilities have been in operation for a number of years. Ore dust pollution is in fact a well-known problem in parts of the city adjacent to the harbour and even a few miles inland. Westerly winds scatter dust, blown off the ore dumps, over the western part of King's Beach, the main bathing beach of the city. This pollution is visible as dark patches of sand on the upper beach (Figure 1) and appears to be very heavy in areas close to the ore dumps. These polluted areas of the upper beach were therefore selected as the sites for the present investigation. The aims of this work were to study the effects of wind-blown ore dust on the physical and chemical properties of the upper beach, as well as effects on the meiofauna and microfauna. It was hoped that this work would give an indication of the problems that could be expected and the lines of research that should be followed concerning the proposed ore berth on St. Croix island. Manganese poisoning in men working in contact with manganese dust and fumes is well known (Mathews 1956; Emera *et al.* 1971) but there is no literature on effects of this dust on marine life.

METHODS

Sampling

Three stations on the upper part of King's Beach, above the berm, were selected. These points were visually se'ected so as to represent relatively unpolluted, moderately polluted and heavily polluted conditions as indicated by the amounts of ore dust on the sand surface. In order to eliminate possible effects of different heights above sea level (which could affect water-table depths, saturation, etc.) the three points were tested with a 'dumpy' level, which insured that their heights differed by less than 4 cm. These stations were U (unpolluted), M (mixed) and P (polluted).

Temperatures were taken at 1 cm and 20 cm depths in the sand with a thermistor calibrated with a mercury thermometer accurate to 0,1° C. The depth of the water table was measured at each station in holes excavated by spade. The salinities of the interstitial water draining into these holes were read on a refractometer accurate to 1°/₀₀. Samples of this interstitial water were also taken back to the laboratory for measurement of pH and iron and manganese concentrations. At each station an area of 2,5 m^2 was marked out on the sand surface and divided into 25 blocks of 0,25 m^2. Using a table of random numbers 10 blocks were selected at each station for sampling meiofauna. From each block a core of area 5,7 cm^2 and length 24 cm was taken by means of a hand-operated brass and copper corer and sectioned into four 6 cm segments. Five 6 cm core sections of the same depth range were pooled and sealed in glass jars. Thus two jars for each 6 cm depth range and four depths resulted in eight jars per site. A further set of five cores was similary taken and used for analysis of the substrate and determination of the amounts of organic matter in the sand.

This sampling was originally done on 3 August 1975 during spring tide. It was repeated during neap tides when, although the sites were above EHWS, the water table was found to have dropped. The same procedure was followed except that on the latter occasion (22 October 1975) interstitial water samples were taken for determination of the amounts of available oxygen. Interstitial water samples were taken at 20 cm and 40 cm depth by syringe, using 30 cm stainless steel needles with sealed ends but a number of 70 μm pores.

Meiofauna

In the laboratory the meiofauna was extracted from the sand samples using a modified Oostenbrink extractor (Furstenberg personal communication). Meiofauna was retained on 75μm and 45 μm screens, stained overnight by addition of a little 0,1 per cent rose bengal, preserved in 10 per cent formalin and later counted under the microscope. A number of nematodes were mounted on slides and examined to determine whether they were of fresh water or marine origin. No macrofauna was present at any of the sites.

Laboratory analyses

Sand samples were subjected to the following analyses. Subsamples were wet-sieved and analysed following the method of Morgans (1956) using screens corresponding to the Wentworth scale. For porosity measurements (*i.e.* total pore space) 30 g subsamples were used. These were placed in a measuring cylinder, covered with sea water and tapped for 90 seconds to allow compaction. The cylinder was then drained for 20 seconds and most of the sand scraped out and weighed. This was then oven-dried at 105°C for 24 hours and weighed again. The difference in weight, expressed as a percentage of the original wet weight, gives the porosity. Permeabilities of sand samples were measured as described in Hulings & Gray (1971). Permeability is the rate of movement (in minutes) of a 50 cm column of water through 10 cm of sand in a tube of 1,5 cm diameter. For this, subsamples were taken from the substrate samples and 10 cm samples were taken *in situ* with permeability tubes (*i.e.* the tubes were thrust 10 cm into the sand to obtain a natural core). Organic matter was estimated by drying 30 g of sand at 105°C for 24 hours, weighing, ashing at 550°C for four hours and weighing again.

Oxygen was measured in the laboratory using a Radiometer Acid-Base Analyser and expressed as percentage saturation, taking into account temperature and salinity values.

Two 100 ml samples of the water draining into holes at stations U, M and P were collected for Fe and Mn analysis. From each station one sample was boiled in acid to dissolve all the ore dust in suspension and the other was left untreated. These samples were then analysed using an atomic absorption spectrophotometer. It was thus expected that the acidified samples would indicate the total amounts of Fe and Mn in solution and in suspension in the interstitial water while the untreated samples would indicate just the amounts in solution.

Bacterial Respiration

As oxygen values in the sand at sites M and P gave results higher than expected on the basis of permeabilities, it was surmised that the presence of iron and manganese in some way inhibited the respiration of aerobic bacteria and thus stopped depletion of interstitial oxygen. To test this hypothesis the following experiment was carried out. Sand was collected from the 20–30 cm layer at Site U. Into each of four 125 ml sterilized bottles 100 g of sand was weighed. Two of the bottles were then topped up with clean, aerated sea water of salinity 30‰ and sealed. The other two bottles were topped up with aerated seawater of 30‰ that had been shaken up with ore dust ($\pm$ 10 g/ℓ). Thus two bottles contained sand with clean sea water and two contained sand with polluted sea water. These bottles were gently shaken every 30 minutes to mix the sediment and water, and the oxygen content of the water was read after 2,5; 5,0; 7,5 and 9,0 hours on the Radiometer Acid Base Analyser. It was expected that if ore dust did inhibit bacterial action the rate of oxygen depletion would be slower in the two bottles with polluted water. Pilot experiments had shown that the bacteria were attached to the sand grains and not free in the interstitial water, and for this reason sand was used. Knowing the approximate numbers of meiofauna in this sand, their contribution to oxygen consumption could be estimated.

Temperature Effects

A final pair of experiments was done to assess the effects of dark ore dust layers on the rate of heating and cooling of beach sand. Clean beach sand was collected from Station U and ore dust from the harbour. The ore dust was passed through a 2 mm and a 1 mm screen to obtain fairly fine dust simulating wind-blown ore dust. A box was made of 2 cm thick polystirene with internal dimensions: 30 cm long $\times$ 13 cm wide $\times$ 10 cm high. In the first experiment this box was filled to a depth of about 8 cm with clean dry sand and one half was then covered with a 0,5 cm layer of ore dust. Mercury thermometers were positioned in the box at depths of 0,5 cm; 2 cm and 4 cm in the centre of each half. The box was placed in the sun at 08h15 on 22 October and temperatures read half-hourly from 08h30 to 16h30. At 14h05 the box was placed in shadow in order to accelerate the rate of cooling.

A second experiment was done similarly except that half of the box contained a mixture of 95 per cent sand and 5 per cent ore dust by volume. (The amount of ore dust in the surface 2 cm at Stations M and P was expected to be in excess of 5 per cent.) Thermometers were placed at 0,5 cm and 4,0 cm. This ran from 09h00 to 16h30, the box being placed in shadow at 14h35.

RESULTS AND DISCUSSION

Sampling Stations

Figure 1 shows Stations U, M and P and the dark areas of ore dust pollution on Kings Beach. Ore dust pollution is heaviest in the centre-right near the ore dumps and lighter below and to the left in Figure 1. Westerly winds scatter the dust over the beach while easterly winds tend to blow layers of sand over the ore dust. In Figure 2 typical cores of sand from Stations U, M and P are shown and the dark layers of ore dust are clearly visible in the M and P cores. Ore dust layers are thickest at the tops of these cores.

Laboratory Analyses

The results of all the physical and chemical analyses are shown in Table 1 (*a*) and (*b*). These reveal some marked differences between the three stations. Station U has the finest substrate with a mean median particle diameter of 189 μm as opposed to 227 μm for site M and 218 μm for site P. All three stations have similar quartile deviation (QD) and skewness (Sk) values. Relatively low quartile deviation values indicate that at all three stations a large proportion of the particles fall in a narrow size range around the median and this is largely responsible for the zero skewness values which indicate equal sorting of particles larger and smaller than the median. The percentage subsieve material is a good indication of the relative amounts of ore dust at the three stations, although the absolute amounts are greater than this due to ore particles being present in the coarser fractions as well. Stations U, M and P had 0,0 per cent, 0,6 per cent and 0,9 per cent mean subsieves respectively, which confirms that they were relatively unpolluted, moderately polluted and more heavily polluted respectively as initially judged visually. At site P there were 1,6 per cent subsieves in the 0–6 cm layer and it may thus be estimated that ore dust constitutes somewhere between 5 and 15 per cent of the top 2–3 cm of substrate which is the most heavily polluted (Figure 2).

Effects of the presence of this ore dust, which is mainly fine and subsieve material, are clearly indicated by the porosity and permeability values. Generally, finer sands have higher porosities (or total pore volumes) than coarser sands (Webb 1958) and it would therefore be expected that porosities would be in the order U $>$ P $>$ M. In actual fact, however, M has a greater porosity than P, indicating that the pore volume in P has been reduced more than that in M by the presence of fine particles of ore dust. This effect of blocking of the interstices

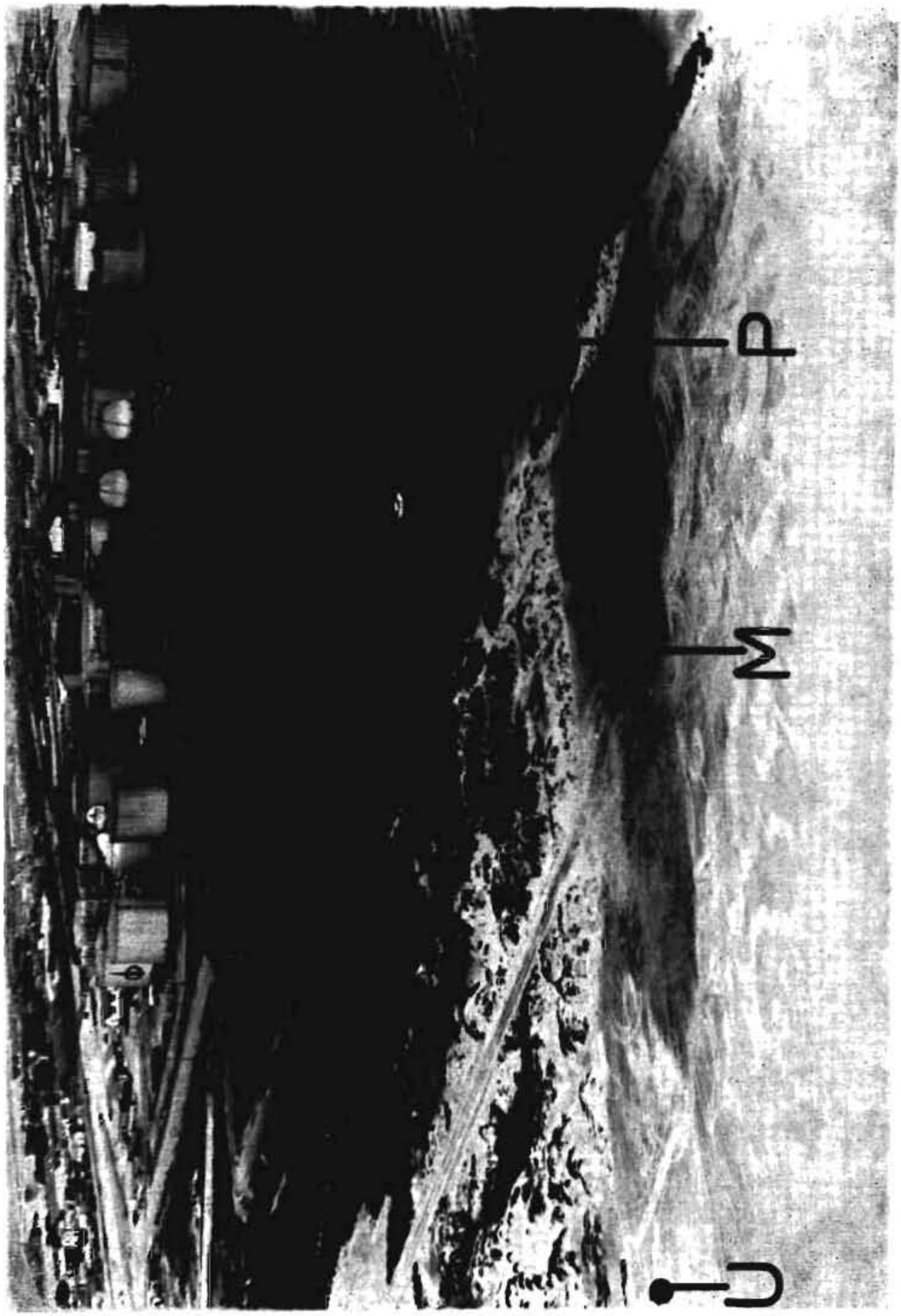

FIGURE 1

Close up aerial photograph of the part of King's Beach sampled. The positions of sites U, M and P are marked. Note the open ore dumps in the background and behind them large oil tanks.

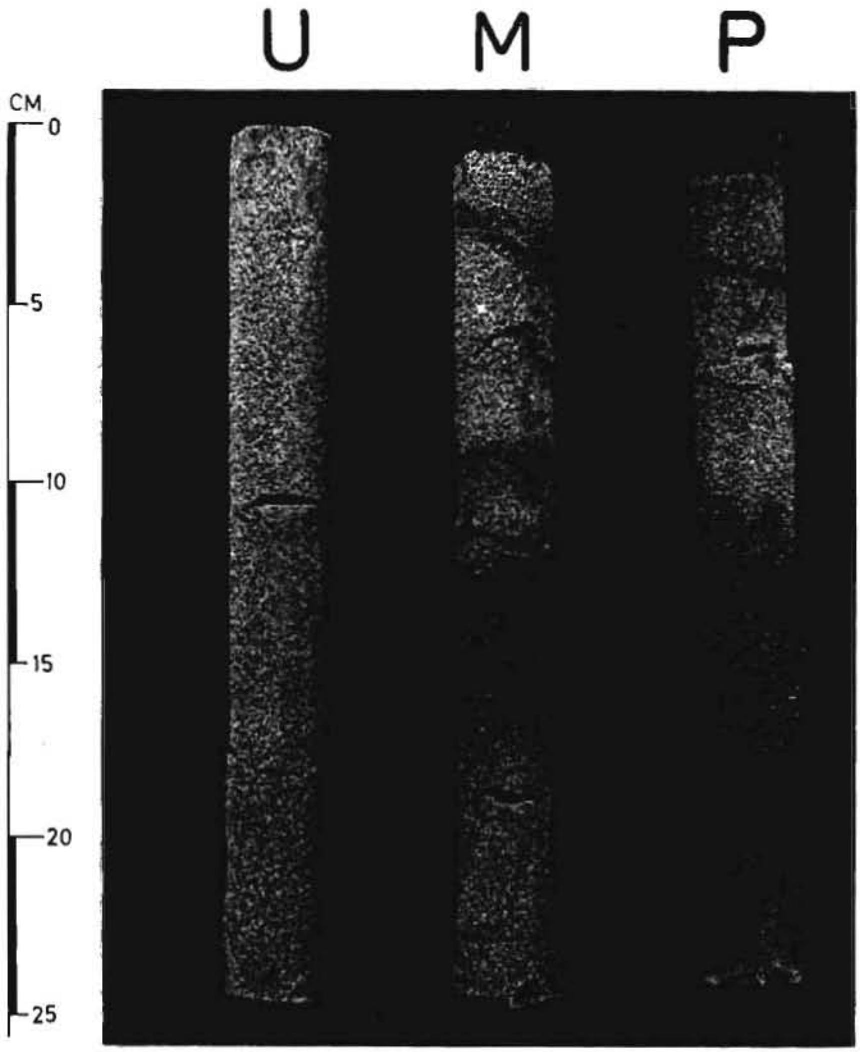

FIGURE 2

Sand cores taken at sites U, M and P to show the dark bands caused by layers of ore dust. Note the thickest bands in the top few centimetres of M and P.

is also reflected in permeability values, which for natural cores of sand from Stations U, M and P were 17; 28 and 46 minutes respectively, which clearly support the porosity values.

Differences in permeabilities result from different ways of packing the sand into the permeability tubes. Maximum permeabilities (*i.e.* lowest rates of drainage) resulted from packing the sand into the permeability tubes from below, closing the bottom of the tubes with gauze and then pouring sea water in the top of the tubes. Minimum permeabilities (*i.e.* maximum rates) resulted from placing the closed tubes in a beaker of sea water and dropping in sand from above so that it sedimented down through the water column to pack the bottom of the tubes. This latter method resulted in a stratification of the particles, with the coarsest sinking fastest to the bottom and the finer particles (*e.g.* ore dust) forming 'sedimentary' layers on top. The effect of this was to reduce drastically the permeability as can be seen by comparing the maximum and minimum rates for Station P, which had the most ore dust. (At each station maximum and minimum porosities were estimated for sand samples from each depth range, but only the full ranges have been given.) This tendency for ore dust to reduce permeability when sedimented out was clearly noticeable within stations where depth ranges with large amounts of ore dust, *e.g.* P: 0–6 cm, had much longer permeability times (maximum = 45 minutes, minimum = 1 800 minutes) than those with little ore dust, *e.g.* P: 6–12 cm (maximum = 25 minutes, minimum = 265 minutes). The fact that the natural permeabilities were much closer to the maximum than to the minimum values indicates that although ore dust might form distinct bands in the sand (Figure 2), these bands must contain a reasonable admixture of coarser sand and cannot be as compact as those formed by sedimentation through a water column. It may therefore be expected that effects on subtidal sands, where ore dust could sediment out to form fine impermeable layers, could be much greater. Even the degree of reduction of permeability on King's Beach has noticeable effects. It tends to trap water in the polluted areas after spring high tides. This water drains away within a day or two near Station U but can remain for many days near Station P. This is further borne out by the depths of the water table. At both times of sampling, water tables were shallower at P than at M and shallower at M than at U.

Organic matter in the sand was found to be considerably more abundant at the two polluted stations than at U and was most plentiful below the surface layers. The source of this organic matter is uncertain but will be discussed at a later stage. The salinity and pH of interstitial water and the sand temperature (morning) show no marked differences, other than a wider salinity range at M and P than at U. Temperature effects of ore dust will be discussed later. Oxygen saturation and iron and manganese concentrations of the interstitial water did show some interesting differences.

At all three stations there was less than 0,1 mg/ℓ iron and less than 0,05 mg/ℓ manganese in solution and only at Stations M and P were the total amounts (after acidification) measurable. Station P had more than three times as much iron and manganese in the interstitial water as Station M. As less than 0,15 mg/ℓ of this was in solution, and total amounts ran into several mg (Table 1), it may be concluded that virtually all (*i.e.* more than 99 per cent) of the iron and manganese is in suspension in the interstitial water and that the solubilities are minimal.

From permeabilities in Table 1 (*a*) it would be expected that Station U would have more available oxygen in the interstitial water than M, and that P would have the least. In actual fact the opposite trend was found at 20 cm and 40 cm depths. Oxygen saturation of the interstitial water dropped from 12–13 per cent at Station P to 2–3 per cent at Station U. Further it was observed that U was the only station where reduced grey layers were clearly visible in the sand below 30 cm. Thus, although more oxygen must enter the sand at U, less reaches the deeper layers than at M or P. The most likely explanation is that bacterial action was responsible for the oxygen depletion at Station U but not at M or P. It was surmised that manganese and iron might inhibit the action of aerobic bacteria and thus prevent them from depleting the interstitial oxygen at Stations M and P. The bacterial respiration experiment was designed to verify this.

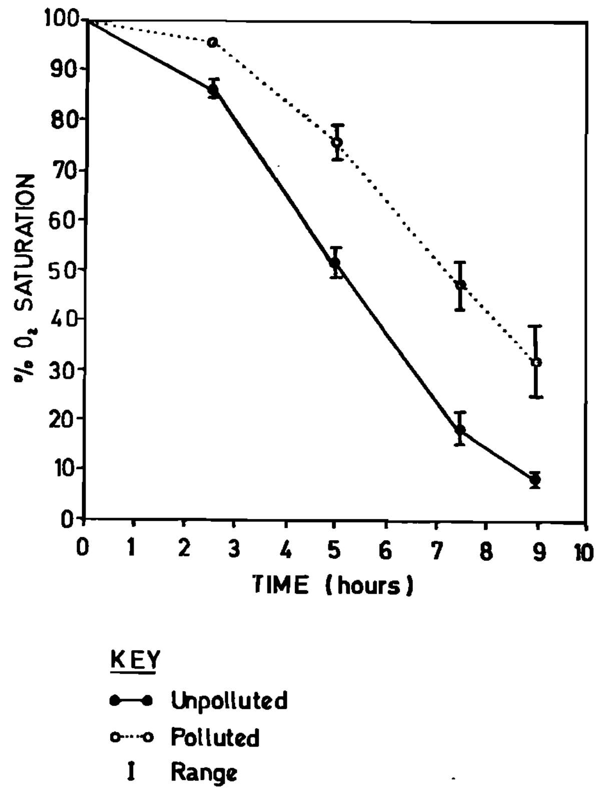

FIGURE 3

Oxygen consumption of clean sand and sand polluted with ore dust. Laboratory temperature was 22–23° C.

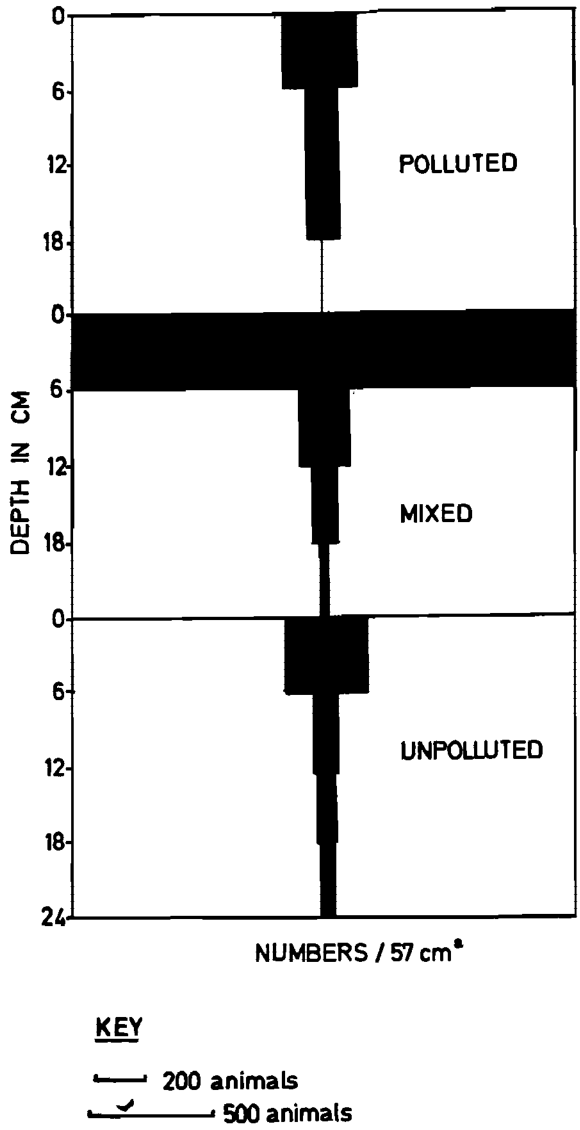

FIGURE 4

Numbers and vertical distribution of the meiofauna at sites P (above), M (centre) and U (below) on 3 August 1975.

TABLE 1 (a)

Substrate properties and amounts of organic matter present at Stations U, M and P. Porosities and organic matter are given on a weight by weight basis. Under permeability, 'natural', maximum and minimum values are given in minutes.

Site	Depth (cm)	Md μ	Md φ	Substrate Qd φ	Sk φ	% subs.	Porosity % w/w	Organic matter % w/w	Permeability (mins.)
	0– 6	170	2,57	0,22	0,00	0,0	22,1	1,5	—
	6–12	211	2,25	0,31	0,00	0,0	21,6	1,0	—
U	12–18	175	2,52	0,18	0,00	0,0	20,0	0,7	—
	18–24	200	2,33	0,17	0,00	0,0	20,5	1,5	—
	MEAN	189	2,42	0,22	0,00	0,0	21,1	1,2	17 (14–17)
	0– 6	240	2,06	0,36	0,00	1,6	21,2	1,5	—
	6–12	219	2,20	0,23	0,00	0,2	20,1	1,6	—
M	12–18	248	2,02	0,15	0,00	0,4	19,9	6,5	—
	18–24	200	2,33	0,19	0,00	0,3	19,8	10,2	—
	MEAN	227	2,15	0,23	0,00	0,6	20,3	5,0	28 (22–420)
	0– 6	216	2,23	0,25	0,00	1,6	19,6	3,3	—
	6–12	216	2,23	0,22	0,00	0,2	20,6	11,2	—
P	12–18	216	2,23	0,22	0,00	0,9	19,9	5,1	—
	18–24	224	2,17	0,20	0,00	0,8	19,4	2,5	—
	MEAN	218	2,22	0,22	0,00	0,9	19,9	5,5	46 (25–1 800)

TABLE 1 (b)

Water table depths, sand temperatures and chemical properties of the interstitial water at Stations U, M and P. A: 3/8/75, B: 22/10/75.

Site	Depth (cm)	Water table Depth (cm) A	B	Sand temp. °C A	B	pH A	Salinity ‰ A	B	% O_2 B	Fe mg/ℓ A	Mn mg/ℓ A
	1	—	—	23,9	24,9	—	—	—	—	—	—
	20	—	—	16,2	16,0	8,6	15	15	3	<0,1	<0,05
U	40	—	—	—	—	—	—	—	2	—	—
	MEAN	19	48	—	—	—	—	—	2,5	—	—
	1	—	—	22,0	25,0	—	—	—	—	—	—
	20	—	—	16,1	16,5	8,8	10	12	8	4,2	4,9
M	40	—	—	—	—	—	—	—	4	—	—
	MEAN	12	43	—	—	—	—	—	6	—	—
	1	—	—	21,1	26,0	—	—	—	—	—	—
	20	—	—	15,8	16,8	8,8	9	18	13	20,8	13,5
P	40	—	—	—	—	—	—	—	12	—	—
	MEAN	10	40	—	—	—	—	—	12,5	—	—

Bacterial Respiration

The results of the oxygen consumption experiment (Figure 3) supported the idea that bacterial respiration was inhibited by the presence of ore dust. It can be seen that oxygen was much more rapidly depleted in the unpolluted samples than in the polluted ones. As oxygen saturation approached zero, however, it tended to level off in the unpolluted sample while the oxygen content of the polluted sample was still dropping rapidly. The contribution of meiofauna to the oxygen consumption in this experiment was calculated to be less than 1 per cent (calculations estimated 0–5 animals per sample of $\pm$ 5 μg wet weight each on average. At an oxygen consumption of 0,5–0,6 μg/mg/h (Wieser *et al.* 1974) this would have totalled 0–0,0015 ml O_2 over nine hours).

Sykes (1965: 424) has stated that although iron and manganese are not known to be toxic to bacteria, in combination they may have some effect. Apparently if iron and manganese are in proportions to form oxidation-reduction combinations they can be toxic. This is probably due to changing of the redox potential (Eh) in the sand.

Meiofauna

The distribution of the meiofauna is shown in Figures 4 and 5. These show the presence of relatively large numbers of animals in the surface layers at all three stations. On 3 August Station M had the highest numbers and on 22 October Station P had the highest numbers. Numbers always decreased more rapidly with depth at P and M than at U. Subsections of the top 6 cm revealed that the meiofauna was concentrated in the top 1 cm in P and M and was fairly uniformly distributed in the top 6 cm at U except for a slight peak in numbers at 3–4 cm. The greater numbers of meiofauna at M and P than at U appear to be related to greater amounts of organic matter (Table 1 (*a*)) and this may be the limiting factor at Station U.

In all cases more than 90 per cent of the meiofauna consisted of marine nematodes. Harpacticoid copepods (mostly burrowing forms as opposed to interstitial sliders) were the second most numerous group. It is well known that harpacticoids are most sensitive to low oxygen tensions (Pennak 1940; Jansson 1968) and their relative abundance again indicated a greater diffusion of oxygen at site U. Harpacticoids were more common at U (40 recorded) than at M (30) or P (19). If any group can therefore serve as an indication of this type of pollution, harpacticoids would seem the most suitable. On the whole, however, it may be concluded that the presence of ore dust has no direct toxic effects on meiofauna. This is probably due to the very low solubility of both iron and manganese.

Temperature Effects

The temperature experiments yielded conclusive results (Figures 6 and 7). Figure 6 shows the effects of a 0,5 cm layer of ore dust on sand temperatures. It can be seen that after five hours (13h00) the temperature just beneath the ore dust layer was 49,7°C, *i.e.* 5°C higher than in the unpolluted sample. The deeper layers under the ore dust were also noticeably warmer than in the unpolluted sample. The rate of cooling after falling under shadow was also faster in the polluted sample than in clean beach sand.

In the second experiment (Figure 7) the polluted sample with 5 per cent admixture of ore dust also heated up faster than the clean sample with the difference during the highest tem-

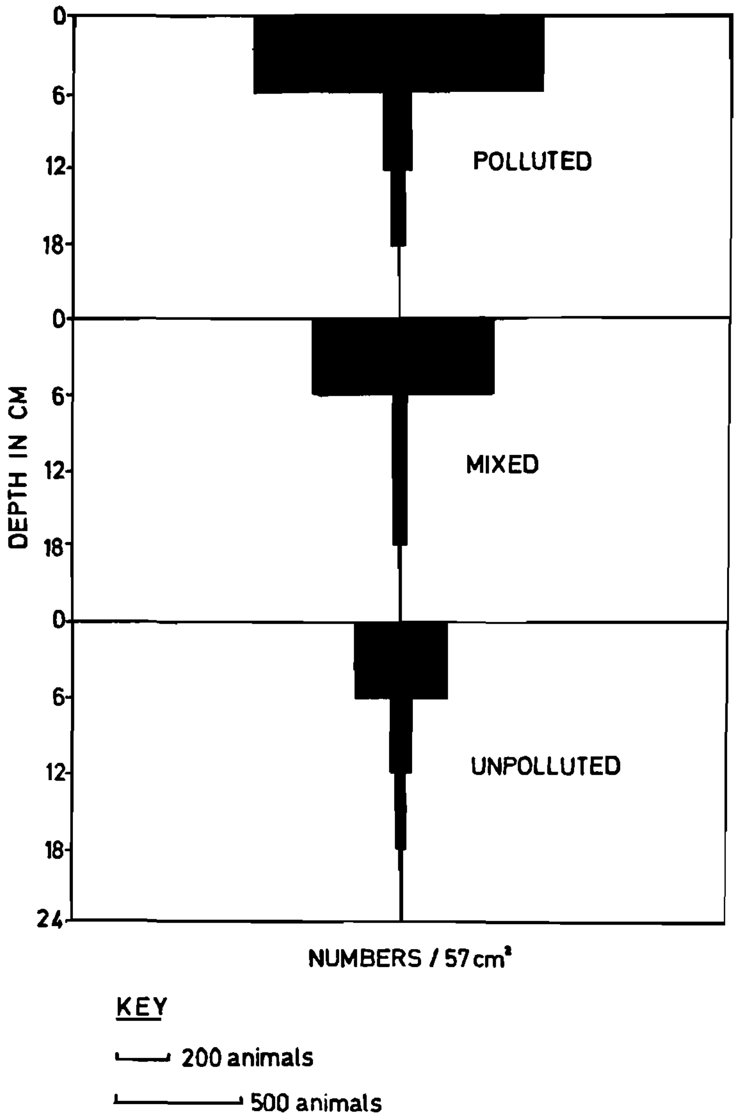

FIGURE 5

Numbers and vertical distribution of the meiofauna at sites P (above), M (centre) and U (below) on 22 October 1975.

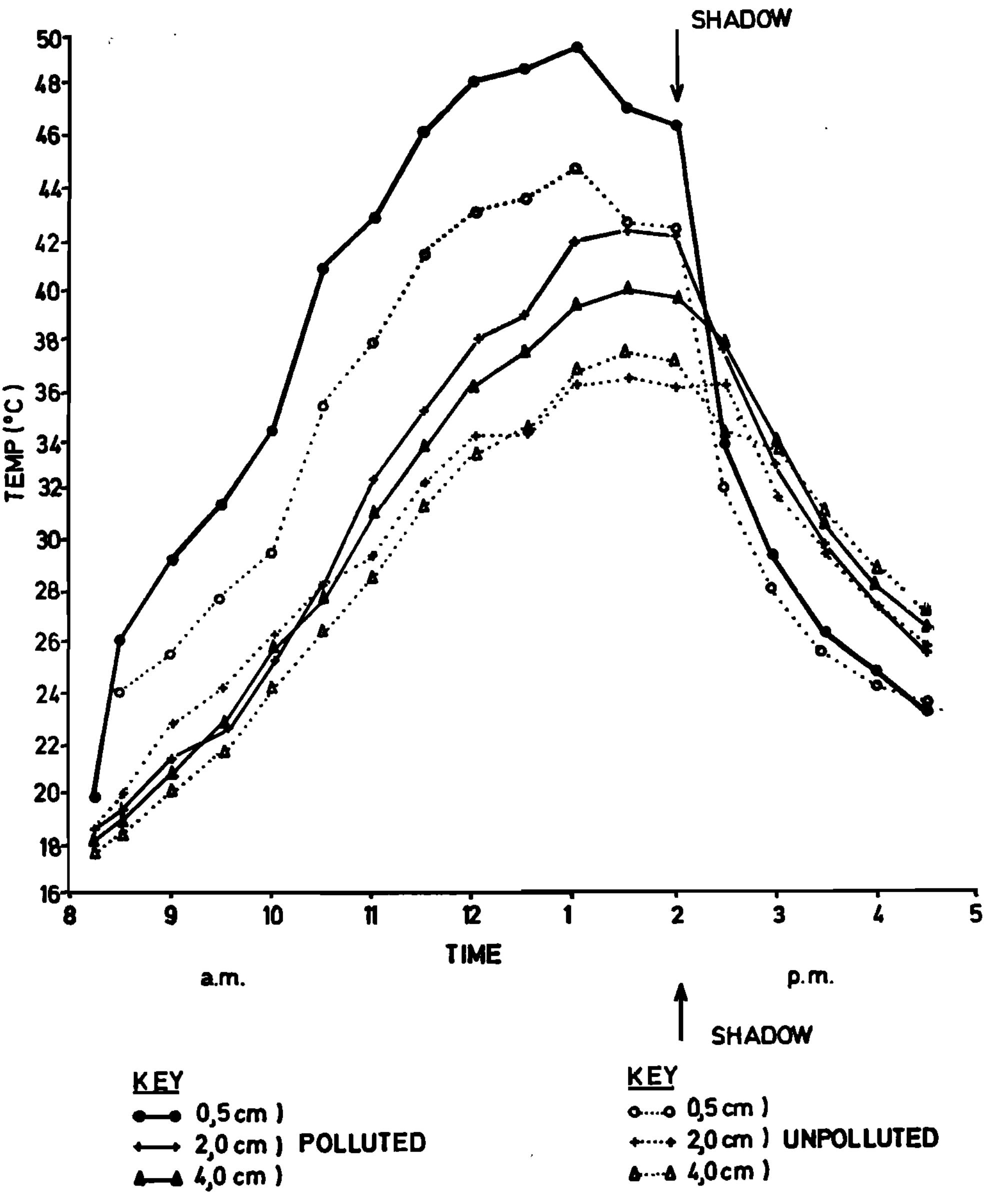

FIGURE 6

Temperatures in sand at various depths below a 0,5 cm layer of ore dust, and without the layer of ore dust, over eight hours. 'Shadow' marks the time when the sand was shaded from the sun in order to allow more rapid cooling.

peratures again being approximately 5°C (46,4°C *vs.* 41,7°C). Cooling also appeared to be more rapid in the polluted sample.

These two experiments thus indicate that ore dust, even in relatively small amounts, drastically affects sand temperatures. This is probably due to both the dark colour and high conductance of ore particles. As these experiments were done during October, and highest temperatures occur in January (McLachlan 1975), it may be estimated that surface temperatures of dry polluted sands could rise to 60°C and more on hot windless days in summer. This could well prove lethal if the fauna does not migrate to deeper layers of the sand.

This raises the question of thermal effects of ore dust on intertidal rocky shore animals that can not burrow to escape the heat. If an ore berth were to be constructed on St. Croix island, intertidal animals would probably be covered by wind-scattered ore dust. Barnacles, limpets and other animals exposed to the sun might then be placed under considerable thermal stress. (This is a facet of ore dust pollution that needs investigation and Mr A. de Villiers of the University of Port Elizabeth is studying this *in situ* on St. Croix.) Upper lethal temperatures of intertidal animals generally lie in the range 40–50°C when heated rapidly (McLachlan & Erasmus 1974; Newell 1970) and shells coated in ore dust might easily exceed these values.

CONCLUSION

From this work it has become evident that wind-blown ore dust has significant effects on the physical and chemical properties of a sandy beach. Physical effects are basically (1) an increased rate of heating and cooling and (2) a reduction of pore space and permeability of the sand. Arising from (2) is a reduction in desiccation and in the amounts of available oxygen in the sand. Ore dust also appears to inhibit aerobic bacterial respiration in the sand, presumably by forming oxidation-reduction combinations and thus changing the redox potential. There are, however, no noticeable effects on the meiofauna except for a decrease in harpacticoid numbers in polluted areas probably due to low diffusion rates of oxygen. The very low solubilities of iron and manganese are assumed to be the reason why these metals have no direct toxic effects on the meiofauna. It may thus be predicted what the major effects of ore dust would be in the vicinity of St. Croix island. The two most harmful effects would be (1) the temperature stress that intertidal animals would suffer when covered in ore dust during low tide in hot (or cold?) weather and (2) the deoxygenation of the seabed that would result from ore dust sedimenting down to blanket the bottom. This latter effect would be much more severe offshore than on the beach and might result in virtual absence of meiofauna and macrofauna.

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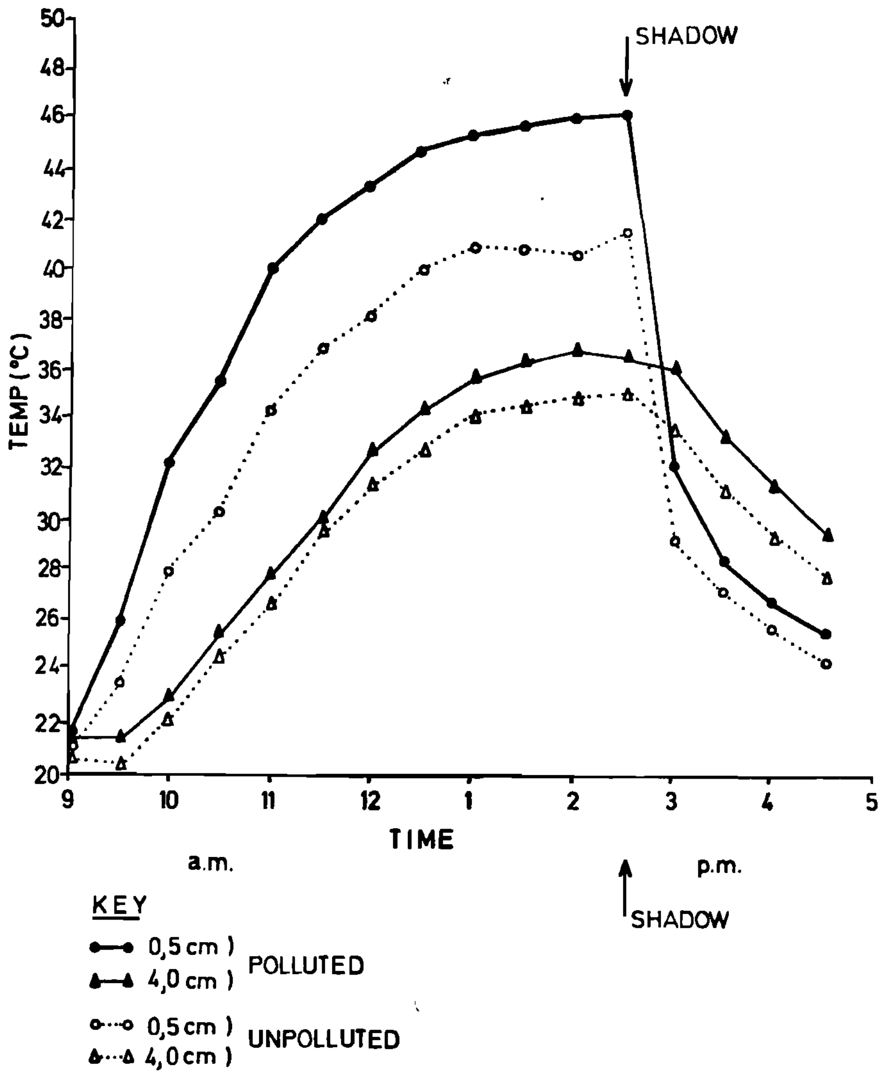

FIGURE 7

Temperatures at various depths in sand mixed with 5% ore dust, and in clean sand. 'Shadow' marks the time when the sand was shaded from the sun in order to allow more rapid cooling.

I thank the students who surveyed the beach for me.

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