TRACE ELEMENT DISTRIBUTION IN DIFFERENT CHEMICAL FRACTIONS OF FALSE BAY SEDIMENTS

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This thesis is dedicated to my beloved parents

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ABSTRACT

Trace metals in the aquatic environment are generally concentrated on solid geochemical phases, which eventually become incorporated into estuarine and marine sediments. The mechanism of trace metal concentration is believed to be adsorption on various geochemical phases, such as hydrous metal oxides, clays and organic matter. Metals in estuarine sediments can thus be expected to be partitioned between different phases, depending on the concentration of the phase and the strength of the adsorption bond.

The bioavailability of sediment-bound metals to deposit-feeding organisms will depend on trace metal partitioning and the kinetics of biological metal uptake from each geochemical phase.

The major objective of this study was to establish an analytical procedure involving sequential chemical extractions for the partitioning of particulate trace metals in sediment samples, collected from False Bay. Eight metals were examined, i.e. Cd, Cu, Cr, Fe, Mn, Ni, Pb and Zn.

Three chemical fractions of the sediments were separated and the concentrations of the trace metals were determined in each. Atomic absorption techniques were used. The three different leaches used were hydroxylamine hydrochloride - acetic acid, hydrogen peroxide, and nitric - perchloric acids. The chemical fractions extracted in these leaches represent the carbonate and easily reducible, organic and sulphide, and residual fractions, respectively, in the sediments.

Experimental results showed that trace metal concentrations have distinct distribution trends. Fe and Pb were concentrated mainly in the residual phase, while Cu, Zn and Ni were found mainly in the organic fraction. Most of the metals in the organic and sulphide phase were found in the central area of the bay, where the concentration of organic material was high. The metal concentrations (except for Pb) correlated well with the organic content of the sediments.

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1. INTRODUCTION

Sediments are usually regarded as the ultimate "sink" for heavy metals discharged into the environment (Gibbs 1973), yet relatively little is known about the way in which heavy metals are bound to sediments, or the ease with which they may be released (Jenne and Luoma, 1977). Part of the difficulty lies in the complex nature of sediments, whether freshwater or marine. Sediments are normally mixtures of several components, including different mineral species and organic debris. In addition, there are many ways in which the heavy metals may be bound e.g. by adsorption, on exchange of sites of clay minerals, coprecipitated with iron oxides, or held inside biological materials such as seagrass fragments, shells, and animal faeces (Dossis and Warren, 1980). Metals in sediments can be expected to be partitioned between different phases, depending on the concentration of the phases and the strength of the respective adsorption bond. This partitioning is greatly influenced by the physical and chemical characteristics of the sediments (Luoma and Bryan, 1981).

Many studies on the composition of marine sediments have been carried out on the bulk sediment, without any attempt to separate the various sedimentary components. The distribution of trace metals in the various fractions of a sediment is of interest to sediment and water chemists for a number of reasons. A quantitative knowledge of the selective distribution of trace metals in sediments can be of value in assessing the potential impact of sediment resuspension upon water quality. The selective distribution of trace metals may also be helpful in evaluating the relative availability of these trace metals to influence biological communities and enter into reactions and transformations. As sediments

Trace metals associated with degradable organic material and with surface coating of mineral particles would be more available than those incorporated in primary minerals or occluded by secondary mineral structures.

Since the bioavailability and recycling of trace metals depend on the geochemical phase with which a metal is associated in sediments (Jenne and Luoma, 1977), the quantitative distribution of metals among the various phases under natural conditions has spurred considerable interest in recent years (Engler et al., 1977). To determine such distribution, several researchers have proposed extraction schemes to determine metal partitioning between the geochemical phases.

A sequence beginning with hydroxylamine-hydrochloride in acetic acid (Chester and Hughes, 1967) followed by an oxidising step with hydrogen-peroxide (Presley et al., 1972) has been used for the study of reduced fjord sediments in British Columbia (Presley et al., 1972), sediment from the Dead Sea in Israel (Nissenbaum 1974), and for sediments from Southern California (Bruland et al., 1974). This resulted in a differentiation of trace metals into reducible, oxidizable and resistant fractions. Studies on sediments from Los-Angeles harbour (Gupta and Chen, 1975) and on contaminated sediments from Lake Erie, and Mobile Bay (Brannon et al., 1977) were performed by applying further sequential extraction techniques. These included the determination of the metal contents in interstitial water and in exchangeable, easily reducible, moderately reducible, organic and residual fractions.

are the dominant sink for transition metals in the marine system, it is desirable to know the pathways by which the metals arrive, and the physico-chemical states in which the metals exist in solid sedimentary phases.

The determination of the chemical phases in which each metal can exist is a very difficult problem. It is complicated by the numerous phases found in marine sediments. These phases include weakly and strongly adsorbed metal ions, metal carbonates, sulphates, sulphides, oxides, hydroxides, phosphates and organometallic compounds (Van Valin and Morse, 1982).

Many transition metals are present as minor or trace components in these phases. The problem is further complicated by the fact that many phases are not crystalline, but are amorphous e.g. oxyhydroxides and sulphides (Berner, 1967; Murray, 1975) or adsorbed (Donnell and Merrill, 1977).

Morel et al. (1975) investigated the trace metal chemistry of oxidized sediments, such as those at the sediment-water interface. They indicated that sulphides dominate the processes controlling the metal form in reducing sediments. However, in oxidized sediments, organic materials, carbonates and hydrous oxides of both Fe and Mn, may all compete for the binding of trace metals. Clays and other silicate mineral surfaces also have some capacity for binding metals.

Malo (1977) pointed out that interest in the source, transport, deposition, biological utilization, and release of trace-metals in the aquatic environment has necessitated the investigation of analytical methods for determining the more readily available forms of metals in sediments.

Förstner and Salomons (1980) have suggested that there is now sufficient information and experience with various extraction techniques using a variety of sediments, to make it possible to propose a "standard extraction method". This should be relatively simple in order to make it possible for routine analysis of large numbers of sediments. At the same time, it should provide sufficient information for tentative assessment of the environmental impact of particulate metals.

Based on an evaluation of the literature and experience in this study the following procedure is suggested :

1. An extraction with acidified hydroxylamine hydrochloride (Gupta and Chen, 1975; Filipek and Owen, 1978). The hydroxylamine step includes the extraction of exchangeable cations and of carbonate-bound metals.

2. An extraction with hydrogen peroxide. This extraction should be followed by an extraction with ammonium acetate to remove any re-absorbed metal ions, as was suggested by Engler et al. (1977).

3. Treatment of the residue remaining after the first two extractions, with a 4:1 mixture of nitric-perchloric acids.

Extraction procedures with sodium hydroxide commonly used for the disintegration of humic and fulvic acids should not be applied in this leaching sequence due to the initial high pH conditions. These could promote the formation of basic metal hydroxides (Förstner and Salomons, 1980). The differentiation of organic and sulphide metal associations is not, as yet, possible.

1.1 Objective of the present study

Very little work has been done so far in understanding the sediment chemistry of False Bay. In 1982 the National Research Institute for Oceanology was asked to determine the present pollution status of False Bay. This preliminary research showed that there are total heavy metal accumulations in the sediments from some areas (NRIO, 1983). However, these seem to be below toxic levels. The main objective of this study was to determine the distribution of heavy metals among the various geochemical fractions of surficial sediments. Analyses were performed on the total sediment, as well as on three extracted fractions :
(a) easily reducible; (b) organic and sulphide; (c) residual fraction.

The organic content of sediments, and the variability of metal contents of organic phases were also determined. Thereafter an assessment of the correlations between organic matter and trace elements was carried out.

2. BACKGROUND

2.1 Study area

False Bay lies at the south-western tip of the African continent. It is the largest bay along the South African Coast, with an area of approximately 1 000 km^2. It is bounded by mountains along the eastern and the western margins and the Cape Flats region extends northwards from the bay. The bay deepens from north to south and is 90 m deep between Cape Point and Cape Hangklip. The average gradient is 1:370 (NRIO, 1982).

The contour map of the sea floor beneath False Bay shows various morphological features, namely, Seal Island, York Shoal, East Shoal, Hangklip Ridge and Rocky Bank (Fig. 1).

2.2 Bedrock geology

The bedrock geology of False Bay consists of three different litho-stratigraphic units :

1. Malmesbury shales.
2. Cape granite.
3. Table mountain sandstone.

The oldest rocks in the area belong to the Malmesbury group, and underlie the eastern part of the Cape Flats. The Cape Peninsula granite underlies the western part of the Cape Flats and most of the western part of False Bay (Glass, 1976). Small sandstone inlayers occur between Muizenberg and Fish Hoek, between Glencairn and Simonstown and between Smitswinkel Bay and Cape Point. Other areas consisting of sandstone are Rocky Bank and

the southeastern part of the bay, including Hangklip Ridge (NRIO, 1982).

2.3 Distribution of sediments

The sediment distribution in False Bay is characterized as follows :

1. Very coarse sand, consisting mainly of shell fragments, extends along the western and eastern margins of the bay.
2. A wide region of fine sediments lies towards the centre of the bay.
3. Very fine sediments lie to the north and south of Seal Island and also in the region of Gordon's Bay.
4. Mud size accumulations occur in the deepest part of the bay between Rocky Bank and Hangklip Ridge. (Fig. 2).

The coarse fraction comprises material of grain size greater than 0,063 mm. Such coarse sands occur along the steep and rocky shorelines between Cape Point and Fish Hoek and between Cape Hangklip and Kogel Bay. A large patch of coarse sands extends between Macassar and the Steenbras River mouth and there are small patches in the vicinities of most other rocks around the bay, especially Seal Island and York Shoal (NRIO, 1982). Deposits of very coarse sands are restricted mainly to the western and eastern margins of the bay, in the vicinity of larger rock outcrops where high energy conditions prevail and where sediment supply is extremely low. These sediments are also characterized by a very high calcium carbonate content and, in fact, consist very largely of coarse, robust shell debris (Bowie et al., 1970).

Deposits of fine sand (0,125 to 0,25 mm) and very fine sand (0,063 to 0,125 mm) occur in close association with each other. A belt of fine sediment stretches from Hangklip Ridge in the south to Muizenberg in the north. Other patches of fine sediment occur nearshore between Gordon's Bay and Macassar, and in the offshore region between Smitswinkel Bay and Buffels Bay. High concentrations of very fine sand lie in relatively shallow water to the southeast of Muizenberg.

The mud fractions occur in the deepest part of the bay, between Rocky Bank and Hangklip.

The rest of False Bay is taken up by medium sand (0,25 to 0,5 mm). There are large concentrations of medium sand in several localities, particularly off Fish Hoek, off Strandfontein, off the Strand and off Kogel Bay. Another major patch is situated in the central part of the bay to the east of Miller's Point (NRIO, 1982).

2.4 Temperature

The seasonal variations in temperature in False Bay have been described by Atkins (1970). In spring, warming takes place in the north-eastern shallows, while cold water remains in the centre of the bay. During summer the warming process occurs in the northern shallows and the current direction is well demarcated by the isotherms extending eastwards. Grindley and Taylor (1970) found that a tongue of cooler water enters the bay from the south-east and wind-induced upwelling may also occur in the Gordon's Bay area. In autumn, rapid cooling takes place in the centre of the bay and the water that enters from the ocean is warmer than

the bay water. In winter the bay is cold, and temperatures are fairly stable (Fig. 3).

2.5 Salinity

The seasonal variations in salinity in the bay were described by Atkins (1970). During spring and autumn salinities are high, usually above $35{,}0 \times 10^{-3}$. Salinities tend to be lowest in the central area of upwelling or in areas of wind-induced upwelling.

In winter, salinities are even higher, but dilution by run-off lowers the average salinity in the north-east zone to below $34{,}8 \times 10^{-3}$ (Fig. 4).

2.6 Rivers entering False Bay

A number of small rivers and streams flow into the bay (Fig. 5). The Sandvlei and Zeekoevlei systems enter in the north-west corner of the bay and the Eerste and Lourens Rivers in the north-eastern corner. The Sandvlei River drains the Westlake River, Keyser River, Langevlei Canal and Sand River.

The largest river entering False Bay is the Eerste River with a mean annual flow of 70×10^6 m^3 (Grindley 1982). The river catchment covers the eastern part of the Cape Flats lying to the west of the Hottentots Holland Mountains and south of the Tygerberg, where the Kuils River tributary rises east of Kanonkop. Other tributaries of the Eerste River are the Blouklip, Bonte, Jonkershoek, Klippies, Krom, Plankenbrug, Sanddrif and Veldwagter.

During the summer and autumn the quality of the water usually deteriorates significantly because of organic pollution combined with low flow regime. Deterioration is particularly severe in the Plankenbrug River (Heinecken, 1982).

The Zeekoevlei Canal opens east of Muizenberg and drains much of the south-western part of the Cape Flats (Grindley, 1980). The Steenbras (50 x 10^6 m^3 per annum) and Rooiels Rivers and some minor streams empty into the eastern side of False Bay (Grindley, 1982).

However a major part of the water entering the northern area of the bay is effluent from the Cape Flats Sewage Works. The flow from this works is seasonal, varying from about 90 x 10^3 m^3/week in March, to about 560 x 10^3 m^3/week in September, with a total flow of about 26 x 10^6 m^3 per annum (I.M. Morrison, Scientific Services Branch, Cape Town City Council, pers. comm.).

Other rivers entering False Bay are the Lourens River (21 x 10^6 m^3 per annum) and Silvermine River (4,5 x 10^6 m^3 per annum) (Grindley, 1982). The Lourens River rises in Watervalkloof in the Hottentots Holland mountains. It has a catchment area of 92 km^2. The river has no major tributaries, but flow is supplemented by streams rising in Landdroskloof and Sneeukopkloof.

The mouth of the Silvermine River is in the north-eastern corner of Fish Hoek Bay. The river has its source in the Steenberg Mountains on the western side of the Cape Peninsula.

2.7 Waste Disposal in the Bay

During this century it has become normal practice to discharge treated sewage effluents, which meet specified regulations, into bodies of water which ultimately enter False Bay. A variety of other effluents also enter False Bay from land sources. The majority of the wastes are discharged along the northern shore and include effluents from the Cape Flats Sewage Works, Mitchells Plain Sweage Works, Macassar Sewage Works, the AECI industrial complex, Gant's food canning factory, Somchem, and Gordon's Bay Sewage Works (Eagle, 1980) (Fig. 6; Tables 1 and 2).

The pollution load of some of the sources may be considerable. Although the measured concentration of pollutants may seem insignificant, the actual mass pollution load of some of the sources is significant if total discharges are taken into account.

False Bay is extensively used for recreational and fishing purposes and these activities may be adversely affected by any marine pollution. It has therefore become important to assess the pollution potential in the area. Heavy metals (arising in part from pollutant sources) are present in False Bay in the aqueous phase, in living organisms and in sediments. Measurements of concentrations in the aqueous phase or in living organisms often do not given an adequate indication of the extent to which the marine environment has been, or is being, polluted. The situation is complicated by the complexity of water movement, and the migration of and variation in life cycles of living organisms.

It is therefore proposed that sediments, whose movements are confined to a specific area, and often act as a sink for metals, can be used to give a good integrated indication of any pollution build up.

ABLE 1 : Sewage effluent discharges into False Bay (from Eagle, 1980)

Location	Discharge	Quality	Volume (10^6 m^3 a^{-1})
Macassar	Estuary/Surf Zone	General Standard	5.1
Cape Flats	Surf Zone	General Standard	25.55
Sand Vlei	Estuary/Surf Zone	General Standard	0.73
Simonstown	Surf Zone	General Standard	0.4

ABLE 2 : Industrial effluent discharges into False Bay (from Eagle, 1980)

Location	Discharge	Type	Volume (10^6 m^3 a^{-1})
omerset West	Surf Zone	Cannery Effluent	1.66
	Surf Zone	Explosives & Plastics	classified
	Surf Zone	Fertilizer	?
ape Flats	Surf Zone	Industrial effluents with domestic sewage	25.55
and Vlei	Estuary/Surf Zone	Service Industries	0.02
imonstown	Surf Zone (pipe)	Marine oil refinery effluent	0.05

3. MATERIALS AND METHODS

3.1 Sampling

Sediment samples from 65 stations were collected from False Bay between 17 and 26 May 1982, using a Shipek grab operated from the fishing vessel "Fred-Marie."

Sampling sites were selected according to the sediment distribution map of Glass (1980) (Fig. 7). Immediately after collection, the sediments were placed in glass jars which had been previously soaked overnight at room temperature in 70% nitric acid and then washed in double distilled water. Samples were stored in ice at $4^{o}C$. At the laboratory, the samples were air dried. Before analysis samples were dried in an oven at $60^{o}C$, homogenized and reduced to a fine powder in a ring mill.

3.2 Determination of total carbon (organic and inorganic) in sediment by CHN analyser

The instrument used for these analyses was a Carlo Erba 1100 CHN analyser. The method used was the standard method taken from the instrument manual, as set out below.

Approximately 1 mg powdered sample was placed in a light-weight tin crucible, previously washed with acetone and chloroform and then dried in an oven at $100^{o}C$. Samples were dropped at preset times into a vertical quartz tube, heated to $1030^{o}C$ and through which a constant flow of helium was maintained. When the samples were introduced, the helium stream was temporarily enriched with pure oxygen. Flash combustion took place, primed by the oxidation of the container.

Quantitative combustion was then achieved by passing the mixture of gases over powdered Cr_2O_3. The combustion gases were passed over copper at 650°C, to remove excess oxygen, and to reduce nitrogen oxides to elemental nitrogen and then separated by a chromatographic column (Porapak QS) at approximately 100°C. Individual components were eluted as N_2 - CO_2 - H_2O and measured by a thermal conductivity detector with associated recorder, integrator and digital print out. The instrument was calibrated by combustion of a benzoic acid standard.

3.3 Determination of organic matter in marine sediments by loss on ignition

The determination of organic matter by loss of weight on ignition has received much attention in the past (e.g. Galle and Runnels, 1960; Konrad et al., 1970; Dean, 1974; Byers et al., 1978). The procedure described below is a modification of that described by Dean (1974).

Silica crucibles were cleaned by soaking in 70% nitric acid for 24 hours, rinsed with double-distilled water, oven-dried at 50°C and then placed in a muffle furnace for 1 hour at 1 000°C and cooled in a desiccator.

The powdered samples were dried in preweighed, cleaned silica crucibles for 5 hours in an oven at 60°C. After having cooled to room temperature in a desiccator, samples and crucibles were weighed again to give the "dry" weight of the sample.

Samples and crucibles were then placed in a muffle furnace and heated to 450°C for 4 hours. After having cooled to room temperature samples

were again weighed. The difference between this weight and the "dry" weight was assumed to be due to loss of organic matter.

3.4 Determination of total leachable heavy metal concentrations (Cu, Cr, Cd, Pb, Mn, Fe, Ni, Zn) in marine sediments

Sample preparation

Approximately 1 g sample was placed in a boiling tube and 10 ml of mixed acids (HNO_3 - $HClO_4$ 4:1 v/v) were added in order to extract all forms of metals except those held in the silicate mineral lattice (Watling and Watling, 1977). Since a high percentage of carbonate was present, the acid mixture was added slowly in small aliquots (1 ml; 1 ml; 2 ml, 5 ml and 7 ml aliquots) allowing the vigorous reaction to subside between each addition. Blanks were run concurrently with samples.

Samples were taken to dryness at $\sim 80^{o}C$ on an air bath, and the residue dissolved in 10 ml 10% (v/v) nitric acid after which solutions were analysed with a Varian Techtron AA-6 atomic absorption spectrophotometer, using the manufacturer's conditions and with background correction. It was established that use of the background corrector improved results, and it was thus used throughout. Samples were diluted when necessary (e.g. for Fe the solutions were diluted 100 times). A calibration curve was prepared using commercial standard solutions.

Preparation of the mixed working standard calibration solutions

The mixed working standard was prepared in 10% nitric acid from commercial standards and contained 100 ppm Cu, Cd, Cr, Fe, Mn, Ni, Pb and Zn. The diluted working standards ranged in concentration from 0,002 to 5 ppm. Analytical conditions for metal determinations are set out in Table 3.

TABLE 3 : Analytical conditions for metal determinations.

Metal	Wavelength (nm)	Lampcurrent (mA)	Fuel	Support	Slit width (nm)
Cu	324,7	3	C_2H_2	air	0,2
Cr	357,9	5	C_2H_2	N_2O	0,2
Cd	228,8	3	C_2H_2	air	0,5
Fe	248,3	5	C_2H_2	air	0,2
Mn	279,5	5	C_2H_2	air	0,2
Ni	232,0	5	C_2H_2	air	0,2
Pb	217,0	5	C_2H_2	air	1,0
Zn	213,9	5	C_2H_2	air	0,2

The fuel/support gas ratios and burner geometry were optimized for each element

3.5 Extraction of different fractions from sediments

The complete extraction scheme is set out in a flow diagram, Fig. 8.

3.5.1 Extraction of carbonate and "easily reducible" fraction

Approximately 5 g powdered sample was placed in a 100 ml conical flask. Then 50ml of a mixture of 0,1 M hydroxylamine hydrochloride and 25% (v/v) acetic acid were added to each, and the samples were shaken for 30 minutes at room temperature using a mechanical shaker (Chester and Hughes, 1967; Presley et al., 1972; Chao, 1972). The solutions were allowed to settle until clear, and residues were separated off by filtration using glass microfibre filters (Whatman GF/C). To destroy excess reducing agent, 5 ml of concentrated redistilled nitric acid were added to the filtrate and solutions were evaporated at low temperature to dryness. The residues were re-dissolved in 5 ml 1% (v/v) nitric acid. The concentration of acid used here was lower than that used in the determination of total leachable metals (section 3.4). The reason for this was that in this case, some of the determinations were carried out using the graphite furnace. With 10% acid solutions, the furnace tube deteriorated significantly after only 10 firings. Using 1% acid solutions, up to 150 samples could be determined in a single furnace without deterioration. Nevertheless, a standard sample was introduced after each 10 determinations, to make certain that no deterioration of the furnace had occurred.

Mn, Fe, Zn and Cr were determined on a Varian Techtron AA-6 flame atomic absorption spectrophotometer, using manufacturer's standard conditions, with background correction. Since their concentration were below flame atomic absorption detection limit, Cu, Ni, Pb and Cd were

determined on a Perkin-Elmer Model 5000 atomic absorption spectrophotometer equipped with a HGA-500 graphite furnace, using manufacturer's standard conditions and with background correction (Table 4).

3.5.2 Extraction of "organic and sulphide" fraction

The residue from the previous step was washed with double distilled water, dried in an oven at 60°C, and weighed. This was followed by addition of 3 ml of 0,002 M nitric acid to each residue, followed by 25 ml of 30% (v/v) hydrogen peroxide (H_2O_2). The mixtures were heated at 90° - 95°C in a water bath for 2 hours after which another 25 ml of 30% hydrogen peroxide were added and then heated for 3 more hours. The solutions were allowed to cool to room temperature, and extracted with 1 M ammonium acetate in 6% (v/v) nitric acid (Gupta and Chen, 1975). The solids were separated by vacuum filtration as before. The extract solutions were evaporated to dryness at low temperature (95°C).

Trace metal analyses were as described previously (Section 3.5.1).

3.5.3 Extraction of "residual" fraction

The residues from the organic extraction were washed with double distilled water and digested in boiling tubes with 100 ml nitric-perchloric mixed acid (4:1 v/v) at 90°C. All samples were then taken to dryness on an air bath (see total analysis, Section 3.4). The residues were taken up in 5 ml 1% (v/v) nitric acid and solutions analysed as described previously.

TABLE 4 : Analytical conditions for metal determinations using graphite furnace atomization

Cu

Wavelength - 324,7 nm
Lamp-current - 10 mA
Slit-width - 0,7 nm ("low")

Cu	Dry	Char	Atomize	Clean
Temperature (°C)	130	900	2 200 (M.p)*	2 700
Ramp-time (s)	5	10	0	1
Hold-time (s)	25	10	3	1
Internal Gas flow (ml/min)	300	300	50	300

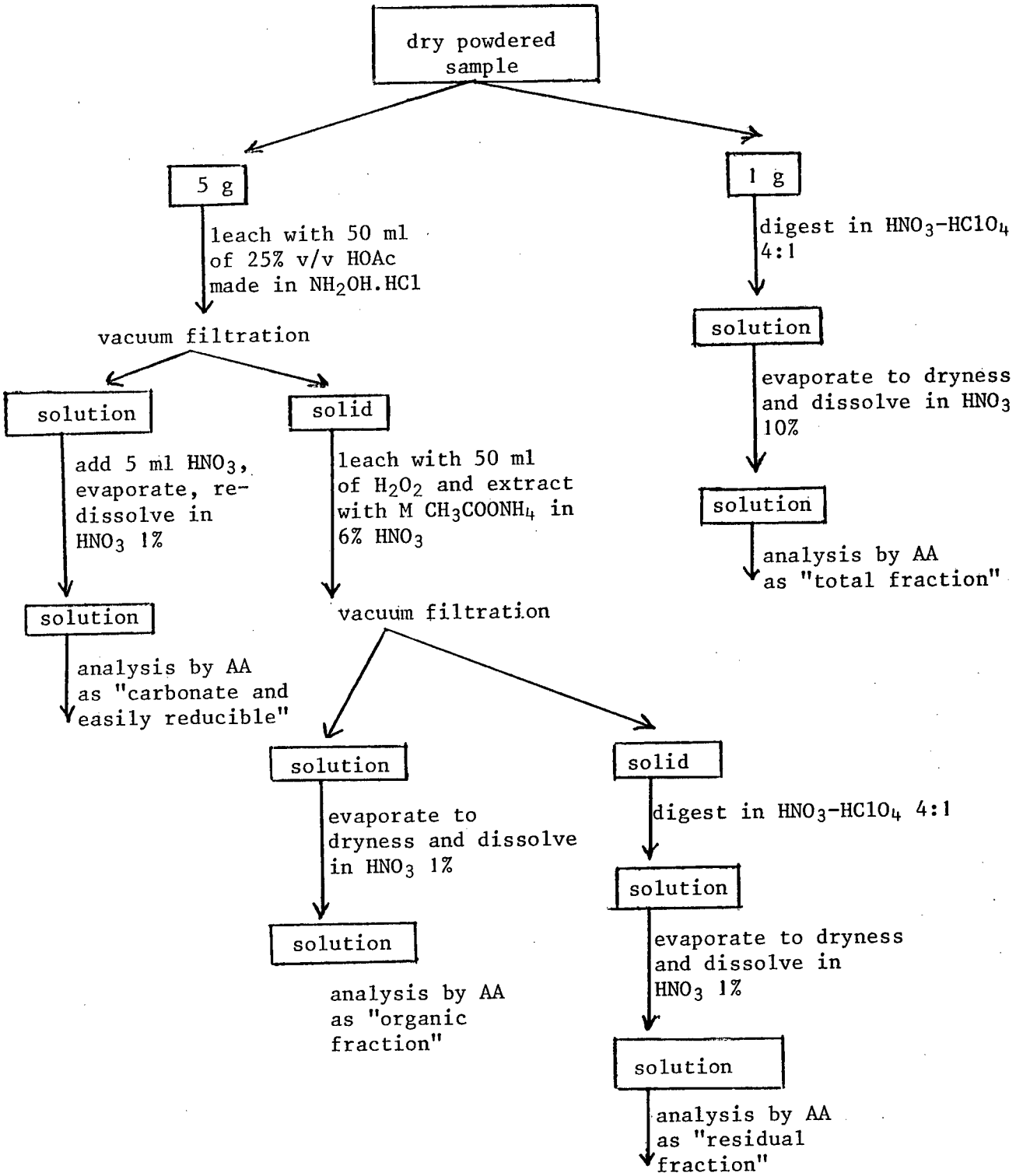
Cd

Wavelength - 228,8 nm
Lamp-current - 4 mA
Slit-width - 0,7 nm ("low")

Cu	Dry	Char	Atomize	Clean
Temperature (°C)	120	250	1 800 (M.p)*	2 700
Ramp-time (s)	1	1	0	1
Hold-time (s)	25	10	5	2
Internal Gas flow (ml/min)	300	300	0	300

* M.p. : For efficient atomization, a fast rate of heating is required. Maximum power (M.p.) heating mode permits the graphite tube to be heated with maximum available power up to the preset atomization temperature.

Fig. 8. Flow diagram of sediment analysis



3.6 Preparation of clays for x-ray diffraction

The first step in this procedure was the removal of carbonate. About 5g of sediment sample in 250 ml glass beakers were treated with 50 ml of 30% (v/v) acetic acid at room temperature overnight to remove carbonate. Excess acid was decanted off and samples washed twice with distilled water, followed by the addition of 100 ml water to each of them.

Organic matter was then removed by adding 25 ml of 30% (v/v) hydrogen peroxide and heating gently on a water bath at 90°C. A further 25 ml of peroxide were added to check for completeness of reaction. Excess liquid was removed by decantation, and four drops of diluted (1:1 v/v) hydrochloric acid added to flocculate the clay where necessary.

This was followed by a "magnesium saturation" procedure step. Each fraction was transferred to a 250 ml conical flask and made up to 150 ml with water. The pH was adjusted to approximately 3,5 - 4,0 with dilute hydrochloric acid, using pH paper, and 3M magnesium chloride was added to each suspension.

The flasks were sealed with rubber stoppers and shaken for 4 hours. Excess magnesium chloride solution was then removed by decantation, and samples were stored in glass vials.

Slide preparation

A glass slide was prepared for each fraction by adding homogenized suspension to the slide with a pipette and oven drying at 50°C.

X-ray diffraction

A Phillips X-ray diffractometer, using nickel-filtered Cu K_α radiation was used to analyse the samples.

Instrument settings were :

Voltage : 48 kV

Current : 20 mA

Scintillation Counter

Rate-meter : Counts/sec, Chart full scale deflection for 10^3 count

Time constant : 2 s

Windows : Lower 38 Upper 40

Slits : $\frac{1}{2} - \frac{1}{2} - 1^{o}$

Each sample was scanned from 3^{o} to 30^{o} at a speed of 20^{o} (2θ) per minute.

3.7 Determination of clay size fraction (<2 μm) by sedigraph particle size analyser

Preparation of sample

Approximately 30 g of sediment samples were homogenized and transferred to 250 ml conical flasks. Distilled water (100 ml) was added to each, and the samples were shaken mechanically for 48 hours. The fine fraction (<63 μm) was then separated from the coarse fraction (>63 μm) by sieving. Coarse fractions were dried in an oven at 60^{o}C and weighed. The fine fractions were treated with 20 ml of 30% (v/v) hydrogen peroxide overnight to disperse the clay. Excess acid was removed and each sample then washed with distilled water and dried in an oven at 60^{o}C. Distilled water (50 ml)

and 4 drops of Calgon were added to each sample.

Sedigraph analyser

The clay fraction (<2 μm) was determined with a Sedigraph 5000 D Particle Size Analyser. The instrument requires that each sample be well dispersed in a liquid of known density and viscosity, and that the difference between powder and liquid densities be known accurately.

The sedigraph measures the sedimentation rates of particles dispersed in the liquid and automatically presents these data as a cumulative mass percent distribution in terms of spherical diameter in micrometres.

4. RESULTS AND DISCUSSION

4.1 Organic matter in sediments

One of the more common methods of determining organic matter in marine sediment samples is to remove the carbonate carbon by acid treatment, and then to analyse the organic carbon in the residue (Froelich, 1980). The most commonly used acids are hydrochloric, sulphuric and phosphoric. In all cases difficulty is experienced in removing excess acid, and the formation of hygroscopic, hydrated and non-stoichiometric salts can lead to physical problems in drying and weighing the residual material.

Efforts to remove excess acid by washing the residue can remove soluble or solubilised organic carbon (Froelich, 1980). It has been reported that up to 44 percent of organic matter can be solubilised and lost during acid pre-treatment of recent carbonate sediments (Roberts et al., 1973). In the present study, preliminary experiments showed that 30 percent of the organic matter in the sediment was solubilized and lost during treatment with dilute hydrochloric acid. As a result this method was not pursued further.

A modified ignition loss method has been developed which equals or exceeds the accuracy and precision of other methods tested, and has the advantage of being considerably faster if large numbers of samples are to be analyzed.

This method may be inaccurate when significant amounts of clay are present in the sediments. Most clays contain five percent or less

lattice water which is removed when the sediments are heated (Dean, 1974). To test the applicability of the method with False Bay sediments very fine samples were analyzed for clay minerals by X-ray diffraction. They were also analysed for clay size particles using a Sedigraph.

Table 5 shows the results of these analyses. The highest level of clay size particles was 5 percent, which was made up mostly of illite. Structural water comprises 8 percent of illite. Assuming that all of this water is lost during heating in a furnace, the maximum error from this source would be about 0,4 percent. In the large majority of samples the percentage of clay was less than 5 percent and therefore the error would be less than that calculated here.

The concentration of organic matter in the sediments was therefore determined by the loss of weight on ignition. Differential thermal analysis thermograms showed that when a dried, powdered sample, containing organic material and calcium carbonate is heated in a muffle furnace the organic material begins to be lost at about 200°C and is completely removed by the time the furnace temperature has reached 500°C (Dean, 1974). The 65 samples collected in False Bay were therefore heated in a muffle furnace to 450°C for 4 hours. The loss of weight was calculated for each sample, giving a mean loss of about 1,7 percent. The results are given in Table 6 and the distribution is illustrated in Fig. 9. Very high concentrations of organic matter were found in the middle of the bay (3,0 - 6,5 percent) especially around stations 65, 66 and 70. This area was characterized by very fine sediments (Fig. 2). Some other areas with high concentrations of organic matter occurred in the vicinity of Fish Hoek

and between Gordon's Bay and the Eerste River, with another very distinct patch to the west of Swartklip, around 18° 35'E.

4.2 Trace element distribution in sediments

Most of the published work on this subject shows that the highest levels of metals occur in marine sediments near the coast (Benon et al., 1978; Griggs and Johnson, 1978; Campbell and Loring, 1980; Meyerson et al., 1981). The distribution is controlled by river inputs, sewage outfalls and industrial dishcarges.

Amiel and Navrot (1978) have found that trace metals which enter the environment through sewage are mostly removed from the aqueous phase and pass into the sediment. Therefore the highest metal concentrations in the sediments are usually found close to the sewage outfall. However, some of the introduced metals are able to move from the source area.

The interrelationship between sedimentary metal levels, organic content and sediment structure has also been reported widely (Forest et al., 1978; Campbell and Loring, 1980; Ward and Young, 1981; Parker, 1982; Calmano et al., 1982). High concentration of metals were found in sediments from the deeper area of bays, where the finest sediment occurred and organic matter concentrations were highest.

The distribution of trace metals in sediments in an area like False Bay may be modified by three major factors :

1. Source of input.
2. Sediment grain size distribution.

3. Organic content of sediments.

The sediment samples were analysed for eight elements, Cu, Cd, Cr, Fe, Mn, Ni, Pb and Zn and the results are presented in the form of countour diagrams (Figs. 10 to 17) while the data are listed in Table 7 .

The distribution patterns for "total metals", of some of the elements for example, Cu, Ni, Cd and Zn, are similar. These metals all had their highest concentrations in the south-central area of the bay. This is the area characterized by very fine sediments and also contains the highest concentrations of organic material.

The coastal margin is of particular interest, since some points of high metal concentrations were found there. These can be summarised as follows:

1. High levels of Cu, Zn and Ni were found off Simonstown as well as in the organic-rich south.
2. High levels of Zn were found off Strand (Fig. 16).
3. An area of high concentrations of Mn and Fe was found in the north east corner of the bay (Figs. 12 and 14). It appears that the main source of Mn is in the Strand area, possibly from the Lourens River.
4. Very high concentrations of Cr were found in the central area of the bay (Station No. 70) and also in the north-west corner of the bay around Fish Hoek and Muizenberg; the latter may possibly originate in the Silvermine River (Fig. 17).

5. Pb showed a completely different distribution from the other metals. The highest concentrations were found near Simonstown, Muizenberg, Swartklip and Strand (Fig. 13). It is difficult to say what the sources of the Pb are, but the high concentrations all along the northern shore of the bay suggest that it comes from urban run-off, probably originating from vehicle exhausts or from industrial discharges.

The various sediment parameters were correlated with each other. The program used was a linear regression, employing parametric statistics. Strictly this should be applied only to normally distributed data. Some of the metals, particularly Cu, Ni and Zn, were correlated (99% confidence) with organic matter. Pb concentration did not correlate at all. This may indicate input from non-natural sources. On the other hand, none of the metal concentrations correlated with particle size. The particle sizes shown here are the mean diameters of the sand fraction of the sediments, from which the mud fraction (<63 μm) had been removed (Fig. 18; Table 8).

Most of the sediment samples from False Bay in fact contained low proportions of mud-sized material. Exceptions were found in the central bay, where sediments had the highest proportion of fine material.

Sediments are normally mixtures of several components, including various mineral species and organic debris. In addition, the heavy metals may be bound in a variety of ways e.g. by adsorption, on exchange sites of clay minerals, coprecipitated with iron oxides, or held inside biological materials such as seagrass fragments, shells and mineral facies.

Individual metallic sulphide or oxide particles may be present (Dossis and Warren, 1980). Therefore, in an attempt to gain some insight into the forms of the various metals, the sediments were separated chemically into three fractions, as described in the introduction. The distributions of the metals in these three fractions are discussed in the following sections.

4.3 Trace metal analysis of different sediment fractions

The sediments under study were separated into three fractions as follows:

1. Carbonate and easily reducible
2. Organic and sulphide
3. Residual.

Trace element analyses were performed on each fraction for Cd, Cu, Cr, Fe, Mn, Ni, Pb and Zn.

The results of metal analyses and the distribution in each sediment fraction from False Bay are illustrated in Figs. 19 to 41. Detailed results are given in Tables 9 to 16. In most cases, the sum of the sequential extractions of trace elements was satisfactorily close (± 10 percent) to the "total" metal concentrations.

The results of the chemical analyses of the three different fractions will be discussed element by element in the following sections and relationships between the various metals will be pointed out.

4.3.1 Cadmium

The highest total levels of Cd were found in the north-west corner of False Bay near Muizenberg (0,37 µg/g) and in the central area (0,6 µg/g) (Fig. 10).

About 60 percent of the total Cd was found in the carbonate and reducible fraction (Fig. 42). In this fraction, the highest concentrations (0,20 µg/g) were found to be associated with the fine sediments in the centre of the bay, but slightly elevated concentrations were also found in the sediments along the northern shore (Fig. 22). In similar studies Gupta and Chen (1975) found that more than 50 percent of the Cd was associated with the carbonate and reducible fraction. Helsinger and Friedman (1982) reported that Cd occurs incorporated within iron and manganese oxides, while similar results were also obtained by Lion et al. (1982).

Approximately 40 percent of the total Cd was bound to the organic and sulphide fraction (Fig. 42). The highest concentration of Cd in this fraction (0,3 µg/g) was found in the centre of the bay, where the fine sediments occur (Fig. 23). This area also contains high concentrations of organic matter.

An average of only about 1 percent of the total Cd was found in the residual fraction (Fig. 42).

It therefore appears that in False Bay there is some association

between organic content and Cd concentrations. Similar results have also been obtained by Gupta and Chen (1975), Lion et al. (1982), Tessier et al. (1979) and Malo (1977). Like Pb, there is evidence of Cd (carbonate phase) input from Simonstown, Muizenberg, Swartklip and especially Strand. It appears that organically bound Cd is naturally occurring, while Cd in the carbonate phase is possibly anthropogenic. Organic Cd near Zeekoevlei may be of sewage origin.

4.3.2 Chromium

The highest Cr concentrations (85 µg/g) were associated with the fine sediments in the centre of the bay (Fig. 17). Fig. 44 shows that about 10 percent of the total Cr was associated with the iron and manganese oxides. In the carbonate and reducible fraction high Cr values (6,0 µg/g) were found in the north-west corner of the bay near Fish Hoek (Fig. 24). Another high point was found in the north-east corner, in the vicinity of the Eerste River and also in the central bay (Station 70).

Approximately 40 percent of the Cr was associated with the organic and sulphide phases (Fig. 44), where the highest concentrations (up to 34 µg/g) were found in the central and east-central parts of the bay (Fig. 25). This is the area characterised by very fine sediment and high concentrations of organic matter.

The residual fraction also contained about 40 percent of the total Cr. High concentrations were found at several points in the bay (Fig. 26), namely:

1. in the north-west corner off Fish Hoek and Muizenberg;

2. in the north-east corner off Strand in the vicinity of the Eerste and Lourens Rivers, and off Gordon's Bay near the Steenbras River;
3. in the centre of False Bay.

Most of the Cr in the coarse sediments off Fish Hoek and Strand is associated with the residual fraction. However in the central area of the bay (fine sediments) the majority of the Cr was associated with the organic and sulphide phase. Therefore it appears that in the coarse sediments the Cr is probably terrestrially derived, while in the finer sediments Cr is complexed with organic matter and held onto sediment particles. Thus the form in which the Cr is held seems to depend on particle size.

Cr is extracted from the sediments by the hydrogen peroxide extraction, through organic decomposition and conversion of Cr (VI) to Cr (III) (Helsinger and Friedman, 1982). Filipek and Owen (1979) indicated that the greatest proportion of Cr (43 percent) occurs in this fraction. This is probably in the Cr (III) oxidation state, which is readily complexed with organic forms on to sediment particles. These complexes are relatively inert, and thermodynamically metastable forms can exist for long periods of time.

4.3.3 Copper

Cu was contained very largely in the organic and sulphide phase, which has an average of 80 percent of the total copper (Fig. 43). The highest concentrations (4,0 µg/g) were found in the central area of the bay (Fig. 20). The concentrations of Cu were found to increase with

increase in the organic content. Many other researchers (Shimp et al., 1971; Copeland and Ayers, 1972; Presley et al., 1972; Nissenbaum, 1972; Foster and Hunt, 1975; Gupta and Chen, 1975; Tessier et al., 1979; Helsinger and Friedman, 1982) have found elevated concentrations of Cu in sediments, and they have suggested that the major form of Cu was as Cu-organic complexes.

Only about 10 percent of the total Cu was found in the reducible phase (Fig. 43). The studies of Presley et al. (1972) and Nissenbaum (1972) have also shown that an almost negligible proportion of copper occurs in this fraction. A single high concentration of Cu (0,36 µg/g) in this fraction was found in a sample from the north-west corner of the bay, near Muizenberg (Fig. 19). There was some doubt as to the validity of this single high result, and the analysis was therefore repeated twice. The same result was obtained on all three occasions. No reason can be suggested for this single high concentration.

In the residual fraction the Cu content was about 10 percent of the total. The only sediments to contain any significant proportion of Cu in this fraction were those from the north-east corner of the bay (Figs. 21 and 43). In this area, particularly near Gordon's Bay, there were also elevated concentrations of organic material. Therefore it may be speculated that the Cu in this fraction could have been associated with the residual organic material which was resistant to attack by peroxide. It could also have been bound in terrestrially-derived minerals.

4.3.4 Iron

Approximately 14 percent of the Fe was associated with the reducible phase although this showed considerable variation. High concentrations of Fe were found in the north-east corner of the bay, off Strand, near the Lourens River, and off Gordon's Bay in the vicinity of the Steenbras River (Fig. 27). Presley et al., (1972) reported that in their studies 1,5 percent of the Fe was removed by this combined acid. Foster and Hunt (1975) indicated that 8 percent of the total Fe was associated with this fraction, and they suggested that Fe is largely present in the lattice structure of minerals, according to data of Chester and Messiha-Hana (1970) and Deurer et al., (1978). On the other hand, Chao (1972) indicated that in this extraction with combined acid, amorphous $Fe(OH)_3$ dissolved to the extent of 8 percent of the total Fe. The hydroxylamine hydrochloride extraction thus suggests that some Fe oxides in sediments are in a form which is intermediate between crystalline iron oxides and amorphous $Fe(OH)_3$.

Approximately 30 percent of the Fe was incorporated in the organic and sulphide phase (Fig. 45). The percentage of Fe in this fraction was, however, variable. This variability probably results from competition between Fe organic complexes and hydrous Fe oxide forms (Filipek and Owen, 1979). This situation is complicated because hydrous Fe oxides themselves can complex with organic, especially humic, substances in sediments (Tschapek and Masowski, 1976; Nissenbaum and Swaine, 1976). The rest of the Fe, about 55 percent, was found in the residual fraction, where the highest concentrations occurred off Strand, near the Lourens River and in the central area of the bay (Fig. 29) and is probably present in minerals carried in by the rivers.

4.3.5 Manganese

The Mn in the reducible fraction was approximately 35 percent of the total (Fig. 46). Very high concentrations in this phase were found in the north-east corner of the bay near the Lourens River mouth (Fig. 30). The observed trends of the various geochemical forms of Mn in False Bay sediments differ from those reported by Nissenbaum (1972), Chester and Hughes (1967) and Chester and Messiha-Hana (1970). These latter studies reported that 68-88 percent of the total Mn was removed by hydroxylamine hydrochloride in acetic acid. However, in False Bay about 35 percent was in the reducible phase and about 40 percent was found in the residual fraction (Fig. 46).

An average of about 30 percent of the total Mn was associated with the organic and sulphide phase. The highest concentration in this fraction was found in the east-central area of the bay, where the organic content was slightly higher than the mean (Fig. 31).

The Mn in the residual fraction arises from precipitation of Mn minerals near the coast. These probably originate in river catchments. The Mn in the reducible fraction is probably in the form of Mn oxides.

The processes by which Mn is deposited in the marine environment are discussed in more detail in a later section.

4.3.6 Nickel

About 62 percent of the nickel was bound to the organic and sulphide fraction, where the highest values for nickel were found in the central

area of the bay (Fig. 34). Again this is the area characterised by high organic content. These results are very similar to those of Presley et al. (1972), working in a reducing fjord sediment in British Columbia.

An average of 7 percent of the total Ni was associated with the reducible fraction. This showed a fairly even distribution over the whole bay with one high value at station 65, which had a high organic content (Fig. 33).

The residual fraction contained about 32 percent of the total Ni (Fig. 47). These results are similar to those of Chester and Hughes (1969). The distribution of the Ni in this fraction is illustrated in Fig. 35, and, like with Fe and Mn, suggests an input from rivers in the Strand area.

The Ni distribution appears to be more closely related to that of the organic content than to the sediment particle size. The high Ni concentrations in the residual fraction also occurred in the organic rich area. This indicates again that there may be some association between Ni and the organic material which is resistant to peroxide attack.

The Ni was spread through all three phases of the sediment (Fig. 47), indicating a rather complicated distribution.

4.3.7 Lead

About 32 percent of the total Pb was found in the reducible fraction (Fig. 48). Slightly higher concentrations of Pb occurred along the western shore

of the bay near Simonstown (Fig. 36). These results are similar to the findings of Chester and Hughes (1969).

Pb is usually divided into two general chemical forms, that is, exchangeable phases and residual phases (Helsinger and Friedman, 1982).

In contrast to Cu, only a small fraction of the Pb was bound in the organic fraction. The average content in this phase was about 20 percent of the total Pb (Fig. 48). Wright (1974) also noted the lack of any association between Pb and organic matter. Exchangeable Pb occurs within manganese oxides. Pb carbonate, an end-product of gasoline combustion, is also present within this chemical phase.

About 46 percent of the total Pb was found in the residual phase, in which the highest concentrations occurred in the north-eastern section of the bay, near Strand (Fig. 38). Pb extracted by nitric/perchloric acids occurs as resistant Pb compounds, formed by gasoline combustion, and in the lithogenic fraction of the sediments. However industrial sources can also be significant as may be the case in the Strand area.

The higher concentrations of lead along the shore strongly suggest that it originates from man-made sources. Since the bay is surrounded by roads which are close to the shore, the most likely source of lead is from gasoline combustion. South African petrol contains lead concentrations which are higher than those found in most other parts of the world. The nature of the industry which is located at Somerset West/Strand (explosives, etc.) is also such that one could expect the effluents to be a relatively high source of lead. However, these were not analysed in the present study.

4.3.8 Zinc

Zinc exists in three chemical forms : exchangeable cations, with organic matter and lithogenic (Helsinger and Friedman, 1982).

The distribution of Zn in the reducible fraction of the sediments was similar to the distributions of Cu and Ni (Fig. 39). An average of about 24 percent of the total Zn was removed with hydroxylamine hydrochloride in acetic acid. About 45 percent of the total Zn was associated with the organic and sulphide phase (Fig. 49). Again, the highest concentrations (9,5 µg/g) occurred in the central area of the bay, which is characterised by high concentrations of organic matter and find sediments (Fig. 40).

The Zn content of the residual fraction was found to be about 31 percent. The highest concentrations (3,1 µg/g) in this fraction were found in the north east corner of the bay, off Strand (Fig. 41) and off Simonstown, probably of industrial origin.

These results are different from those obtained by others. Filipek and Owen (1979) found slightly higher concentrations of zinc in the carbonate and reducible fraction. They suggested that Zn, perhaps from some pollution souces, enters the sediment as an absorbed ion or as some carbonate species.

Calmano et al., (1982) found high concentrations of Zn in the reducible and exchangeable phases, from which they can be released under anaerobic conditions. Helsinger and Friedman (1982) suggested that exchangeable

Zn in this fraction decreases due to :

1. rapid adsorption onto clay particles;
2. the incorporation within Mn oxides;
3. rapid deposition of Zn enriched particles.

4.4 Chemical fractionation of sediments

4.4.1 Hydroxylamine hydrochloride-acetic acid extraction (reducible fraction)

The purpose of this first leach of the sediments was intended to remove that part of a metal which is associated with a carbonate or an iron-manganese oxide phase. Some other adsorbed ions are also certain to be included in this leachate, and acid soluble sulphide may contribute some heavy metal ions in sulphide-rich sediments (Presley et al., 1972; Malo, 1977). However this contribution should, in most circumstances, be minor compared to metal ions contained in carbonates and oxides. Ions bound structurally in silicates are hardly affected by this treatment, according to the data of Chester and Hughes (1967) and Malo (1977). This phase is composed of hydrous oxides of Fe and Mn, as well as hydroxides of Fe and Mn. These are relatively stable under anaerobic conditions but may go into solution under reducing conditions (Engler et al., 1977).

In his study Chao (1972) indicated that hydrous Mn and Fe oxides in sediments are strong scavenging agents for heavy metal ions. Mn oxides in sediments are found to be readily dissolved by hydroxylamine hydrochloride solution, leaving the major part of iron oxides in the residue. Similar results were found in False Bay, during this study. Small amounts of Fe were found in this fraction, while more than 50 percent was found in the residue (Fig. 45). No relationship was found between these two

elements using parametric statistics. It may be possible that various Mn compounds respond differently to the action of hydroxylamine hydrochloride solution. Since the major function of this solution is both to reduce and to dissolve, the more readily soluble fraction would represent the more reactive secondary Mn oxide which also presumably possesses a stronger scavenging action on heavy metal ions (Chao, 1972).

In False Bay sediments, Fe, Ni, Cu and Cr responded similarly to each other in this first treatment. A relatively small percentage of the total concentration (5 to 15 percent) was removed. This is in agreement with the results of Presley et al., (1972).

These metals could be associated with a carbonate phase in the sediments, but it may be that they were bound partially in acid soluble sulphides. A minor contribution could come from ions physically adsorbed on to the particle surfaces. It is interesting to note that those samples which contained a very high concentration of Mn in this first leach were not significantly enriched in Fe, Ni, Cu and Cr. This shows that rather pure Mn phases can precipitate under some conditions (or be carried in from terrestrial deposits).

Most of the Cd was removed with this first treatment. It therefore seems that Cd occurs incorporated within Fe and Mn oxides and/or adsorbed as exchangeable cations on the surface of clay minerals.

4.4.2 Hydrogen peroxide extraction (oxidizable fraction)

The hydrogen peroxide treatment should remove mainly sulphides and organic matter, and have only a minor effect on the silicate lattice. Some of the organic matter may be very difficult to oxidize by this method, especially any detrital particulate matter, such as organic

matter trapped inside diatom frustules. Despite these problems, it is felt that most of the organic matter was broken down by the peroxide treatment.

The association of heavy metals with organic matter in sediments has frequently been observed in the past. Cooper and Harris (1974) found that the distribution of metals as organic complexes in sediments were very sensitive indicators of contamination. Presley et al. (1972) concluded that diagenesis within sediment in Saanich Inlet, British Columbia, appeared to be time dependent. They found mobilization of Cu, Fe, and Zn from the insoluble silicate phase to the peroxide phase, suggesting organic complexing.

Of the metals studied in this work Cu had the highest relative amount in this fraction. This is probably an indication of the often-proposed close association of Cu and organic matter. Oxidizable Cu correlates well with organic matter (Fig. 51) and with Zn and Ni in this fraction (Figs. 58,59). Other metals also correlated with the organic content but correlations decreased in the following order : Zn > Ni > Mn > Cr > Cd > Fe (Figs. 50 to 56). Pb did not correlate at all (Fig. 57).

These results are in agreement with those of McLaren and Crawford (1973). They found the majority of Cu in soil to be organically bound as well as in the clay lattice structure. Other researchers, including Filipek and Owen (1978, 1979) and Brannon et al., (1977) have found elevated concentrations of Cu in sediments, and have suggested Cu-organic complexes as the major form of Cu.

Zn and Ni extracted in the peroxide digestion were correlated well with each other (Fig. 62) and with the organic matter.

There were also good correlations between Zn and Mn (Fig. 60) and Ni and Mn (Fig. 61) in this fraction.

Thus it is clear that the heavy metal concentrations of sediments were higher when the concentration of organic matter increased.

4.4.3 Nitric-perchloric acid extraction (residual fraction)

The residue remaining after the hydroxylamine hydrochloride-acetic acid, and the hydrogen peroxide leaches could be expected to consist almost entirely of detrital silicate minerals, and organic matter, such as humic material, which is resistant to peroxide attack. This residual solid should contain mainly primary and secondary minerals, which may hold trace metals within their crystal structure. These metals would not be expected to be released in solution over a reasonable time span under the conditions normally encountered in nature (Tessier et al., 1979).

Agemian and Chau (1976) in their study, investigated different extraction techniques, to obtain the best technique applicable to environmental analysis. Since hydrofluoric acid readily dissolves silica, it has been used in conjunction with nitric, hydrochloric or perchloric acid in the total decomposition of silicates. Nitric acid attack has been used either alone or combined with either hydrochloric or perchloric acids. Such methods do not attack silicates extensively but destroy organic matter, dissolve all precipitated and adsorbed metals and also leach a certain amount of the metals from the silicate lattice.

However, the amount of metal extracted by the nitric-perchloric acid, depends on the type of sample (both mineral type and organic matter content). For many types of samples, this acid is suitable for total metal extraction (Van Valin and Morse, 1982).

The result of this study (using nitric-perchloric) shows that approximately half of the total concentration of Fe, Cr, and Pb is located in the residual fraction. These results are similar to those of Filipek and Owen (1978, 1979). The highest concentrations of these elements were found in the north-west and north-east of the bay. Probably these minerals are part of the fluvial material entering the bay (Figs. 26, 29, 38). There was no relationship between Fe and Mn in this fraction (Fig. 63).

The amount of trace metal in the residue decreases in the order

Fe > Pb > Cr > Mn > Ni > Zn > Cu > Cd

5. CONCLUSIONS

Selective extraction schemes have been used widely to determine the chemical association of heavy metals with specific sedimentary phases. Based on an evaluation of the literature and on the experience gained in this study, the procedure below is suggested for selective metal extractions. This divides the metals into three fractions of ecological importance:

1. Extraction with hydroxylamine hydrochloride in acetic acid. This yields a fraction which is referred to as the carbonate and easily reducible fraction.
2. Extraction with hydrogen peroxide, followed by extraction with ammonium acetate, giving a sulphide and organic fraction.
3. Treatment with nitric-perchloric acids (4:1), for the residual fractions remaining after the first two extractions, but excluding the silicate lattice of the sediments.

Based on this selective leaching procedure, it has been possible to establish the percentages of the various elements which are associated with certain fractions of the sediments, and also the distribution patterns of each of these in the sediments of False Bay.

The main conclusions which can be drawn from this study are the following:

1. The organic content of the sediments was found to be generally low, the average concentration being about 1,7 percent. The highest concentrations of organic material were found in the central area of the bay, where the finest sediments were also found.

2. The heavy metals showed distinct distribution trends. The distribution patterns of the total metals were similar in some cases. However, on separating the metals into different chemical fractions, it was found that the distribution patterns of the metals in the separate fractions differed considerably. This stresses again the importance of knowing the form of trace metals in the environment.

3. Fe and Pb were concentrated mainly in the residual phases of the sediments, while Ni, Cu and Zn were concentrated mainly in the organic fractions.

4. Metal concentrations (except for Pb) correlated well with the organic content of the sediments. Correlation coefficients indicated greater than 99 percent confidence in some cases. No relationship could be found between the metal concentrations and the particle size of the sediments.

5. Most of the sediments collected from the central area of the bay yielded high metal concentrations in the peroxide leach. This area was characterised by fine sediments with a high organic content. Metal concentrations and organic content were low in most other areas of the bay.

6. In the case of Pb, the highest concentrations were found along the northern shore of the bay. This indicates that there is input of lead from the land. This lead, possibly originating from vehicle exhausts, enters the marine environment through land runoff.

7. The overall elemental concentrations and the relationships apparent in the sediments were controlled by the non-detrital,

i.e. easily reducible and organic, fractions. This was found particularly in the cases of Cu, Ni, Zn, Cr, Cd and Mn.

8. Very high concentrations of Mn in the reducible phase were found in the north-east corner of the bay. It is not possible at this stage to say whether this is the result of anthropogenic input, or whether it arises from natural Mn enrichment in the catchment of the Lourens River.

9. Although the distributions of total Fe and Mn were similar to each other, this was not the case once the metals had been separated chemically. In the case of Fe, the majority of the metal was found in the residual fraction. This indicates that there are different origins for these two metals.

REFERENCES

AGEMIAN, H. and CHAU, A.S. 1976. Evaluation of extraction techniques for the determination of metals in aquatic sediments. *Analyst* 101: 761-767.

AMIEL, A.J. and NAVROT, J. 1978. Nearshore sediment pollution in Israel by trace metals derived from sewage effluent. *Mar. Pollut. Bull.* 9(1): 10-14.

ATKINS, G.R. 1970. Thermal structure and salinity of False Bay. *Trans. roy. Soc. S. Afr.* 39: 117-128.

BENON, P., BLANC, F., BOURGADE, B., DAVID, P., KANTIN, R., LEVEAU, M., ROMANO, J.C. and SAUTRIOT, D. 1978. Distributions of some heavy metals in the Gulf of Fos. *Mar. Pollut. Bull.* 9(3): 71-75.

BERNER, R.A., 1967. Thermodynamic stability of sedimentary iron sulphides. *Am. J. Sci.*, 265: 773-785.

BOWIE, D.K., FULLER, A.O. and SIESSER, W.G. 1970. The marine sediments of False Bay. *Trans. roy. Soc. S. Afr.* 39, 149-162.

BRANNON, J.M., ROSS, J.R., ENGLER, R.M. and SMITH, I. 1977. The distribution of heavy metals in sediment fractions from Mobile Bay, Alabama. In : *Chemistry of Marine Sediments* (edited by Yen, T.F.) 125-149. Ann Arbor. Science MI.

BRULAND, K.W., BERTINE, K., KOIDE, M. and GOLDBERG, E.D. 1974. History of metal pollution in southern California coastal zone. *Environ. Sci. Technol.* 8: 425-432.

BYERS, S.C., MILIS, E.L. and STEWART, P.L. 1978. A comparison of methods of determination organic carbon in marine sediments, with suggestions for a standard method. *Hydrobiologia* 58, 43-47.

CALMANO, W., WELLERSHAUS, S. and FORSTNER, U. 1982. Dredging of contaminated sediments in the Weser estuary : chemical form of some heavy metals. *Environ. Technol. Lett.* 3: 199-208.

CAMPBELL, J.A. and LORING, D.H. 1980. Baseline levels of heavy metals in the waters and sediments of Baffin Bay. *Mar. Pollut. Bull.* 11(9): 257-261.

CHAO, T.T. 1972. Selective dissolution of manganese oxides from soils and sediments with acidified hydroxylamine hydrochloride. *Soil. Sci. Soc. Amer. Proc.* 36: 764-768.

CHESTER, R. and HUGHES, M.J. 1967. A chemical technique for the separation of ferro-manganese minerals, carbonate minerals and adsorbed trace metals from pelagic sediments. *Chem. Geol.* 2: 249-262.

CHESTER, R. and HUGHES, M.J. 1969. The trace element geochemistry of a North-Pacific pelagic clay core. *Deep Sea Res.* 16: 639-654.

CHESTER, R. and MESSIHA-HANA, R.G. 1970. Trace element partition patterns in North Atlantic deep sea sediments. *Geochim. Cosmochim. Acta.* 34 : 1121-1128.

COOPER, R.S. and HARRIS, R.C. 1974. Heavy metals in organic phases of river and estuarine sediments. *Mar. Poll. Bull.* 5 : 24-26.

COPELAND, R.A. and AYERS, J.C. 1972. Trace element distribution in water, sediment, phytoplankton, zooplankton and benthos of Lake Michigan: A baseline study with calculation of concern-factors and of radioisotopes in the food web. *Environmental Research Group, Ann. Arbor.* 271 pp.

DEAN, W.E. Jr. 1974. Determination of carbonate and organic matter in calcareous sediments and sedimentary rocks by loss on ignition : comparison with other methods. *Jour. Sed. Petrology* 44: 242-248.

DEURER, R., FORSTNER, U. and SCHMOLL, G. 1978. Selective chemical extraction of carbonate associated metals from recent lacustrine sediments. *Geochim. Cosmochim. Acta.* 42 : 425-427.

DONNELL, T.W. and MERRILL, L. 1977. The scavenging of magnesium and other chemical species by biogenic opal in deep sea sediments. *Chem. Geol.* 19: 167-186.

DOSSIS, P. and WARREN, L.J. 1980. Distribution of heavy metals between the minerals and organic debris in a contaminated marine sediment. *Contaminants and Sediments*, (Edited by Baker, R.A.) Ann Arbor Science Publishers, Ann Arbor, MI, Vol. 1: 119-139.

EAGLE, G.A. 1980. Waste disposal into the bay. In : The future management of False Bay. (Ed. B. Gasson), False Bay Conservation Society 93-96.

ENGLER, R.M., BRANNON, J.M. and ROSE, J. 1977. A practical selective extraction procedure for sediment characterization. In : *Chemistry of Marine Sediments* (Edited by Yen, T.F.) 163-171. Ann Arbor Science MI.

FILIPEK, L.H. and OWEN, R.M. 1978. Analysis of heavy metal distribution among different mineralogical states in sediments. *Can. J. Spectrosc.* 23 : 31-34.

FILIPEK, L.H. and OWEN, R.M. 1979. Geochemical associations and grain-size partitioning of heavy metals in lacustrine sediments. *Chem . Geol.* 26: 105-117.

FOREST, A., MURPHY, S.P. and PETTIS, R.W. 1978. Heavy metals in sediments from the central New South Wales coastal region. *Aust. J. Mar. Freshwater Res.* 29 : 777-785

FORSTNER, U. and SALOMONS, W. 1980. Trace metal analysis on polluted sediments : I : Assessment of sources and intensities. II : Evaluation of environmental impact. *Environ. Technol. Lett.* 1 : 494-518.

FOSTER, P. and HUNT, D.T.E. 1975. Geochemistry of surface sediments in an acid stream estuary. *Marine Geology* 18 : 13-21.

FROELICH, P.N. 1980. Analysis of organic carbon in marine sediments. *Limnol. Oceanogr.* 25(3) : 572-576.

GALLE, O.K. and RUNNELS, R.T. 1960. Determination of CO_2 in carbonate rocks by controlled loss on ignition. *Jour. Sed. Petrology* 30 : 613-618.

GIBBS, R.J. 1973. Mechanisms of trace metal transport in rivers. *Science* 180 : 71-72.

GLASS, J.G. 1976. The bathymetry and geology of False Bay. University of Cape Town, Marine Geoscience Group, Technical Report No. 8 : 60-63.

GLASS, J.G. 1980. Geology, morphology, sediment cover and movement. In : *The future management of False Bay.* Ed. B. Gasson, False Bay Conservation Society 15-25.

GRIGGS, G.B. and JOHNSON, S. 1978. Bottom sediment contamination in the bay of Naples, Italy. *Mar. Pollut. Bull.* 9(8) : 208-214.

GRINDLEY, J.R. 1980. The hydrological environment of False Bay. In : *The future management of False Bay.* Ed. B. Gasson, False Bay Conservation Society 26-33.

GRINDLEY, J.R. 1982. Estuaries of the Cape. Part II. Synopsis of available information on individual systems (Ed. Heydorn, A.E.F. and Grindley, J.R.) *CSIR Research Report* 415 : 51 pp.

GRINDLEY, J.R. and TAYLOR, F.J.R. 1970. Factors affecting plankton blooms in False Bay. *Trans. roy. Soc. S. Afr.* 39 : 201-210.

GUPTA, S.K. and CHEN, K.Y. 1975. Partitioning of trace metals in selective chemical fractions of nearshore sediments. *Environ. Lett.* 10 : 129-158.

HEINECKEN, T.J.E. 1982. Estuaries of the Cape. Part II. Synopsis of available information on individual systems (Ed. Heydorn, A.E.F. and Grindley, J.R.). *CSIR Research Report* 412, 43 pp.

HELSINGER, M.H. and FRIEDMAN, G.M. 1982. Distribution and incorporation of trace elements in the bottom sediments of the Hudson River and its tributaries. *Northeastern Environmental Science* 1(1) : 33-47.

JENNE, E.A. and LUOMA, S.N. 1977. The forms of trace elements in soils, sediments and associated waters : an overview of their determination and biological availability. In : *Biological Implications of Metals in the Environment* (Ed. by Wildung, R.E. and Drucken, H.) 110-143. NTIS, Springfield, VA.

KONRAD, J. G., CHESTERS, G. and KEENEY, D.R. 1970. Determination of organic and carbonate carbon in freshwater lake sediments by a microcombustion preocedure. *Jour. Thermal, Analysis* 2: 746-748.

LION, L.W., HARVEY, R.V. and LECKIE, J.O. 1982. Mechanisms for trace metal enrichment at the surface microlayer in an estuarine salt marsh. *Marine Chemistry* 11(3): 236-244.

LUOMA, S.N. and BRYAN, G.W. 1981. A statistical assessment of the form of trace metals in oxidized estuarine sediments employing chemical extraction. *The Science of the Total Environment* 17: 165-196.

MALO, B.A. 1977. Partial extraction of metals from aquatic sediments. *Environ. Sci. Technol.* 11: 277-282.

McLAREN, R.G. and CRAWFORD, D.V. 1973. Studies on soil copper. I. The fractionation of copper in soils. *J. Soil Sci.* 24: 172 pp.

MEYERSON, A.L., LUTHER, G.W.(III), KRAJEWSKI, J. and HIRES, R.J. 1981. Heavy metal distribution in Newark Bay sediments. *Mar. Pollut. Bull.* 12(7): 244-250.

MOREL, F., WESTALL, J.C., O'MELIA, C.R. and MORGAN, J.J. 1975. Fate of trace metals in Los Angeles County wastewater discharge. *Environ. Sci. & Tech.* 9: 756-

MURRAY, J.W. 1975. The interaction of metal ions at the manganese dioxide-solution interface. *Geochim. Cosmochim. Acta.* 39: 505-519.

NISSENBAUM, A. 1972. Distribution of several metals in chemical fractions of sediment core from the sea of Okhotsk. *Israel.Jour. Earth Science* 21: 143-154.

NISSENBAUM, A. 1974. Trace elements in Dead Sea sediments. *Israel J. Earth Sci.* 24(4): 111-116.

NISSENBAUM, A. and SWAINE, D.J. 1976. Organic matter-metal interactions in recent sediments : the role of humic substances. *Geochim. Cosmochim. Acta* 40: 809-816.

NRIO 1982. The geology of False Bay, with special emphasis on modern sediments. *CSIR Report C/SEA* 8253, 44 pp.

NRIO, 1983. Status report on pollution in False Bay;chemical and biological aspects. *CSIR Report C/SEA* 8362, 59 pp.

PARKER, J.G. 1982. Structure and chemistry of sediments in Belfast Lough, a semi-enclosed marine bay. *Estuarine, Coastal and Shelf Science* 15: 373-384.

PRESLEY, B.J., KOLODNY, Y., NISSENBAUM, A. and KAPLAN, I.R. 1972. Early diagnesis in a reducing fjord Saanich, Inlet, British Columbia. II Trace element distribution in interstitial water and sediment. *Geochim. Cosmochim. Acta* 36: 1073-1090.

ROBERTS, A.A., PADACAS, J.G. and FROST, I.C. 1973. Determination of organic carbon in modern carbonate sediments. *J. Sed. Petrol.* 43: 1157-1159.

SHIMP, N.F., SCHLEICHER, J.A., RUCH, R.R., HECK, D.B. and LELAND, H.V. 1971. Trace element and organic carbon accumulation in the most recent sediments of southern Lake Michigan. *Illinois Geological Survey Environmental Geology Geology* Note 41, 25 pp.

TESSIER, A., CAMPBELL, P.G.C. and BISSON, M. 1979. Sequential extraction procedure for the speciation of particulate trace metals. *Anal. Chem.* 51(7): 844-851.

TSCHAPEK, M. and MASOWSKI, C. 1976. The surface activity of humic acid. *Geochim. Cosmochim. Acta* 40: 1343-1345.

VAN VALIN, R. and MORSE, J.W. 1982. An investigation of methods commonly used for the selective removal and characterization of trace metals in sediments. *Marine Chemistry* 11, 535-564.

WARD, T.J. and YOUNG, P.C. 1981. Trace metal contamination of shallow marine sediments near a lead smelter, Spencer Gulf, South Australia. *Aust. J. Mar. Freshwater Res.* 32: 45-56.

WATLING, H.R. and WATLING, R.J. 1977. Metal concentration in surface sediments from the Knysna estuary. *CSIR Special Report, FIS* 122 p. Pretoria.

WRIGHT, P.L. 1974. The chemistry and mineralogy of the clay fraction of sediments from the Southern Barents Sea. *Chem. Geol.* 13: 197-216.

TABLE 5: Analysis of clay minerals and clay size fraction of False Bay sediments

Sample no.	Clay size fraction (percent)	Clay minerals
54	1,5	illite, chlorite, kaolinite + chlorite
65	5,0	illite, chlorite, kaolinite + chlorite
66	3,2	illite, chlorite, kaolinite + chlorite
67	1,3	illite, chlorite, kaolinite + chlorite
68	3,0	illite, chlorite, kaolinite + chlorite
70	3,5	illite, chlorite, kaolinite + chlorite
79	2,3	illite, chlorite, kaolinite + chlorite
84	1,5	illite, chlorite, kaolinite + chlorite

TABLE 6 : Total Carbon and Organic matter content of sediment samples from False Bay

Station No.	Organic-matter (%)	Total Carbon (%)
2	1,15	7,09
3	1,41	5,66
4	1,48	3,56
5	0,79	2,14
6	0,32	0,71
7	1,07	2,89
8	0,31	0,15
9	1,78	6,23
10	0,36	0,60
11	1,73	6,14
12	2,28	6,56
13	1,26	4,32
14	1,77	5,32
15	1,86	6,18
16	0,86	2,73
17	0,79	2,16
18	0,59	4,99
19	1,10	3,57
20	1,59	5,31
21	1,33	4,21
23	1,54	4,69
24	1,58	5,40
25	1,36	5,24
26	2,22	7,14
27	0,58	3,95
28	1,44	
29	1,65	5,67
30	1,13	4,53
31	0,88	5,72
33	0,18	0,18
34	1,58	9,23
35	1,41	6,01
37	1,60	6,33
38	1,75	6,12
39	1,43	5,34

TABLE 6 (cont)

Station No.	Organic-matter (%)	Total Carbon (%)
40	2,54	9,55
41	2,59	9,70
43	2,20	7,38
46	1,80	8,79
47	1,39	4,38
49	2,27	9,25
50	1,92	8,45
51	2,15	8,56
52	2,07	8,55
53	0,66	4,69
54	2,02	7,11
55	1,58	6,23
58	1,40	9,06
65	6,95	5,51
66	3,75	8,22
67	2,14	6,42
68	2,76	6,72
69	2,02	4,56
70	4,07	6,40
71	1,46	5,25
72	0,81	4,50
79	2,93	8,48
80	1,00	6,28
81	0,72	1,71
82	2,34	4,36
83	1,30	4,18
84	2,28	4,07
85	0,71	1,69

TABLE 7 : Total heavy metal content of False Bay sediments, from analysis with nitric-perchloric acids (µg/g)

Station No.	Cu	Cd	Cr	Fe	Mn	Ni	Pb	Zn	Organic matter (%)
2	0,66	0,17	3,7	448	6,3	0,93	1,83	1,4	1,15
3	1,69	0,18	7,1	942	4,0	2,06	3,04	3,0	1,41
4	0,78	0,14	7,8	766	3,0	0,73	3,64	3,1	1,48
5	0,73	0,15	7,8	256	2,9	0,71	1,15	1,3	0,79
6	0,77	0,13	57,8	274	3,7	1,38	0,87	0,7	0,32
7	0,62	0,15	8,8	252	3,2	0,74	1,31	1,1	1,07
8	0,57	0,13	57,2	365	3,4	0,58	0,65	0,4	0,31
9	0,58	0,11	27,9	367	5,9	1,22	3,92	1,3	1,78
10	1,03	0,14	53,8	528	5,0	1,48	1,20	0,8	0,36
11	1,04	0,13	24,6	485	6,1	0,80	2,33	1,2	1,73
12	0,91	0,11	25,6	379	5,6	0,62	1,72	1,2	2,28
13	0,88	0,20	16,8	343	6,0	0,78	2,04	1,1	1,26
14	0,92	0,11	14,6	430	5,1	0,71	1,99	1,0	1,77
15	0,81	0,21	13,5	266	5,5	1,06	0,92	1,1	1,86
16	0,88	0,19	21,6	333	4,7	0,96	0,53	0,8	0,86
17	0,78	0,15	19,2	301	3,4	1,29	0,42	0,8	0,79
18	0,76	0,20	16,5	422	4,8	1,11	1,53	1,1	1,59
19	1,17	0,20	26,3	326	6,0	0,74	1,47	1,2	1,10
20	0,78	0,21	19,3	375	5,2	1,13	3,10	1,0	1,59
21	0,84	0,18	17,9	376	5,6	0,70	0,97	1,2	1,33
23	0,59	0,13	9,3	418	3,9	0,71	2,27	1,4	1,56
24	0,87	0,19	6,2	446	4,5	0,78	2,20	1,5	1,58
25	0,67	0,15	14,9	643	5,2	1,00	0,76	1,6	1,36
26	0,74	0,11	9,8	431	4,3	0,92	1,13	1,6	2,22
27	0,56	0,12	7,8	306	2,9	1,02	1,19	0,9	0,58
28	0,63	0,14	17,2	522	5,4	0,60	1,02	1,6	1,44
29	0,55	0,10	5,0	536	5,3	0,54	1,97	1,3	1,65
30	0,78	0,10	12,3	652	6,7	0,79	2,40	1,5	1,13
31	0,31	0,12	7,3	1016	4,7	0,49	0,93	1,4	0,88
33	0,56	0,14	27,3	1033	1,9	0,90	1,35	1,6	0,18
34	0,77	0,12	8,7	789	1,7	0,92	3,79	1,8	1,58
35	0,56	0,13	11,8	548	4,7	0,88	2,42	0,9	1,41
37	0,59	0,11	11,7	465	5,0	0,91	1,58	1,8	1,60
38	0,44	0,13	14,4	459	5,3	0,73	1,49	1,4	1,75
39	0,41	0,14	12,8	509	4,7	0,64	1,72	1,5	1,43
40	0,61	0,18	12,1	287	7,8	0,78	2,53	1,9	2,54

TABLE 7 (cont.)

Station No.	Cu	Cd	Cr	Fe	Mn	Ni	Pb	Zn	Organic matter (%)
41	0,78	0,19	5,3	453	14,7	0,98	0,96	1,5	2,59
43	0,81	0,14	26,7	1247	14,0	0,91	1,22	3,0	2,20
46	0,57	0,19	8,4	2189	14,4	0,91	4,33	2,8	1,80
47	0,60	0,15	12,7	1683	24,2	0,93	4,63	2,4	1,39
49	0,56	0,13	9,2	877	9,5	0,63	1,61	2,5	2,27
50	0,76	0,13	11,1	922	6,4	0,43	2,32	1,6	1,92
51	0,61	0,17	7,4	705	7,7	0,77	1,22	1,8	2,15
52	0,65	0,14	16,0	687	9,7	0,81	1,59	1,8	2,07
53	0,31	0,19	11,6	2004	12,8	0,38	1,87	2,0	0,66
54	1,14	0,21	17,2	2908	12,8	1,43	2,26	5,5	2,02
55	0,87	0,12	31,7	2871	14,5	1,22	2,05	3,8	1,58
58	0,59	0,12	11,3	480	6,5	1,00	0,87	1,1	1,40
65	4,13	0,41	29,6	4330	13,5	7,83	2,85	12,7	6,95
66	2,01	0,17	22,3	2109	9,7	3,17	1,89	6,0	3,75
67	1,46	0,10	29,0	3520	14,8	2,75	1,50	5,4	2,14
68	1,34	0,12	34,7	4121	23,1	2,23	2,40	6,6	2,76
69	1,08	0,39	24,6	1118	6,8	2,72	1,76	1,8	2,02
70	2,42	0,62	84,4	2360	11,3	4,47	1,64	6,4	4,07
71	1,24	0,20	28,7	1044	6,6	1,51	1,59	3,0	1,46
72	0,52	0,17	5,2	860	4,4	0,79	1,31	1,9	0,81
79	1,81	0,15	17,2	1422	6,5	2,72	1,13	4,6	2,93
80	0,51	0,20	7,3	752	4,4	0,43	0,61	1,8	1,00
81	0,56	0,18	17,9	491	2,6	1,15	0,51	1,2	0,72
82	0,97	0,37	21,1	484	6,6	2,30	2,25	3,4	2,34
83	0,67	0,29	15,8	824	4,9	1,00	1,57	1,9	1,30
84	0,89	0,29	16,8	965	6,2	2,15	1,51	3,1	2,28
85	0,58	0,13	12,0	257	1,7	1,07	1,01	1,1	0,71

TABLE 8 : Sediment Characteristics - particle size parameters

Station No.	Mean Diameter Φ	Mean Diameter µm	Skewness	Kurtosis
2	0,86	551	-0,33	2,68
3	0,42	747	0,11	2,89
4	1,27	225	-0,24	1,66
5	1,87	241	-0,09	2,17
6	0,45	732	0,73	4,42
7	1,61	210	-0,50	2,14
8	1,17	444	0,16	2,87
9	2,93	131	-2,57	13,62
10	1,60	330	-0,29	3,42
11	2,97	128	-1,87	18,79
12	2,94	130	-2,34	13,07
13	2,80	144	-1,74	5,76
14	2,92	132	-2,47	11,86
15	3,09	117	-1,78	15,21
16	2,25	139	-0,31	2,48
17	2,43	186	-0,83	3,92
18	2,82	142	-2,42	9,57
19	2,78	146	-1,23	3,54
20	-	-	-	-
21	2,91	133	-1,82	7,35
23	-	-	-	-
24	2,89	135	-0,79	4,08
25	2,93	131	-2,54	10,29
26	-	-	-	-
27	-	-	-	-
28	-	-	-	-
29	2,82	142	-2,24	9,21
30	2,77	147	-1,91	6,56
31	1,53	346	-0,11	3,86
33	0,55	683	1,37	5,59
34	0,40	758	-0,15	2,71
35	2,85	139	-2,43	11,95
37	2,76	148	-2,99	12,69
38	2,90	134	-1,56	13,44
39	2,82	142	-1,60	7,60
40	1,46	363	-0,23	2,42
41	0,75	595	0,58	4,99
43	0,03	732	-0,80	2,71
46	0,46	727	-0,25	2,99
47	0,15	707	-0,31	2,17
49	0,92	529	0,16	2,32
50	2,03	245	0,01	2,91
51	2,22	215	-0,51	3,43
52	2,28	206	-0,61	3,56
53	0,99	503	0,80	3,82
54	2,01	248	0,30	2,93
55	0,47	722	-0,04	3,41
58	1,45	366	-0,26	3,11
65	2,36	195	0,36	2,94
66	2,18	221	0,33	2,17
67	-	-	-	-
68	0,34	790	-0,04	2,96
69	3,04	122	-1,29	5,56
70	2,40	121	-0,45	1,81

TABLE 8 (cont.)

Station No.	Mean Diameter ϕ	µm	Skewness	Kurtosis
71	2,25	210	-0,54	3,10
72	1,20	435	0,22	3,17
79	2,35	159	-0,65	2,84
80	-	-	-	-
81	-	-	-	-
82	-	-	-	-
83	-	-	-	-
84	-	-	-	-
85	-	-	-	-

TABLE 9 : Cadmium content in chemical fractions from False-Bay sediments (µg/g)

Sample No.	Carbonate and easily reducible	Organic and Sulphide	Residual	Total Content
2	0,09	0,04	n.d.	0,17
3	0,08	0,04	n.d.	0,18
4	0,08	0,03	n.d.	0,14
5	0,03	0,09	n.d.	0,15
6	0,05	0,05	n.d.	0,13
7	0,06	0,07	n.d.	0,15
8	0,04	0,04	n.d.	0,13
9	0,08	n.d.	n.d.	0,11
10	0,05	0,05	n.d.	0,14
11	0,05	0,05	n.d.	0,13
12	0,09	n.d.	n.d.	0,11
13	0,07	0,08	0,01	0,20
14	0,04	0,04	n.d.	0,11
15	0,09	0,10	n.d.	0,21
16	0,08	0,08	n.d.	0,19
17	0,06	0,06	n.d.	0,15
18	0,08	0,09	n.d.	0,20
19	0,08	0,08	0,01	0,20
20	0,08	0,08	0,01	0,21
21	0,09	0,05	n.d.	0,18
23	0,07	0,01	n.d.	0,13
24	0,09	0,05	n.d.	0,19
25	0,07	0,04	n.d.	0,15
26	0,08	n.d.	n.d.	0,11
27	0,04	0,04	n.d.	0,12
28	0,09	0,02	n.d.	0,14
29	0,08	n.d.	n.d.	0,10
30	0,08	n.d.	n.d.	0,10
31	0,04	0,04	n.d.	0,12
33	0,04	0,04	0,01	0,14
34	0,08	0,03	n.d.	0,12
35	0,05	0,05	n.d.	0,13
37	0,04	0,04	n.d.	0,11
38	0,05	0,05	n.d.	0,13
39	0,08	0,03	n.d.	0,14
40	0,10	0,03	n.d.	0,18

TABLE 9 (cont.)

Sample No.	Carbonate and easily reducible	Organic and Sulphide	Residual	Total Content
41	0,10	0,03	n.d.	0,19
43	0,08	0,02	n.d.	0,14
46	0,11	0,03	n.d.	0,19
47	0,09	0,01	n.d.	0,15
49	0,08	0,02	n.d.	0,13
50	0,08	0,02	n.d.	0,13
51	0,08	0,04	n.d.	0,17
52	0,05	0,06	n.d.	0,14
53	0,12	0,05	n.d.	0,19
54	0,12	0,07	n.d.	0,21
55	0,07	0,03	n.d.	0,12
58	0,07	0,02	n.d.	0,12
65	0,15	0,22	0,02	0,41
66	0,03	0,12	n.d.	0,17
67	0,03	0,05	n.d.	0,10
68	0,06	0,04	n.d.	0,12
69	0,11	0,20	0,02	0,39
70	0,20	0,30	0,09	0,62
71	0,08	0,09	n.d.	0,20
72	0,08	0,04	n.d.	0,17
79	0,06	0,06	n.d.	0,15
80	0,06	0,09	n.d.	0,20
81	0,04	0,08	n.d.	0,18
82	0,15	0,25	n.d.	0,37
83	0,10	0,12	n.d.	0,29
84	0,10	0,13	n.d.	0,29
85	n.d.	n.d.	n.d.	0,31

n.d. = not detected.

TABLE 10 : Copper content in different fractions of False Bay sediments (µg/g)

Sample No.	Carbonate and easily reducible	Organic and Sulphide	Residual	Total Content
2	0,18	0,34	0,07	0,66
3	0,11	1,60	0,10	1,69
4	0,08	0,70	n.d.	0,78
5	0,08	0,55	n.d.	0,73
6	0,10	0,42	0,08	0,77
7	0,04	0,44	0,03	0,62
8	0,06	0,26	0,08	0,57
9	n.d.	0,69	n.d.	0,58
10	0,36	0,53	0,03	1,03
11	n.d.	1,16	n.d.	1,04
12	0,04	0,71	0,13	0,91
13	0,07	0,65	n.d.	0,88
14	0,04	0,82	n.d.	0,92
15	0,08	0,70	n.d.	0,81
16	0,12	0,67	n.d.	0,88
17	0,03	0,67	n.d.	0,78
18	0,10	0,67	n.d.	0,76
19	0,04	0,79	n.d.	1,17
20	0,04	0,50	n.d.	0,78
21	0,04	0,42	n.d.	0,84
23	0,04	0,55	n.d.	0,59
24	0,04	0,49	n.d.	0,87
25	0,05	0,49	n.d.	0,67
26	0,08	0,80	n.d.	0,74
27	0,07	0,09	n.d.	0,56
28	0,03	0,61	0,07	0,63
29	0,08	0,26	0,14	0,55
30	0,06	0,55	0,09	0,78
31	0,06	0,25	n.d.	0,31
33	0,13	0,13	0,15	0,56
34	0,05	0,73	0,07	0,77
35	0,05	0,44	0,09	0,56
37	0,07	0,38	0,12	0,59
38	0,11	0,30	0,04	0,44
39	0,14	0,30	n.d.	0,41

TABLE 10 (cont.)

Sample No.	Carbonate and easily reducible	Organic and Sulphide	Residual	Total Content
40	0,04	0,50	0,15	0,61
41	0,06	0,55	0,20	0,78
43	0,08	0,38	0,22	0,81
46	0,05	0,35	0,20	0,57
47	0,03	0,35	0,20	0,60
49	n.d.	0,47	0,05	0,56
50	n.d.	0,51	0,20	0,76
51	0,05	0,49	0,10	0,61
52	0,06	0,42	0,10	0,65
53	0,08	0,12	0,10	0,31
54	0,11	0,65	0,38	1,14
55	0,05	0,74	0,10	0,87
58	0,05	0,39	0,10	0,59
65	0,05	4,00	0,16	4,13
66	0,06	2,00	0,15	2,01
67	0,05	1,30	0,05	1,46
68	0,05	1,34	0,05	1,34
69	0,04	1,20	n.d.	1,08
70	0,08	2,43	0,05	2,42
71	0,05	1,00	0,18	1,24
72	0,04	0,12	0,30	0,52
79	0,04	2,00	0,04	1,81
80	0,03	0,57	n.d.	0,51
81	0,07	0,41	n.d.	0,56
82	n.d.	1,47	n.d.	0,97
83	n.d.	0,87	n.d.	0,67
84	n.d.	0,91	n.d.	0,89
85	0,05	0,54	n.d.	0,58

n.d. = not detected

TABLE 11: Chromium Content in difficient fractions of False Bay sediments (µg/g)

Sample No.	Carbonate and easily reducible	Organic and Sulphide	Residual	Total Content
2	0,7	1,8	0,6	3,7
3	0,7	2,7	2,9	7,1
4	1,5	2,7	3,1	7,8
5	1,3	1,6	4,0	7,8
6	7,9	4,8	42,1	57,8
7	1,4	3,7	3,8	8,8
8	6,6	3,4	41,9	57,2
9	2,1	6,5	13,5	27,9
10	4,9	2,0	46,4	53,8
11	2,0	6,5	14,8	24,6
12	1,7	6,8	14,5	25,6
13	3,5	6,0	5,3	16,8
14	2,4	6,1	3,3	14,6
15	2,1	6,9	3,4	13,5
16	4,1	6,9	10,6	21,6
17	2,5	4,1	7,7	19,2
18	2,2	6,7	4,5	16,5
19	2,7	6,9	10,9	26,3
20	2,5	7,0	9,9	19,3
21	2,2	4,5	6,8	17,9
23	1,5	4,4	1,7	9,3
24	1,2	4,3	1,4	6,2
25	1,4	7,9	2,9	14,9
26	0,9	7,8	3,4	9,8
27	0,8	2,9	3,9	7,8
28	1,2	7,3	5,3	17,2
29	1,8	2,9	0,6	5,0
30	1,8	6,3	6,5	12,3
31	0,9	2,1	3,8	7,3
33	6,4	6,1	20,2	27,3
34	0,4	6,5	3,3	8,7
35	1,7	4,9	4,1	11,8
37	1,4	4,7	4,1	11,7
38	1,8	7,1	4,7	14,4
39	1,9	5,4	4,0	12,8
40	0,4	6,4	8,8	12,1
41	0,2	6,9	0,8	5,3

TABLE 11(cont.)

Sample No.	Carbonate and easily reducible	Organic and Sulphide	Residual	Total Content
43	0,6	7,5	14,5	26,7
46	0,2	4,1	8,6	8,4
47	0,4	5,1	7,5	12,7
49	0,3	5,2	3,9	9,2
50	0,6	5,6	4,3	11,1
51	0,3	4,8	4,5	7,4
52	0,4	6,5	9,8	16,0
53	0,7	1,3	12,2	11,6
54	0,6	7,2	9,6	17,2
55	0,9	7,0	22,1	31,7
58	0,3	2,5	10,3	11,3
65	2,9	14,4	11,1	29,6
66	1,6	15,6	6,1	22,3
67	0,9	11,7	14,7	29,0
68	0,7	30,3	1,3	34,7
69	1,6	14,7	10,2	24,6
70	0,9	34,0	47,9	84,4
71	0,8	9,2	18,9	28,7
72	0,3	1,2	5,0	5,2
79	0,5	7,1	8,1	17,2
80	0,4	6,3	2,0	7,3
81	1,1	6,4	8,9	17,9
82	1,4	14,0	5,2	21,1
83	0,9	12,5	2,5	15,8
84	1,4	12,9	1,8	16,8
85	1,4	8,4	2,1	12,0

TABLE 12 : Iron content in different fractions of False Bay sediments (µg/g)

Sample No.	Carbonate and easily reducible	Organic and Sulphide	Residual	Total Content
2	31	129	285	448
3	41	827	177	942
4	21	373	85	766
5	15	13	250	256
6	121	13	71	274
7	19	10	226	252
8	92	14	205	365
9	82	38	282	367
10	30	101	388	528
11	97	18	345	485
12	105	31	195	379
13	77	265	53	343
14	88	401	103	430
15	88	241	103	266
16	29	249	51	333
17	28	177	151	301
18	74	320	56	422
19	42	275	19	326
20	91	254	50	375
21	50	31	236	376
23	63	328	52	418
24	72	318	52	446
25	65	351	201	643
26	101	274	66	431
27	80	17	166	306
28	151	320	81	522
29	97	19	401	536
30	87	13	503	652
31	84	17	857	1016
33	146	31	767	1033
34	66	18	683	789
35	196	21	275	548
37	123	9	327	465
38	145	12	298	459
39	120	15	353	509
40	101	26	150	287

TABLE 12 (cont.)

Sample No.	Carbonate and easily reducible	Organic and Sulphide	Residual	Total Content
41	75	23	350	453
43	402	24	830	1247
46	18	22	2150	2189
47	16	16	1590	1683
49	127	18	729	877
50	116	13	794	922
51	12	29	660	705
52	341	28	312	687
53	146	13	1821	2004
54	196	25	2472	2908
55	161	1161	2200	2871
58	60	26	374	480
65	37	2020	2329	4330
66	82	995	1011	2109
67	27	1341	2202	3520
68	92	2693	1501	4121
69	19	730	310	1118
70	86	463	1602	2360
71	27	230	712	1044
72	12	29	805	860
79	50	970	421	1422
80	15	731	52	752
81	18	307	156	491
82	14	288	170	484
83	25	765	45	824
84	21	595	321	965
85	29	263	71	257

TABLE 13 : Manganese content in different fraction of False Bay sediments (µg/g)

Sample No.	Carbonate and easily reducible	Organic and Sulphide	Residual	Total Content
2	1,4	1,6	0,4	6,3
3	1,1	2,5	0,3	4,0
4	1,1	1,4	0,6	3,0
5	1,0	0,6	1,0	2,9
6	0,8	0,7	1,0	3,7
7	1,3	0,7	0,5	3,2
8	0,7	0,4	1,5	3,4
9	1,6	1,1	2,1	5,9
10	1,3	0,6	1,6	5,0
11	1,5	1,5	2,7	6,1
12	1,5	1,7	2,5	5,6
13	1,7	1,5	2,9	6,0
14	1,6	1,4	1,6	5,1
15	1,9	1,4	1,8	5,5
16	1,7	0,8	2,3	4,7
17	1,3	0,5	1,2	3,4
18	1,7	1,4	0,8	4,8
19	1,8	1,5	1,5	6,0
20	1,7	1,4	1,8	5,2
21	1,6	1,5	2,0	5,6
23	1,5	1,8	0,5	3,9
24	1,6	1,8	0,6	4,5
25	1,6	1,8	0,9	5,2
26	1,3	2,0	0,4	4,3
27	1,1	0,1	0,9	2,9
28	1,6	2,6	0,8	5,4
29	1,7	1,3	2,0	5,3
30	1,7	3,2	1,2	6,7
31	1,8	0,2	2,0	4,7
33	0,7	0,3	0,6	1,9
34	0,7	0,5	0,2	1,7
35	1,7	0,5	1,5	4,7
37	1,5	1,3	3,1	5,0
38	1,6	1,3	2,0	5,3
39	2,6	1,3	1,2	4,7

TABLE 13 (cont.)

Sample No.	Carbonate and easily reducible	Organic and Sulphide	Residual	Total Content
40	1,3	1,6	5,2	7,8
41	2,3	1,6	10,7	14,7
43	3,0	1,9	9,1	14,0
46	2,7	1,2	10,9	14,4
47	18,3	0,9	5,2	24,2
49	1,1	0,6	8,6	9,5
50	1,2	1,0	4,3	6,4
51	1,1	1,5	5,1	7,7
52	1,2	1,5	5,3	9,7
53	9,2	0,5	2,5	12,8
54	1,7	5,2	6,3	12,8
55	1,7	5,8	6,5	14,5
58	1,5	1,5	3,1	6,5
65	1,9	11,3	1,5	13,5
66	1,7	4,4	3,5	9,7
67	1,4	10,6	2,1	14,8
68	2,3	17,9	2,7	23,1
69	1,5	3,4	1,2	6,8
70	1,3	7,6	2,6	11,3
71	1,6	1,0	3,6	6,6
72	1,4	0,1	2,7	4,4
79	0,9	4,1	1,2	6,5
80	1,2	2,1	1,1	4,4
81	0,8	0,8	0,8	2,6
82	1,6	3,5	1,1	6,6
83	1,7	1,6	1,0	4,9
84	1,5	3,2	1,5	6,2
85	0,7	1,5	0,5	1,7

TABLE 14 : Nickel content in different fractions of False Bay sediments (µg/g)

Sample No.	Carbonate and easily reducible	Organic and Sulphide	Residual	Total Content
2	0,06	0,67	0,22	0,93
3	0,06	1,65	0,21	2,06
4	0,05	0,53	0,20	0,73
5	0,07	0,42	0,51	0,71
6	0,06	0,72	0,28	1,38
7	0,10	0,36	0,17	0,74
8	0,09	0,12	0,31	0,58
9	0,10	0,60	0,35	1,22
10	0,14	0,87	0,15	1,48
11	0,07	0,70	0,36	0,80
12	0,05	0,50	0,12	0,62
13	0,09	0,52	0,10	0,78
14	0,06	0,67	0,20	0,71
15	0,03	1,03	0,10	1,06
16	0,08	0,47	0,25	0,96
17	0,07	0,72	0,55	1,29
18	0,02	0,69	0,35	1,11
19	0,07	0,51	0,18	0,74
20	0,02	0,71	0,22	1,13
21	0,03	0,54	0,13	0,70
23	0,07	0,70	0,13	0,71
24	0,03	0,72	0,10	0,78
25	0,02	0,70	0,24	1,00
26	0,01	0,79	0,22	0,92
27	0,01	0,68	0,42	1,02
28	0,03	0,32	0,29	0,60
29	0,03	0,23	0,32	0,54
30	0,03	0,68	0,10	0,79
31	0,01	0,37	0,17	0,49
33	0,18	0,37	0,25	0,90
34	0,03	0,30	0,56	0,92
35	0,02	0,57	0,25	0,88
37	0,02	0,54	0,29	0,91
38	0,03	0,48	0,25	0,73
39	0,02	0,35	0,21	0,64

TABLE 14(cont.)

Sample No.	Carbonate and easily reducible	Organic and Sulphide	Residual	Total Content
40	0,01	0,22	0,58	0,78
41	0,06	0,24	0,60	0,98
43	0,08	0,26	0,54	0,91
46	0,07	0,31	0,52	0,91
47	0,10	0,22	0,60	0,93
49	0,02	0,19	0,40	0,63
50	0,03	0,14	0,35	0,43
51	0,03	0,33	0,40	0,77
52	0,01	0,38	0,42	0,81
53	0,10	0,28	0,12	0,38
54	0,07	0,65	0,73	1,43
55	0,10	1,01	0,29	1,22
58	0,01	0,49	0,49	1,00
65	1,00	5,76	0,69	7,83
66	0,25	2,16	0,86	3,17
67	0,13	2,41	0,37	2,75
68	0,10	1,78	0,35	2,23
69	0,08	2,11	0,23	2,72
70	0,19	3,95	0,69	4,47
71	0,13	1,40	0,18	1,51
72	0,03	0,33	0,31	0,79
79	0,19	2,21	0,43	2,72
80	0,01	0,42	0,13	0,43
81	0,15	0,62	0,18	1,15
82	0,18	2,09	0,31	2,30
83	0,12	0,95	0,17	1,00
84	0,18	1,80	0,16	2,15
85	0,13	0,70	0,30	1,07

TABLE 15 : Lead content in different fractions from False Bay sediments (µg/g).

Sample No.	Carbonate and easily reducible	Organic and Sulphide	Residual	Total Content
2	0,45	0,09	1,13	1,83
3	1,23	0,12	1,53	3,04
4	1,50	0,11	1,40	3,64
5	0,60	0,04	0,41	1,15
6	0,48	0,16	0,16	0,87
7	0,32	0,26	0,48	1,31
8	0,11	0,09	0,10	0,65
9	1,06	0,30	1,68	3,92
10	0,45	0,15	0,65	1,20
11	0,68	0,16	0,96	2,33
12	0,78	0,18	0,48	1,72
13	0,36	0,93	0,57	2,04
14	0,39	0,74	0,60	1,99
15	0,15	0,30	0,26	0,92
16	0,11	0,18	0,16	0,53
17	0,10	0,12	0,14	0,42
18	0,24	0,52	0,58	1,53
19	0,33	0,66	0,39	1,47
20	0,65	1,30	0,90	3,10
21	0,30	0,04	0,56	0,97
23	0,50	0,80	0,58	2,27
24	0,60	0,60	0,70	2,20
25	0,17	0,23	0,12	0,76
26	0,31	0,44	0,45	1,13
27	0,36	0,24	0,40	1,19
28	0,46	0,07	0,53	1,02
29	0,52	0,08	1,20	1,97
30	0,96	0,12	1,01	2,40
31	0,26	0,06	0,52	0,93
33	0,43	0,13	0,73	1,35
34	0,98	0,45	1,78	3,79
35	0,84	0,75	0,54	2,42
37	0,55	0,05	0,49	1,58
38	0,69	0,15	0,57	1,49
39	0,51	0,13	0,91	1,72
40	0,56	0,22	1,63	2,53

TABLE 15 (cont.)

Sample No.	Carbonate and easily reducible	Organic and Sulphide	Residual	Total Content
41	0,39	0,06	0,43	0,96
43	0,33	0,03	0,79	1,22
46	1,19	0,34	2,48	4,33
47	1,08	0,15	2,48	4,63
49	0,46	0,07	0,76	1,61
50	0,78	0,11	1,26	2,32
51	0,23	0,21	0,73	1,22
52	0,28	0,08	0,81	1,59
53	0,54	0,10	0,82	1,87
54	0,68	0,06	1,11	2,26
55	1,03	0,09	0,79	2,05
58	0,15	0,10	0,55	0,87
65	0,69	0,77	0,83	2,85
66	0,46	0,66	0,34	1,89
67	0,35	0,54	0,49	1,50
68	0,45	1,02	0,71	2,40
69	0,30	0,68	0,71	1,76
70	0,45	0,40	0,43	1,64
71	0,15	0,06	0,20	0,45
72	0,33	0,09	0,63	1,31
79	0,19	0,43	0,32	1,13
80	0,12	0,36	0,18	0,61
81	0,15	0,16	0,15	0,51
82	0,94	1,08	0,46	2,25
83	0,33	0,53	0,73	1,57
84	0,39	0,50	0,37	1,51
85	0,21	0,35	0,55	1,01

TABLE 16 : Zinc content in different fractions from False Bay sediments (µg/g)

Sample No.	Carbonate and easily reducible	Organic and Sulphide	Residual	Total Content
2	0,7	0,6	0,5	1,4
3	0,8	0,3	2,0	3,0
4	1,0	0,9	1,5	3,1
5	0,5	1,1	0,2	1,3
6	0,2	0,5	0,4	0,7
7	0,5	0,5	0,3	1,1
8	n.d.	0,5	n.d.	0,4
9	0,2	0,8	0,4	1,3
10	0,4	0,5	0,3	0,8
11	0,3	0,6	0,4	1,2
12	0,4	0,6	0,4	1,2
13	0,3	0,8	0,3	1,1
14	0,3	0,6	0,3	1,0
15	0,3	0,6	0,4	1,1
16	0,3	0,6	0,3	0,8
17	0,4	0,5	0,1	0,8
18	0,3	0,6	0,4	1,1
19	0,4	0,3	0,3	1,2
20	0,4	0,4	0,3	1,0
21	0,4	0,5	0,5	1,2
23	0,2	0,9	0,3	1,4
24	0,2	0,5	0,4	1,5
25	0,3	0,7	0,2	1,6
26	0,5	1,0	0,3	1,6
27	0,3	0,2	0,3	0,9
28	1,2	0,3	0,3	1,6
29	0,4	0,4	0,7	1,3
30	0,3	0,5	0,7	1,5
31	0,2	0,5	0,5	1,4
33	0,5	0,6	0,6	1,6
34	0,3	0,9	1,0	1,8
35	n.d.	0,8	0,2	0,9
37	0,6	0,5	0,4	1,8
38	0,3	0,5	0,2	1,4
39	0,3	0,5	0,2	1,5
40	0,2	0,9	1,2	1,9

TABLE 16(cont.)

Sample No.	Carbonate and easily reducible	Organic and Sulphide	Residual	Total Content
41	n.d.	1,0	0,7	1,5
43	0,7	0,6	1,5	3,0
46	0,3	1,0	1,9	2,8
47	0,2	0,4	1,6	2,4
49	1,2	0,3	0,9	2,5
50	0,4	0,5	0,7	1,6
51	0,3	0,7	1,2	1,8
52	0,4	0,7	1,0	1,8
53	0,7	0,2	0,9	2,0
54	1,2	0,9	3,1	5,5
55	0,8	1,0	1,3	3,8
58	0,3	0,1	0,6	1,1
65	2,1	9,5	0,2	12,7
66	0,5	4,0	1,9	6,0
67	0,9	3,8	0,5	5,4
68	0,7	5,1	0,9	6,6
69	0,5	1,4	0,1	1,8
70	0,9	4,1	1,1	6,4
71	0,4	0,9	1,3	3,0
72	0,5	0,2	0,5	1,9
79	1,0	3,0	1,1	4,6
80	0,4	1,2	0,4	1,8
81	0,3	0,5	0,2	1,2
82	0,5	2,0	0,8	3,4
83	0,6	1,2	0,4	1,9
84	0,5	1,7	0,5	3,1
85	0,1	1,0	0,3	1,1

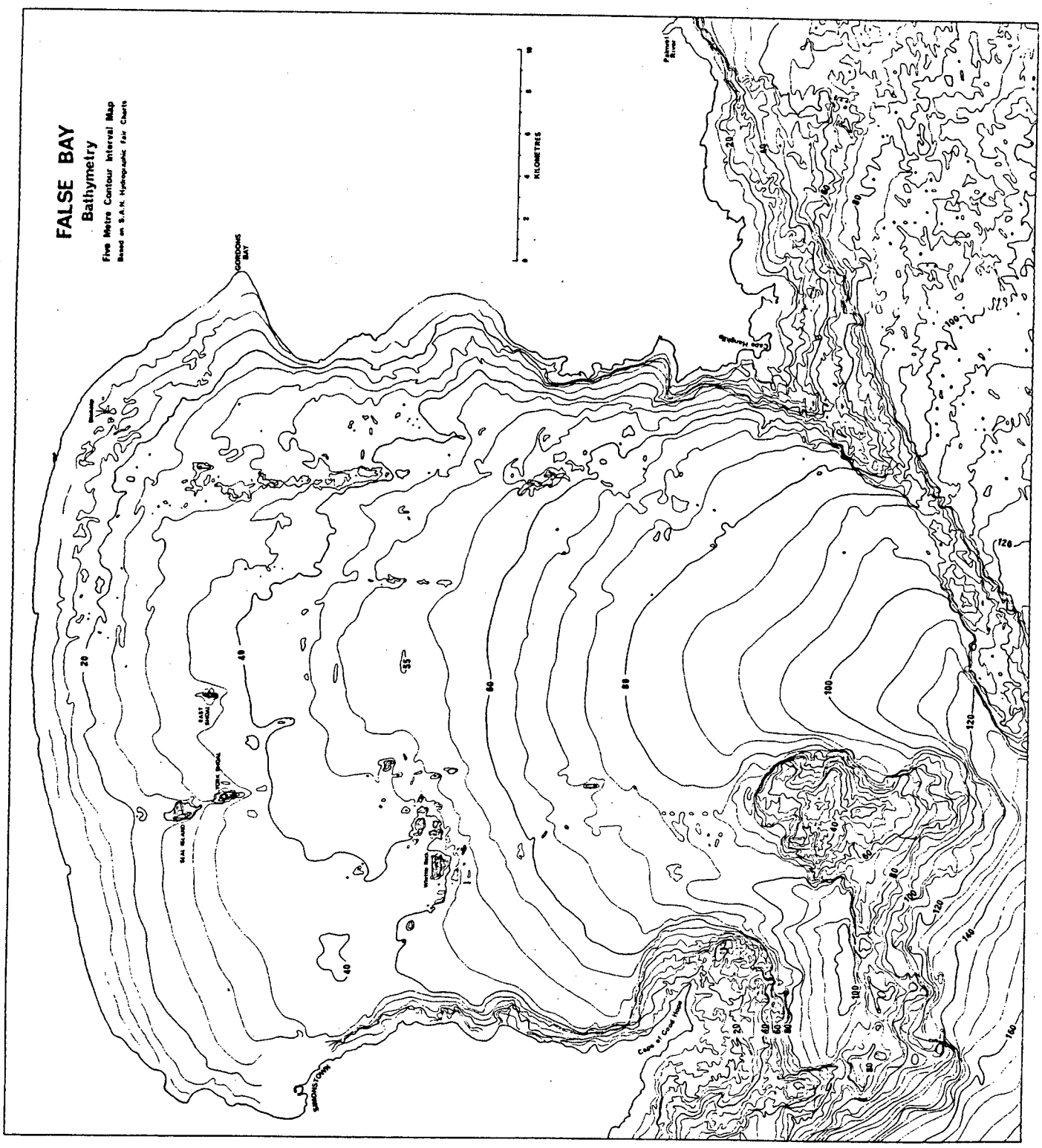


Fig. 1. Bathymetry of False Bay (5 m contour interval) (From Glass, 1976)

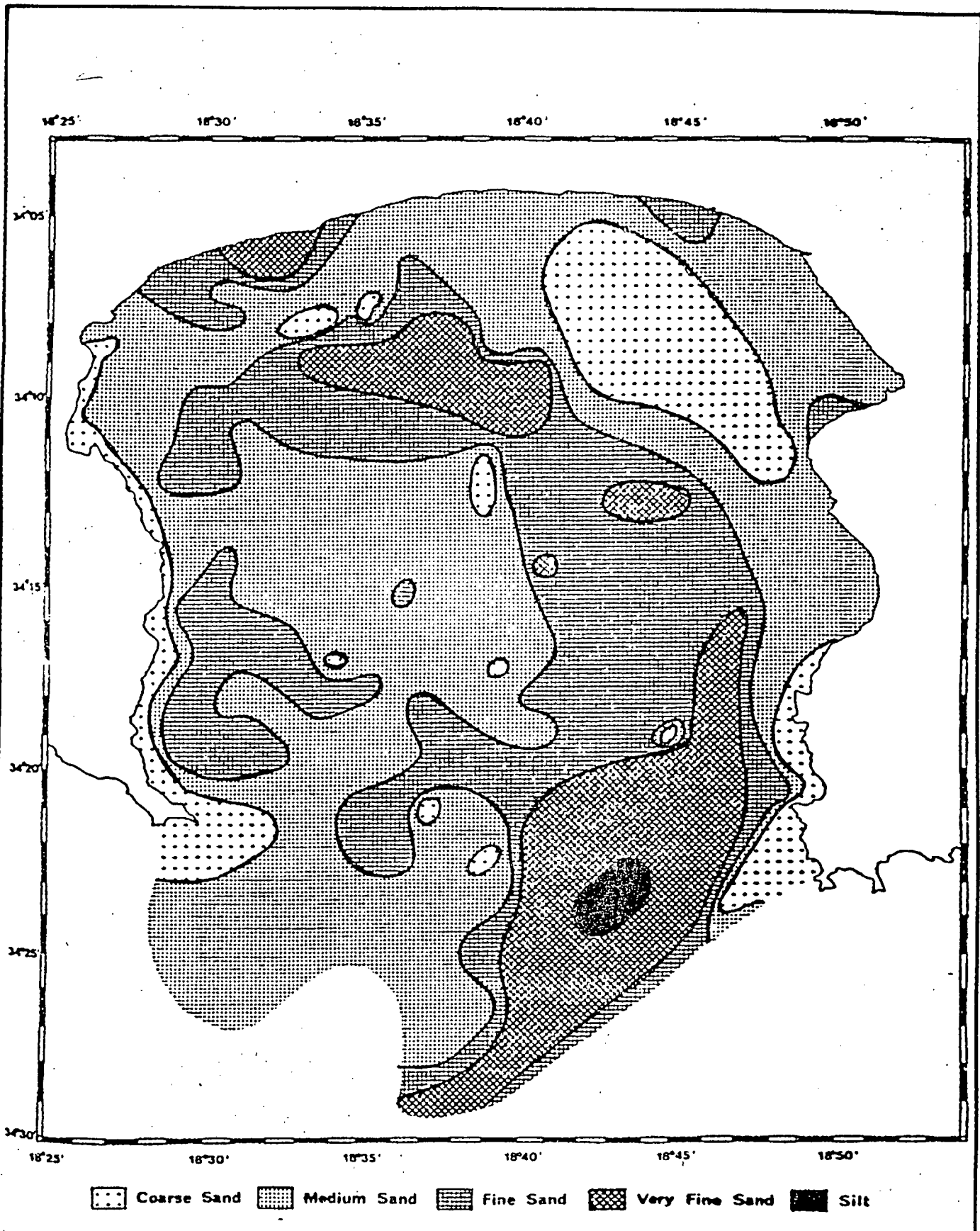


Fig. 2. The distribution of mean grain size diameters of the sand fraction (From NRIO, 1982)

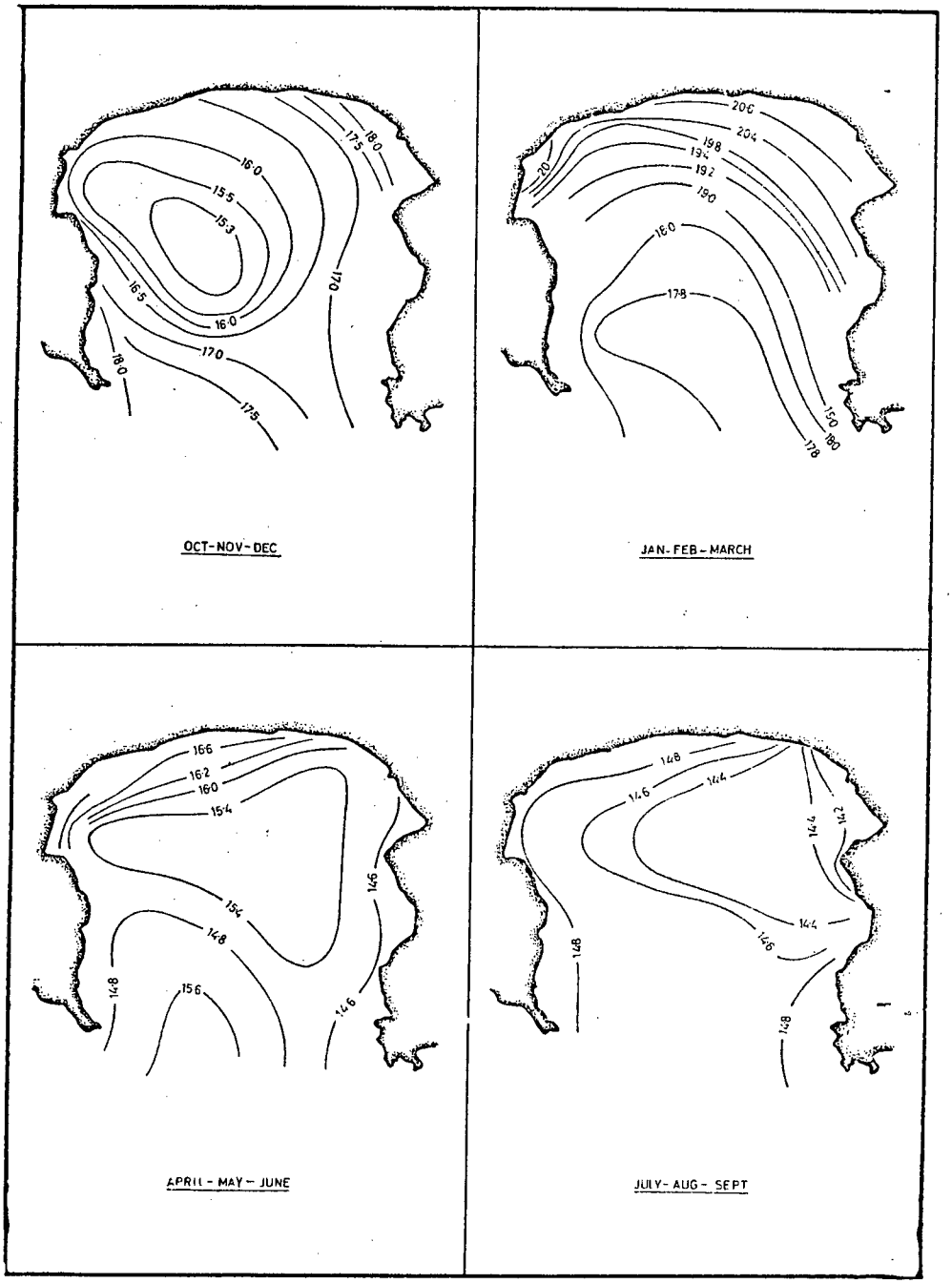


Fig. 3. Surface isotherms - False Bay. Degrees Centigrade (Atkins, 1970)

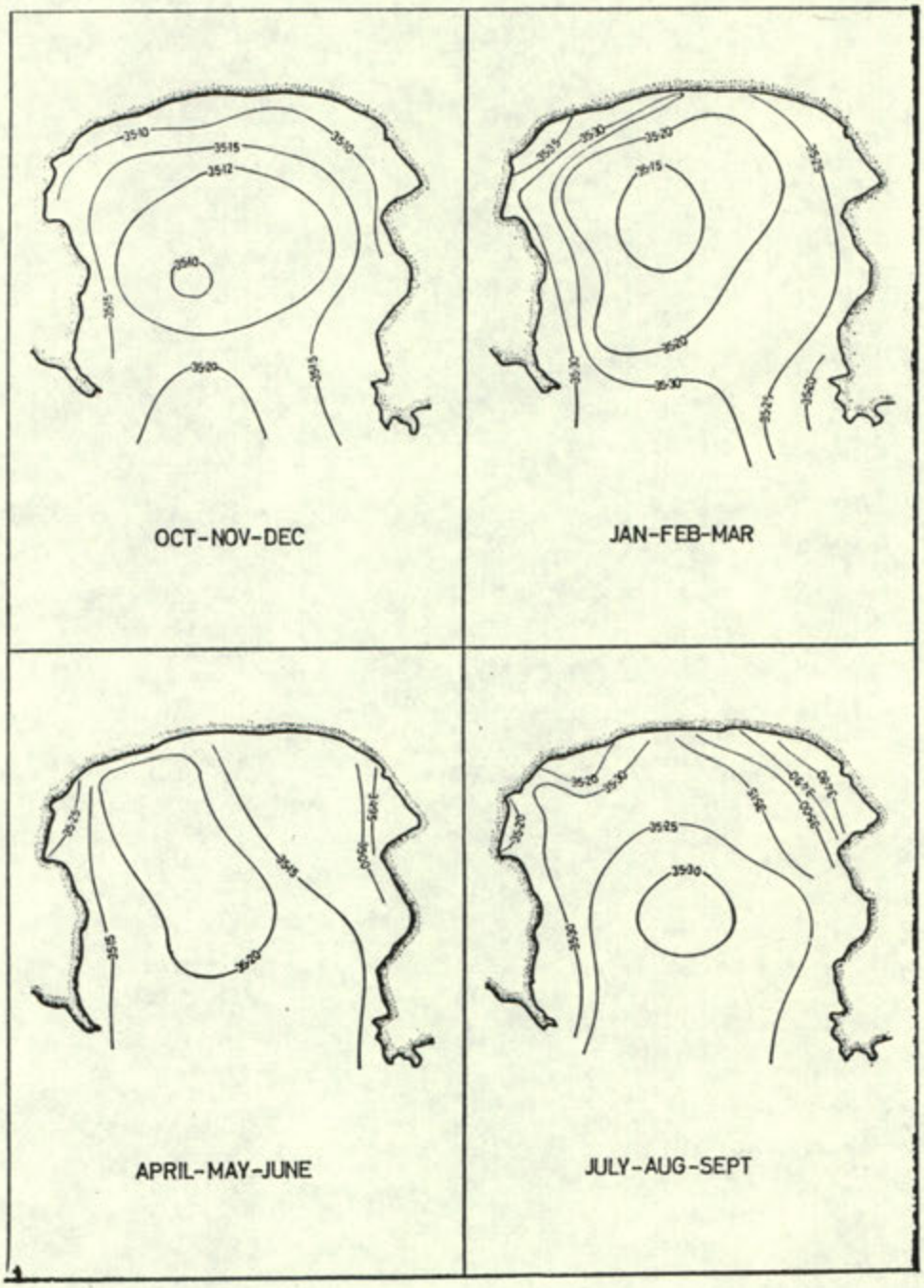


Fig. 4. Isohalines - False Bay. Salinity °/oo surface (Atkins, 1970)

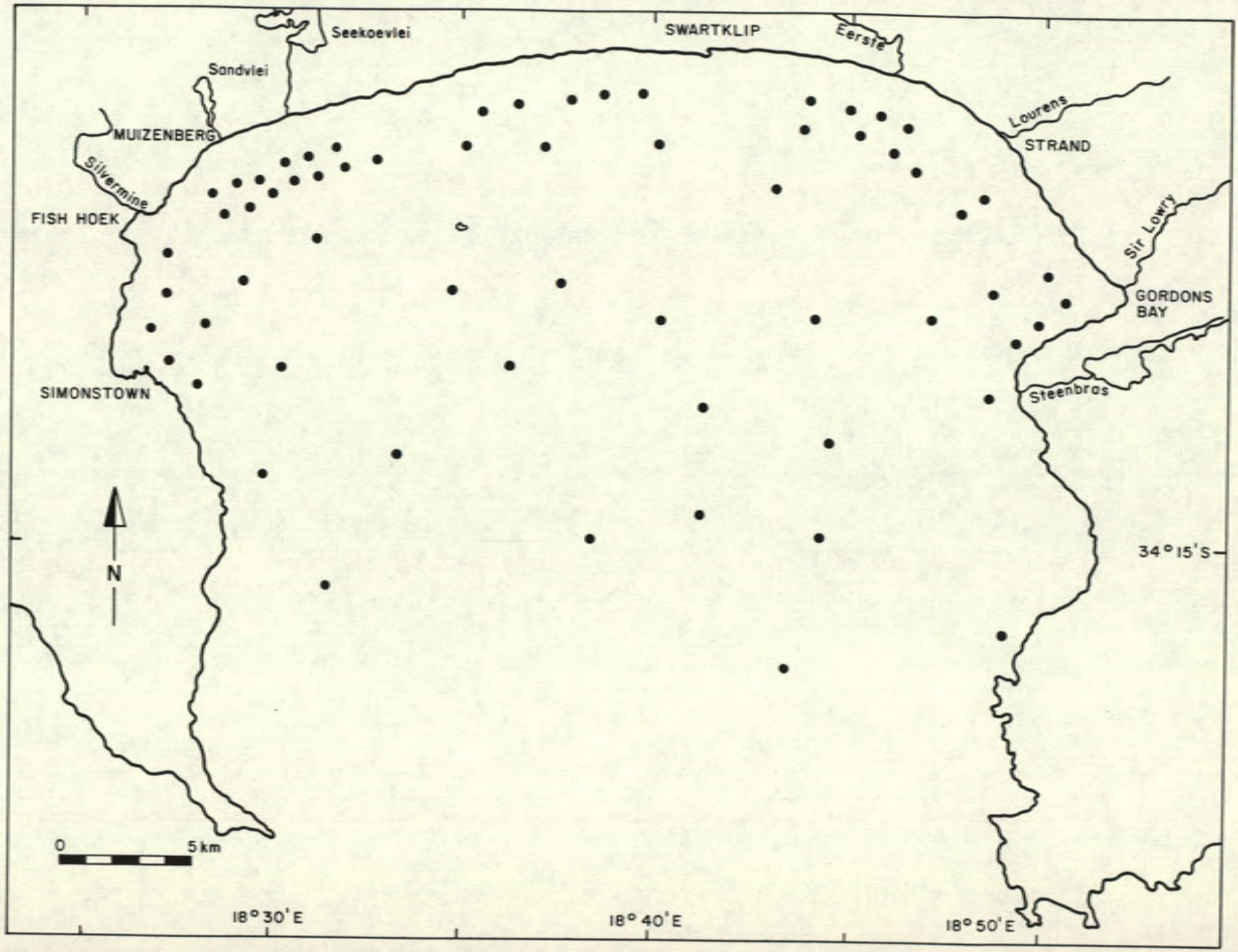


Fig. 5. Rivers entering into False Bay

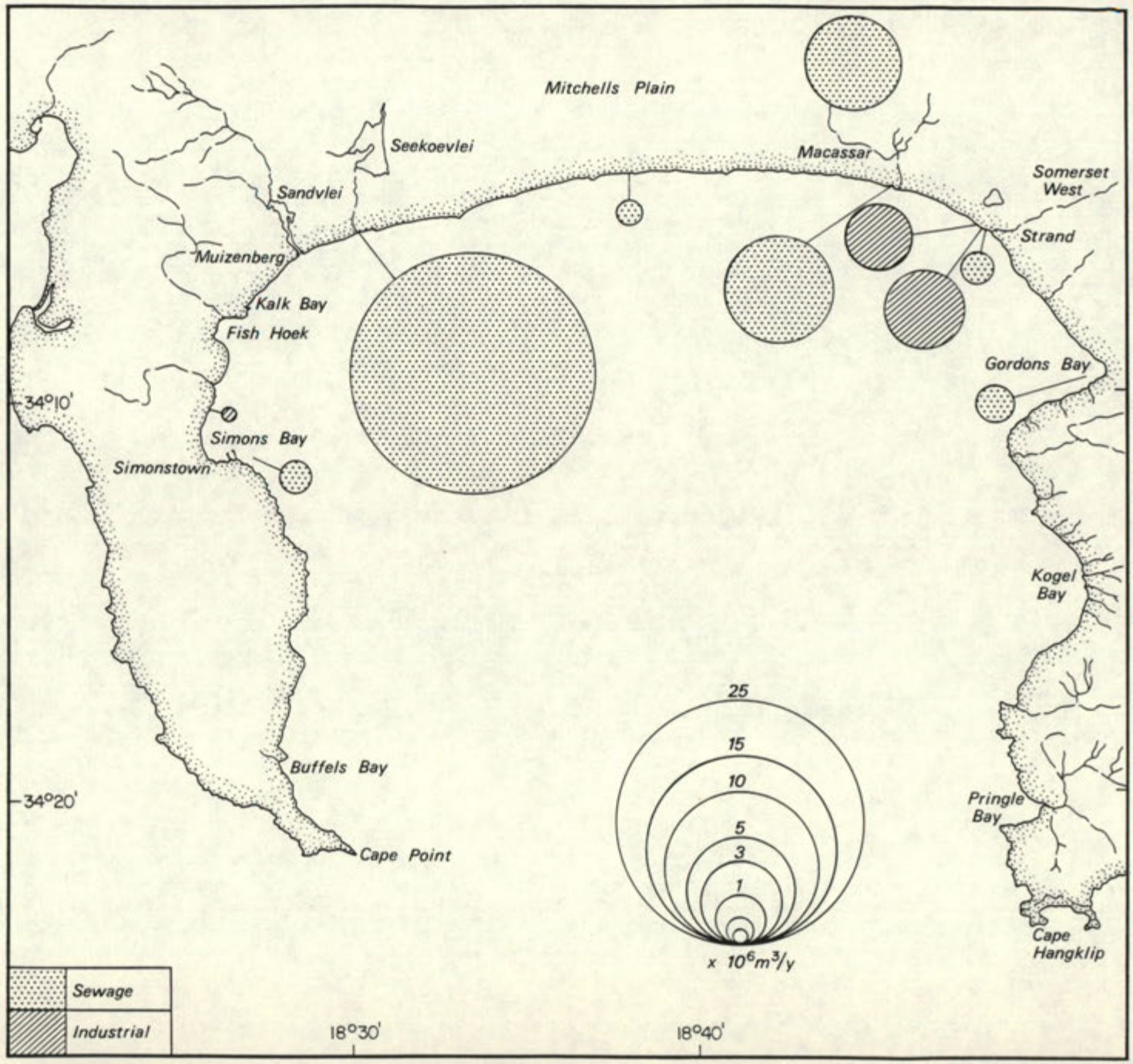


Fig. 6. Waste disposal in False Bay (Eagle, 1980)

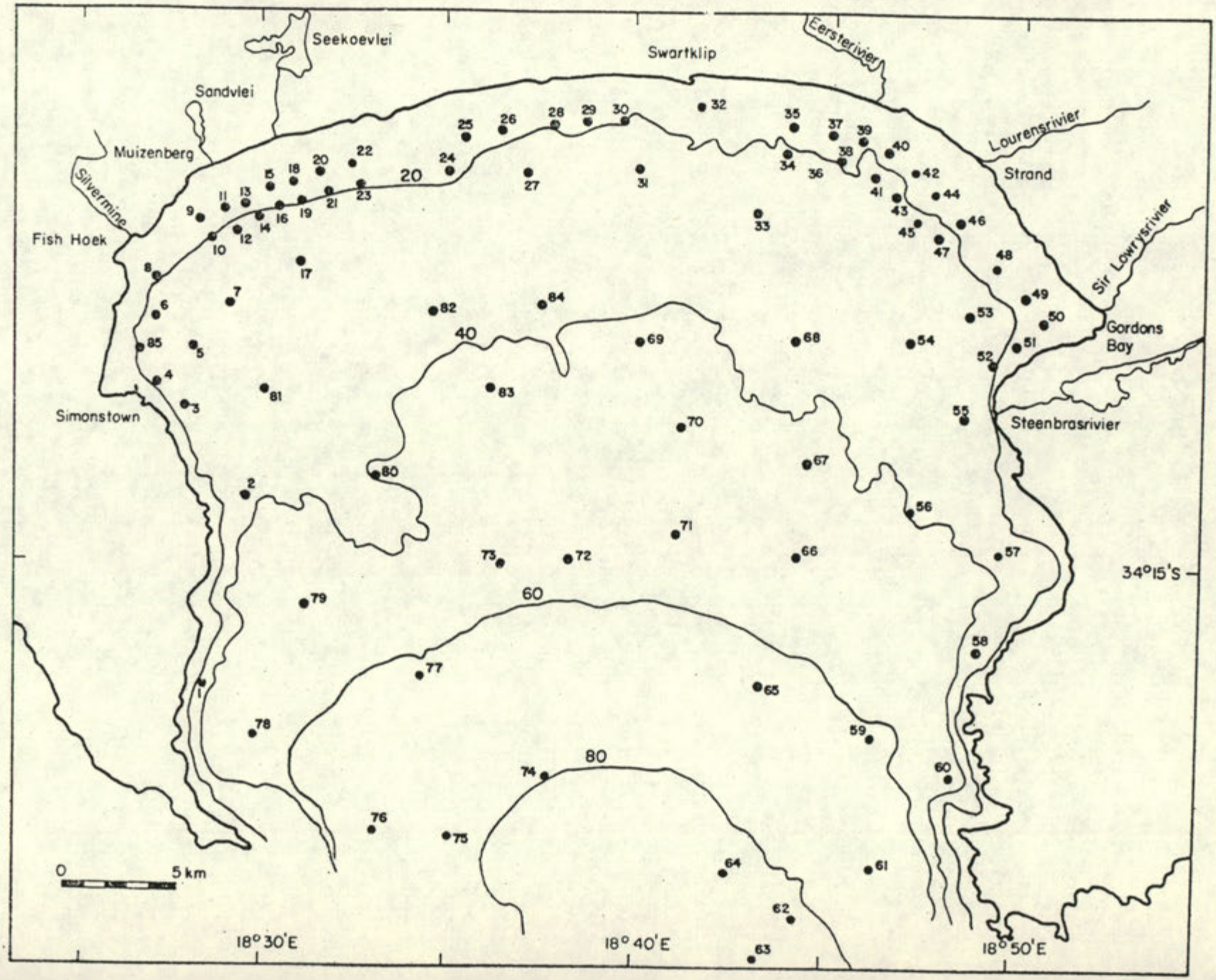


Fig. 7. Sampling positions and depth contours (m)

For Fig. 8 see page 21

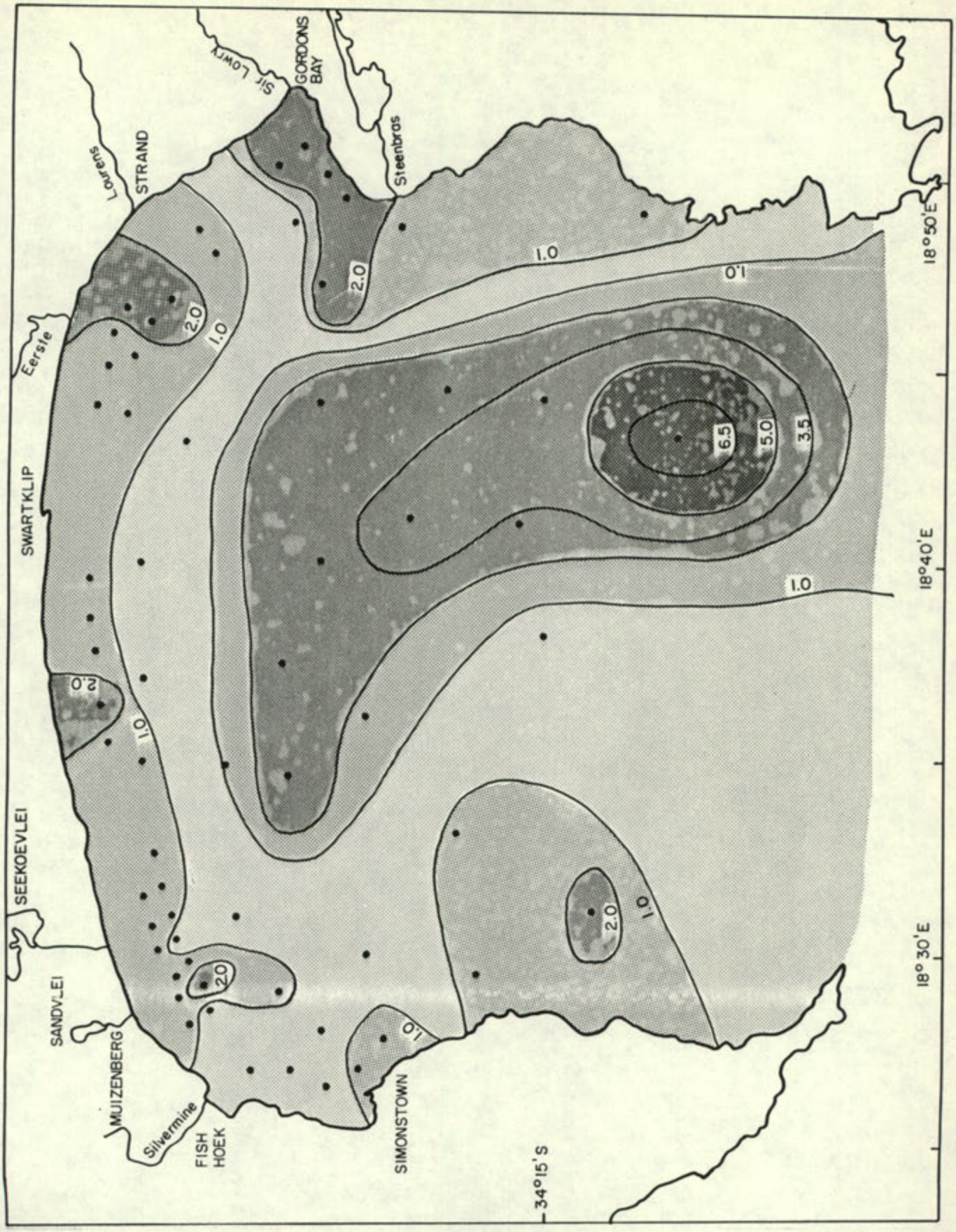


Fig. 9. Distribution of organic matter in False Bay sediments

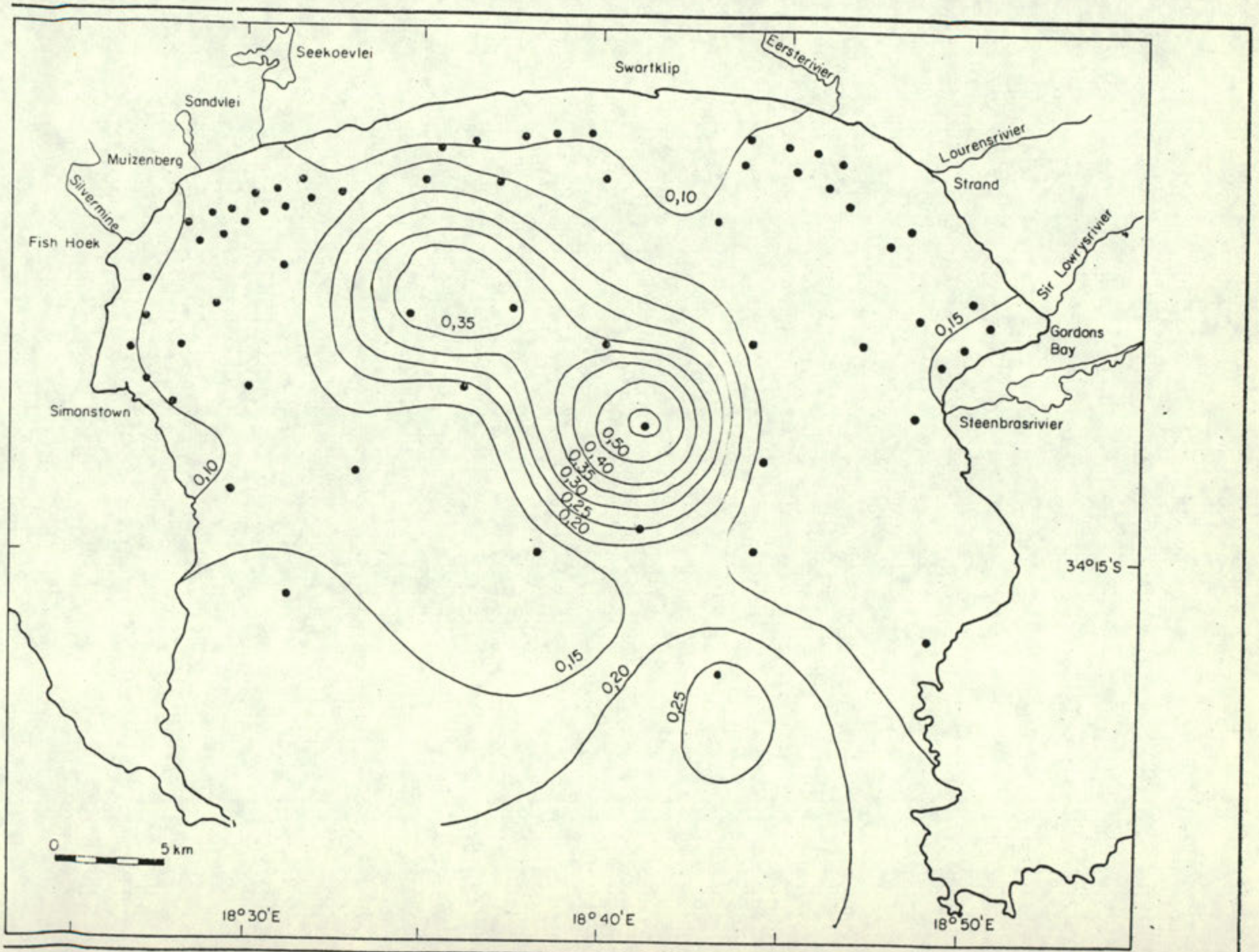


Fig. 10. Distribution of Cd in False Bay sediments (µg/g) (From NRIO, 1983)

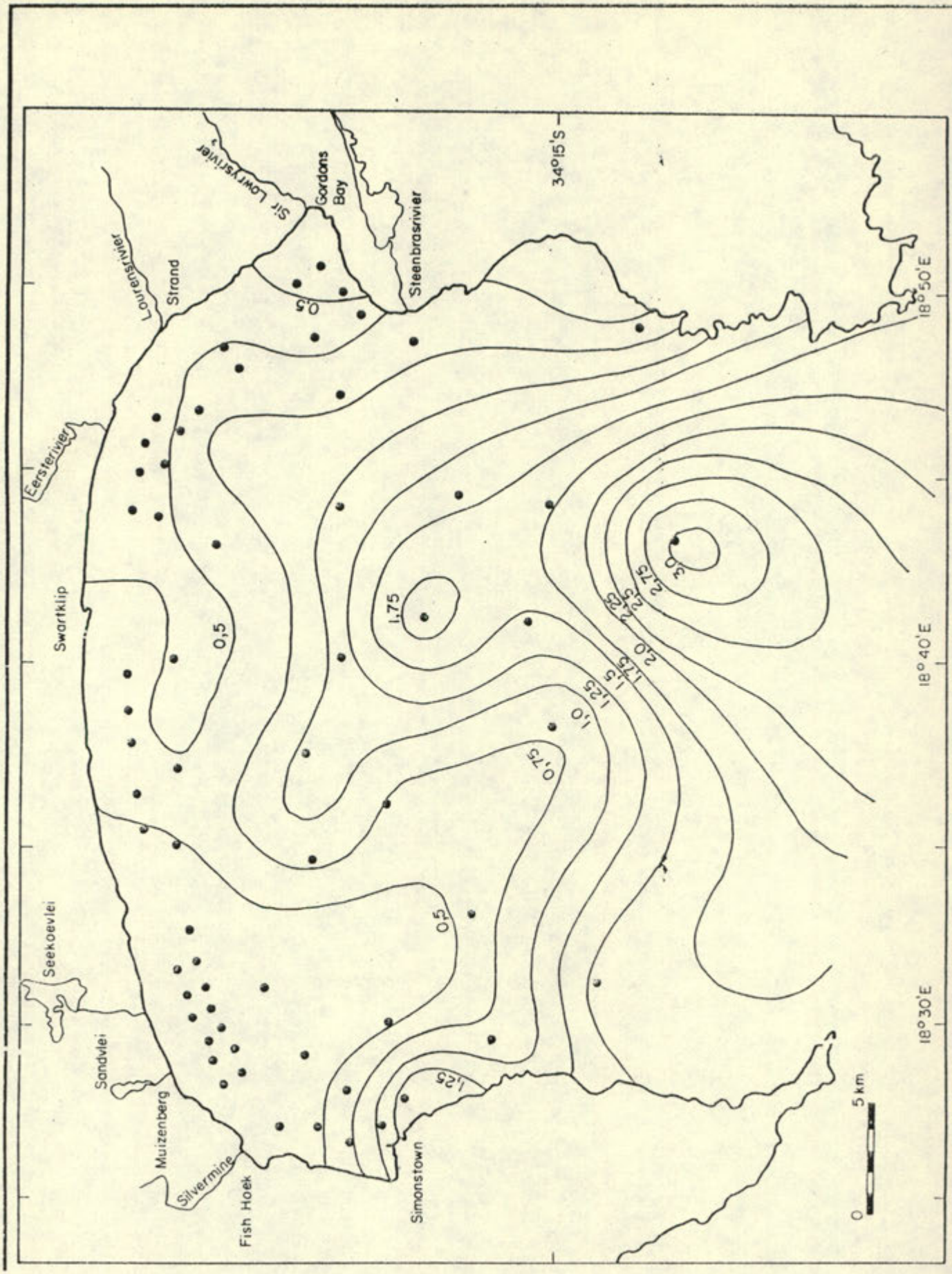


Fig. 11. Distribution of Cu in False Bay sediments (µg/g) (From NRIO, 1983)

Note: This diagram has been reproduced directly from the reference. The contours surrounding the highest concentration (station 65) are misleading, cf. Table 7.

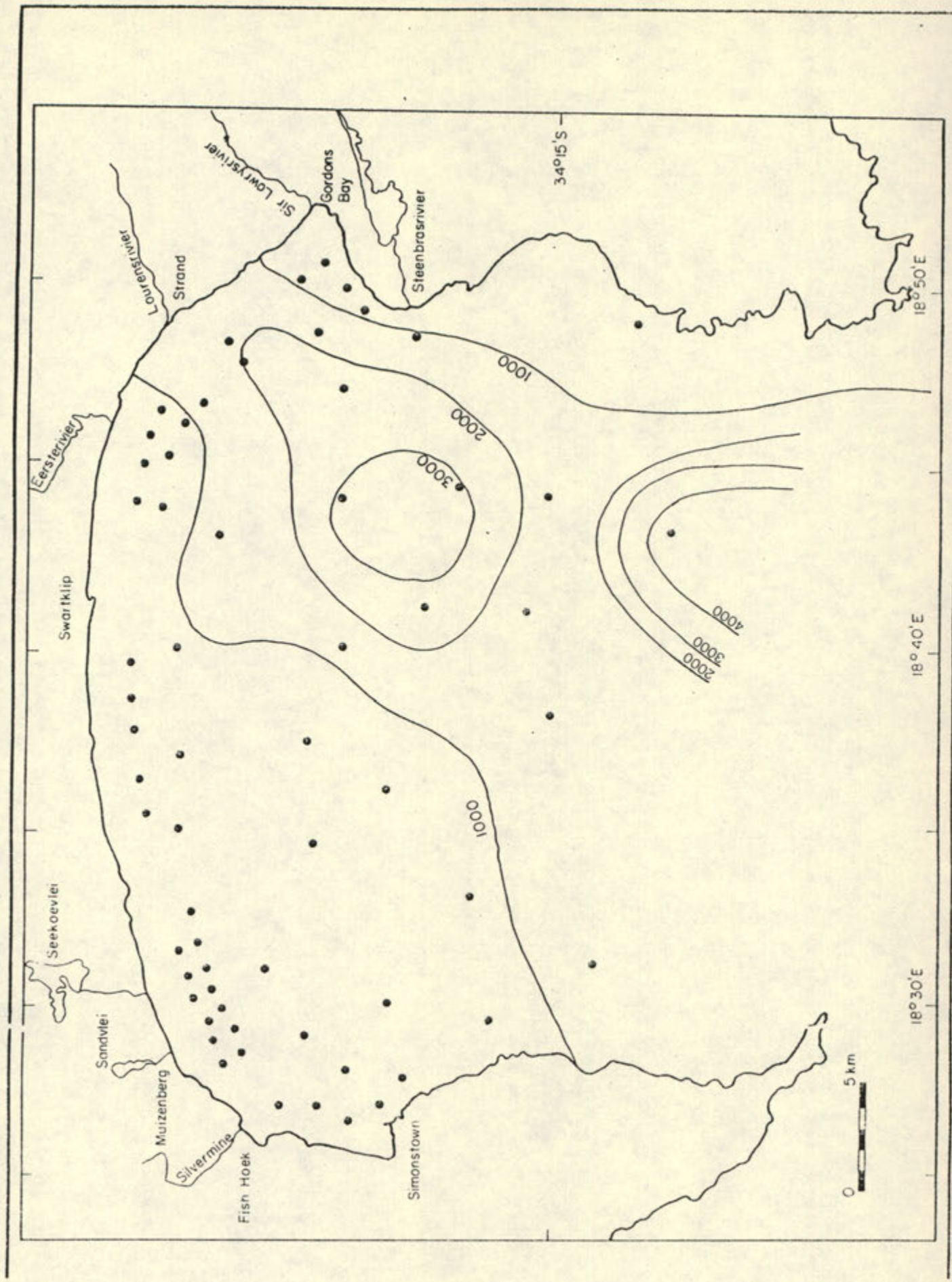


Fig. 12. Distribution of Fe in False Bay sediments (μg/g) (From NRIO, 1983)

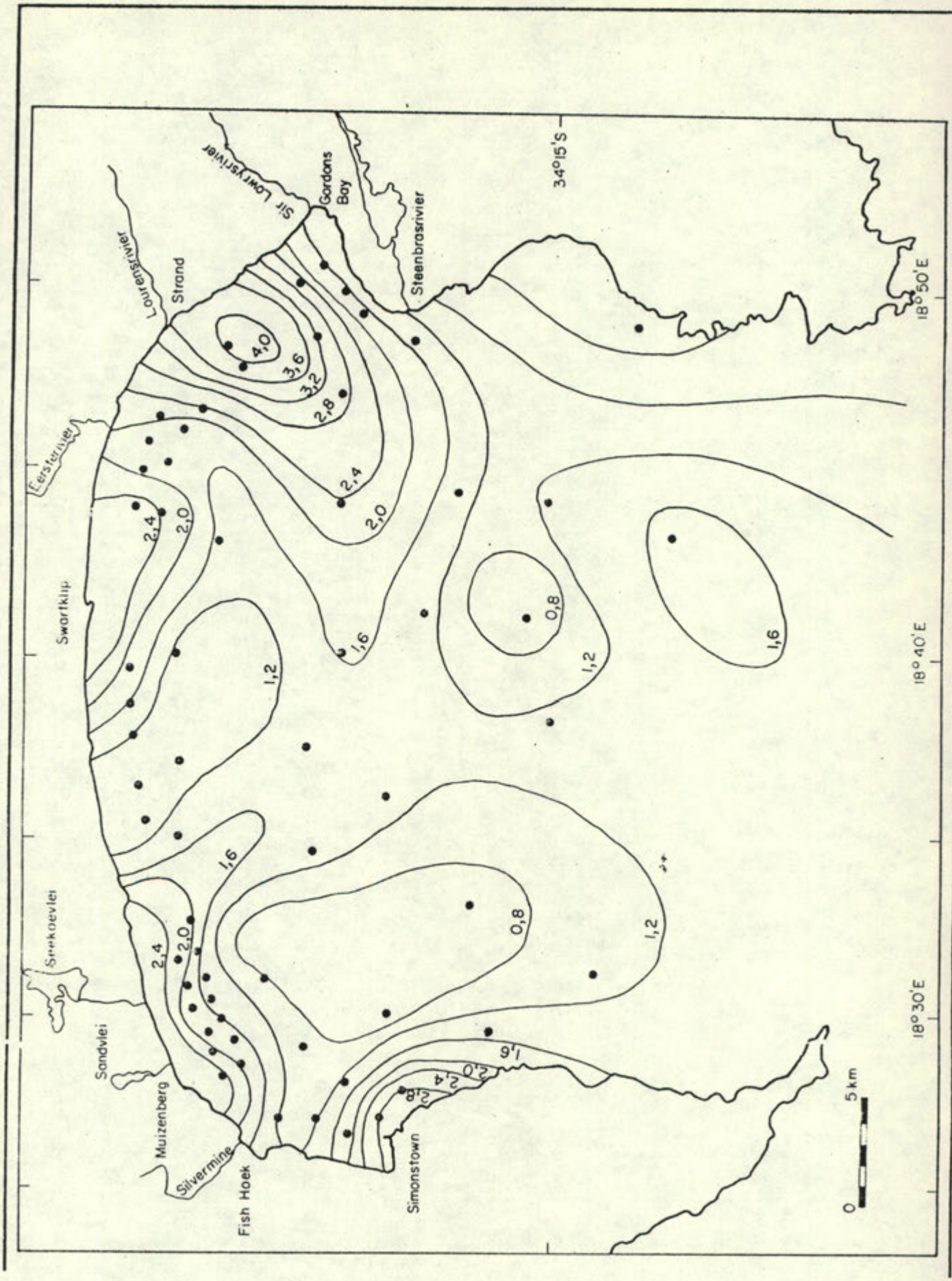


Fig. 13. Distribution of Pb in False Bay sediments (μg/g) (From NRIO, 1983)

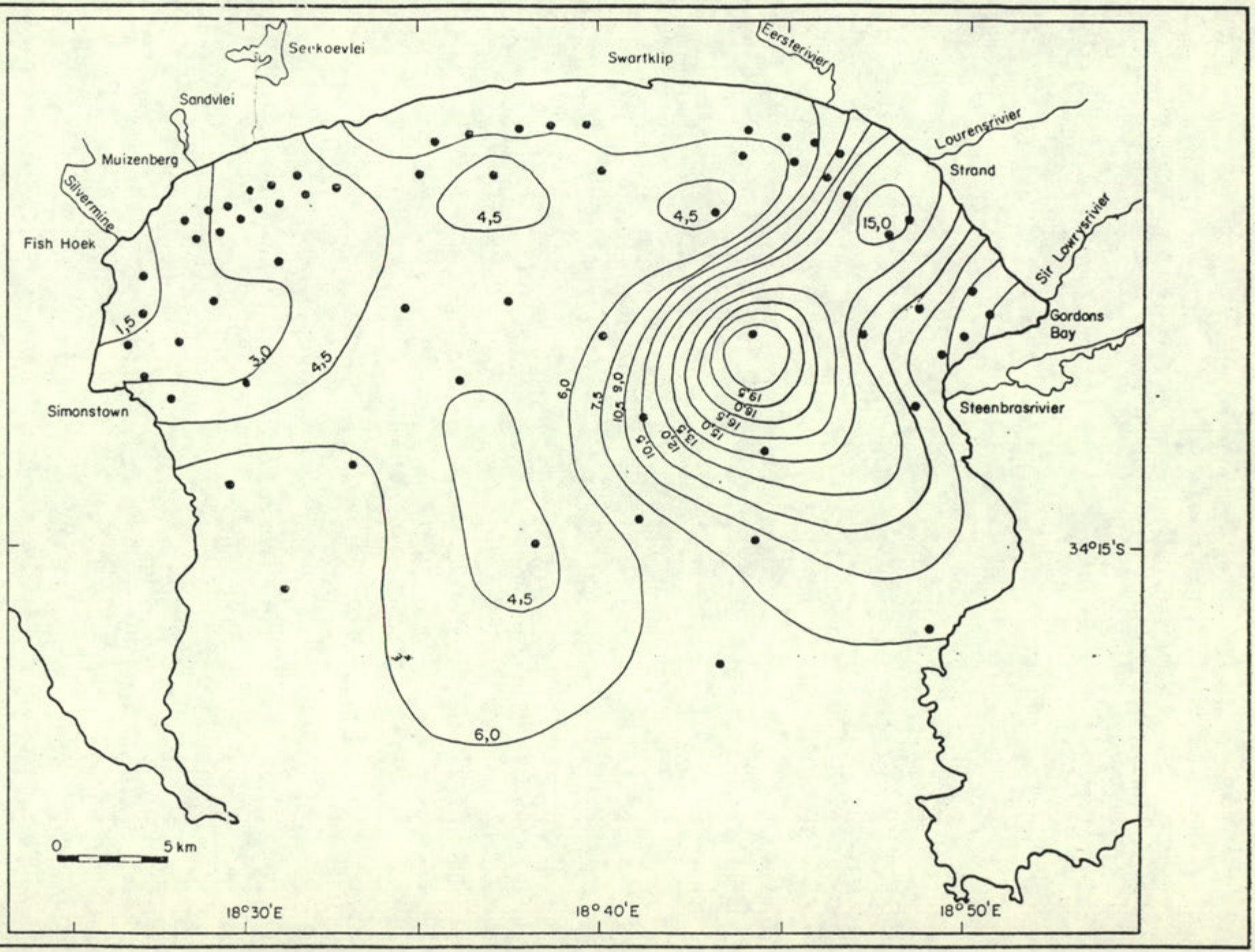


Fig. 14. Distribution of Mn in False Bay sediments (µg/g) (From NRIO, 1983)

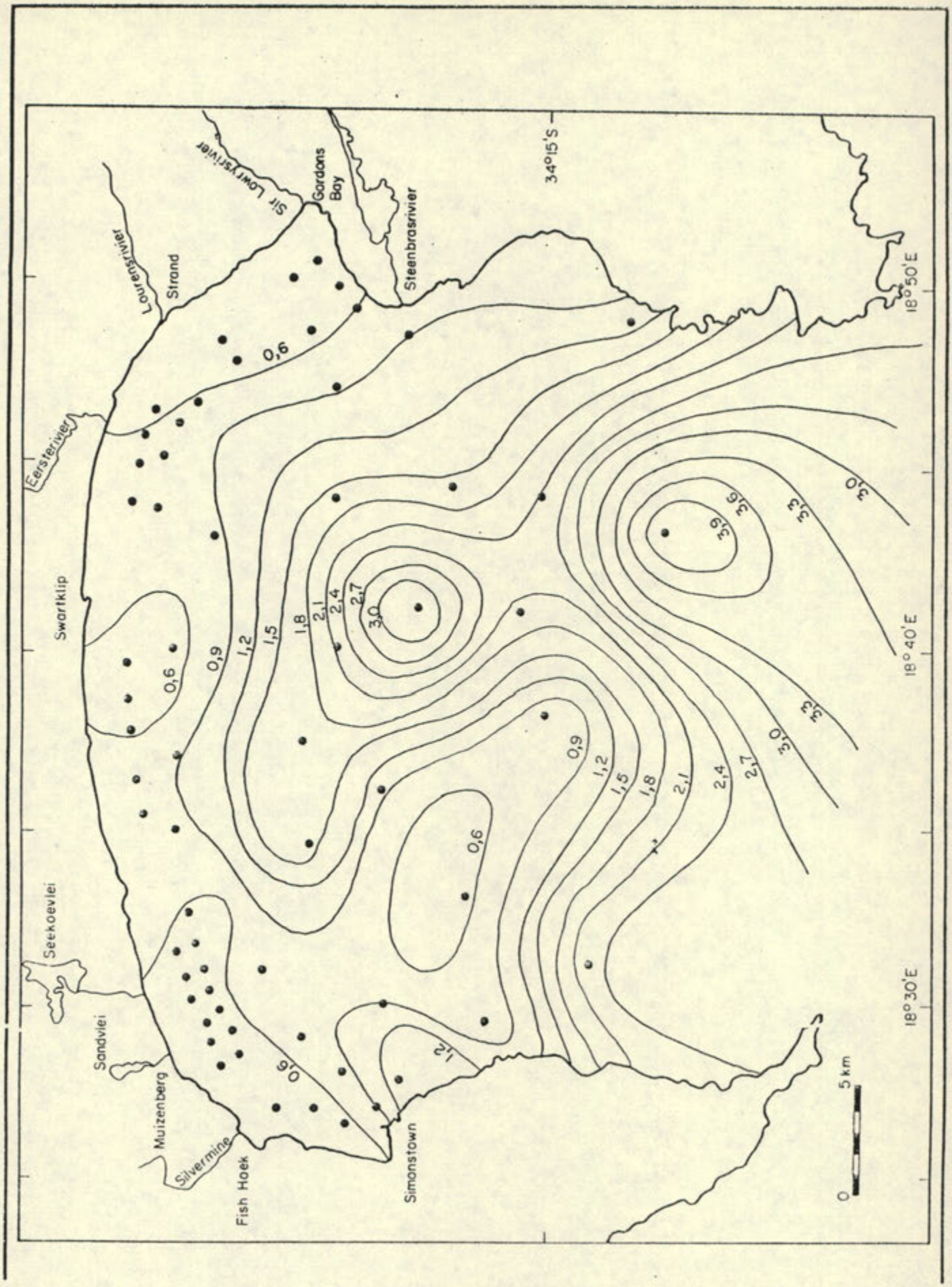


Fig. 15. Distribution of Ni in False Bay sediments (µg/g) (From NRIO, 1983)

See Note, Fig. 11

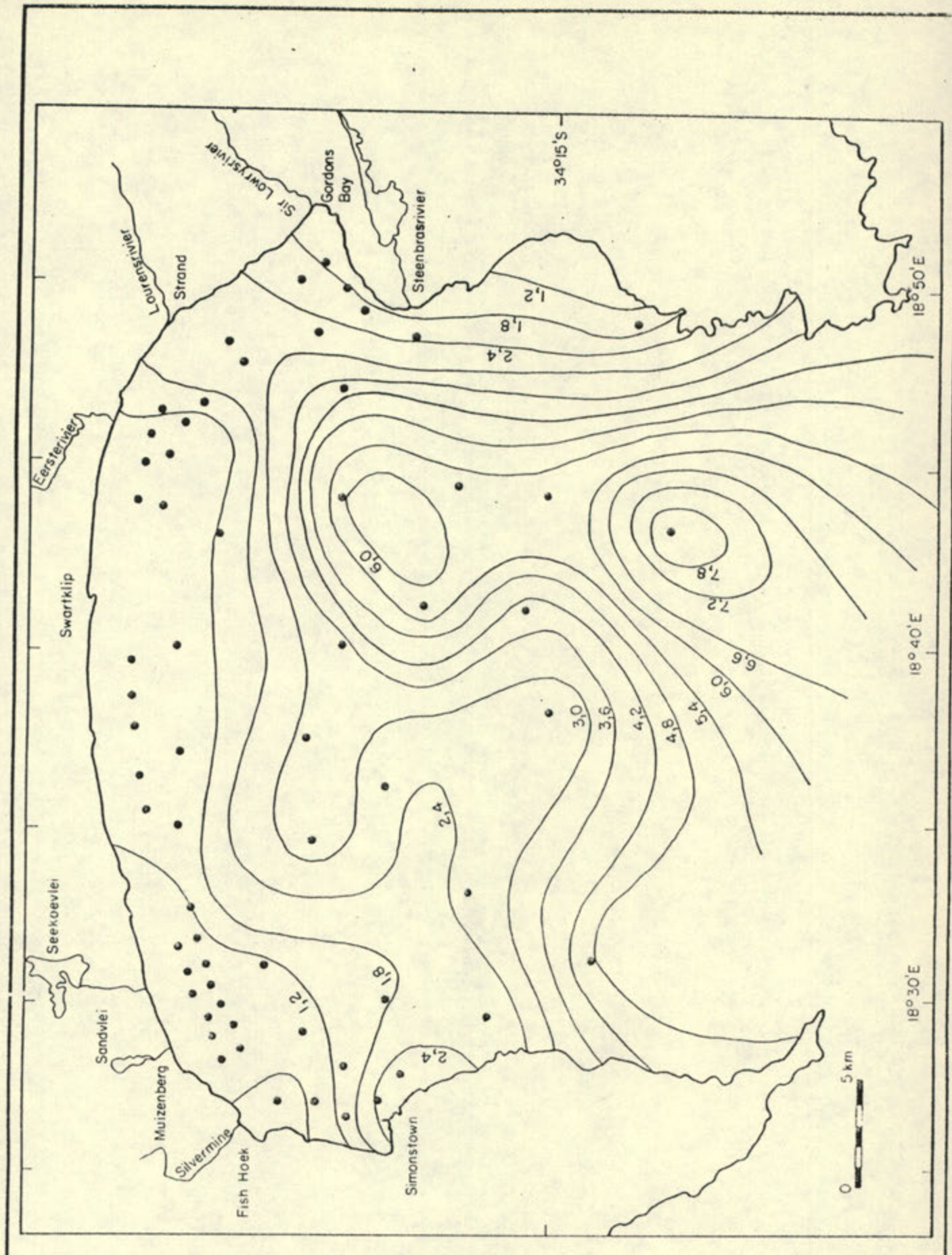


Fig. 16. Distribution of Zn in False Bay sediments (µg/g) (From NRIO, 1983)

See Note, Fig. 11

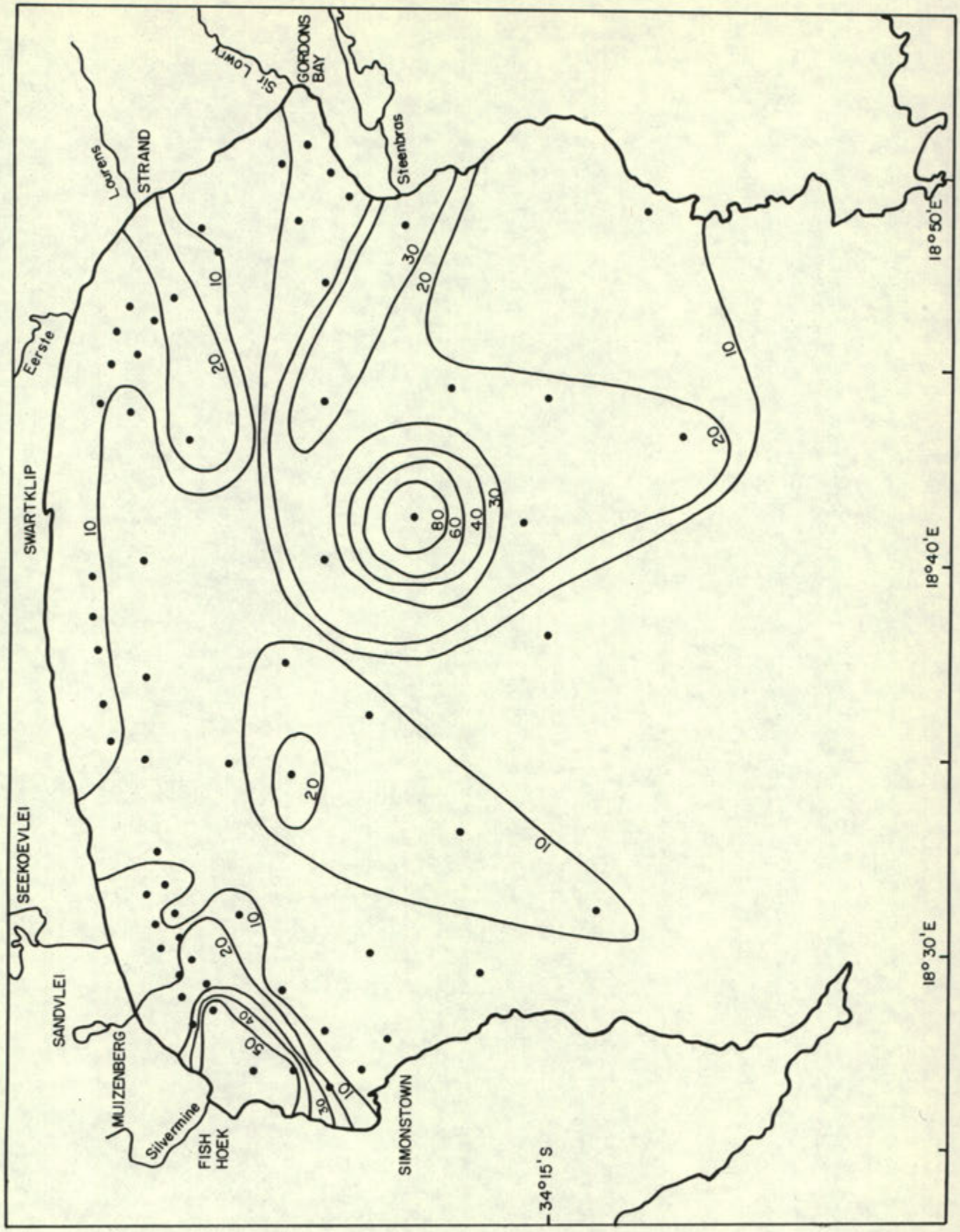


Fig. 17. Distribution of Cr in False Bay sediments (μg/g)

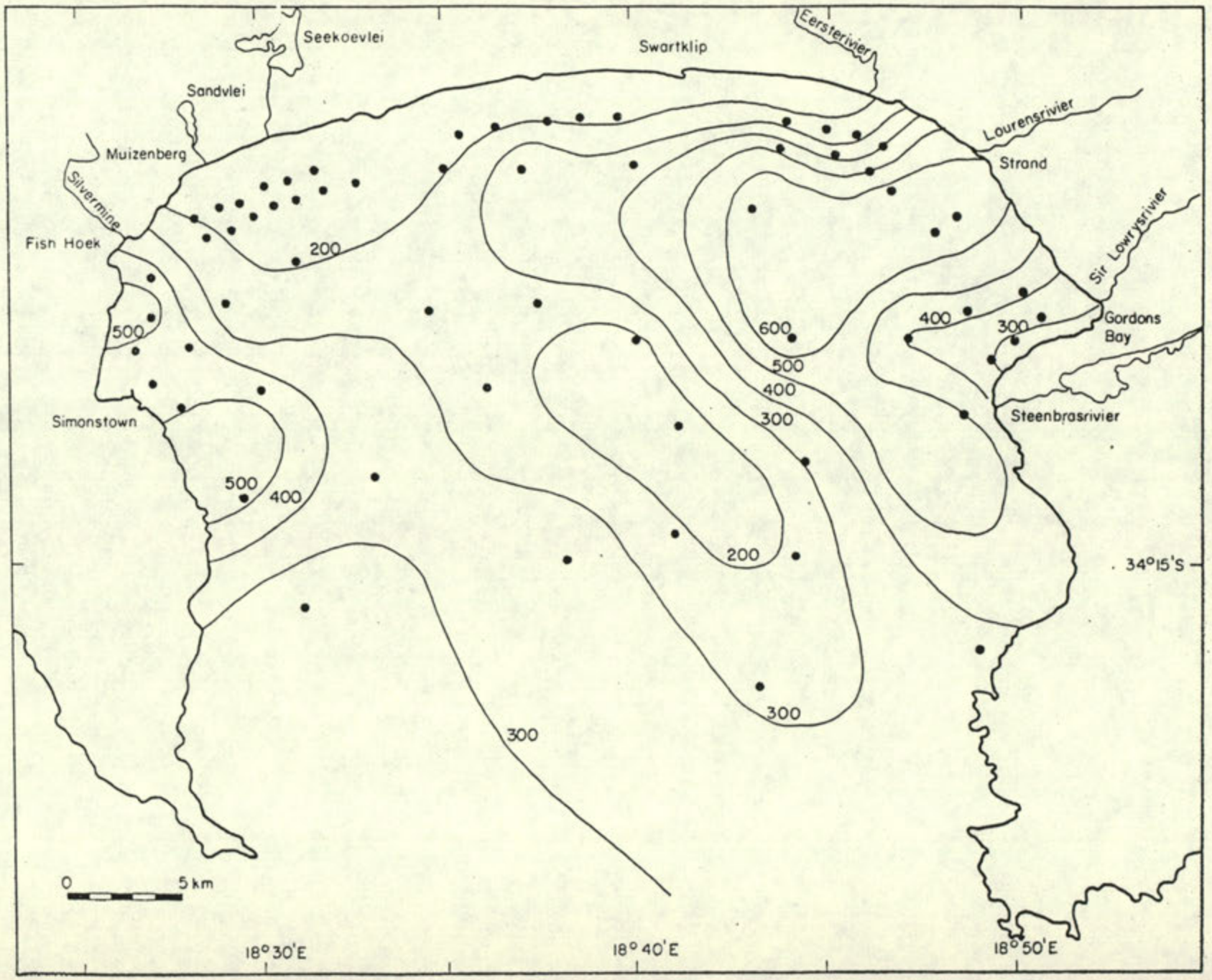


Fig. 18. Mean sediment particle size (μm) (From NRIO, 1983)

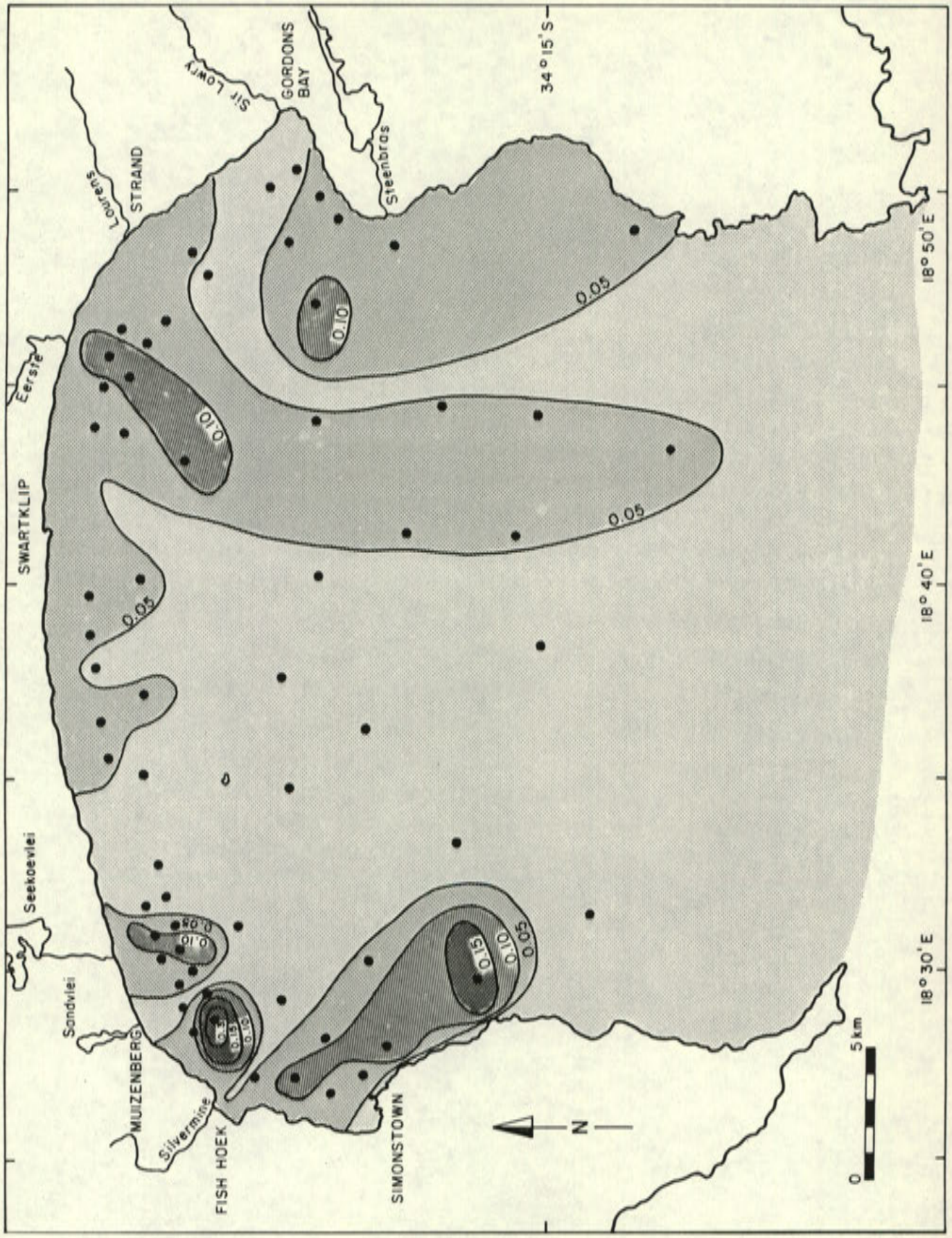


Fig. 19. Distribution of Cu in carbonate and reducible fraction of False Bay sediments (µg/g)

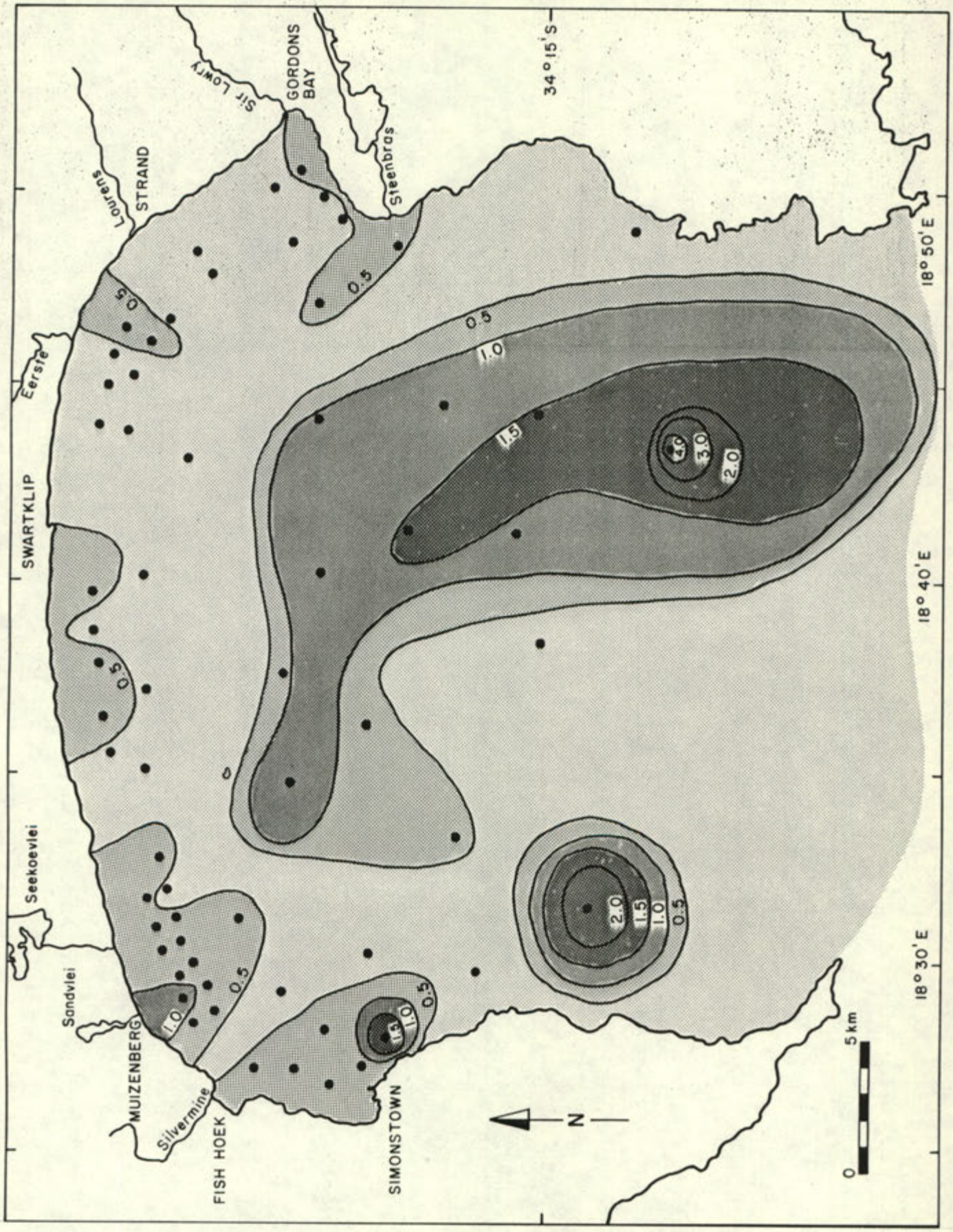


Fig. 20. Distribution of Cu in organic and sulphide fraction of False Bay sediments (µg/g)

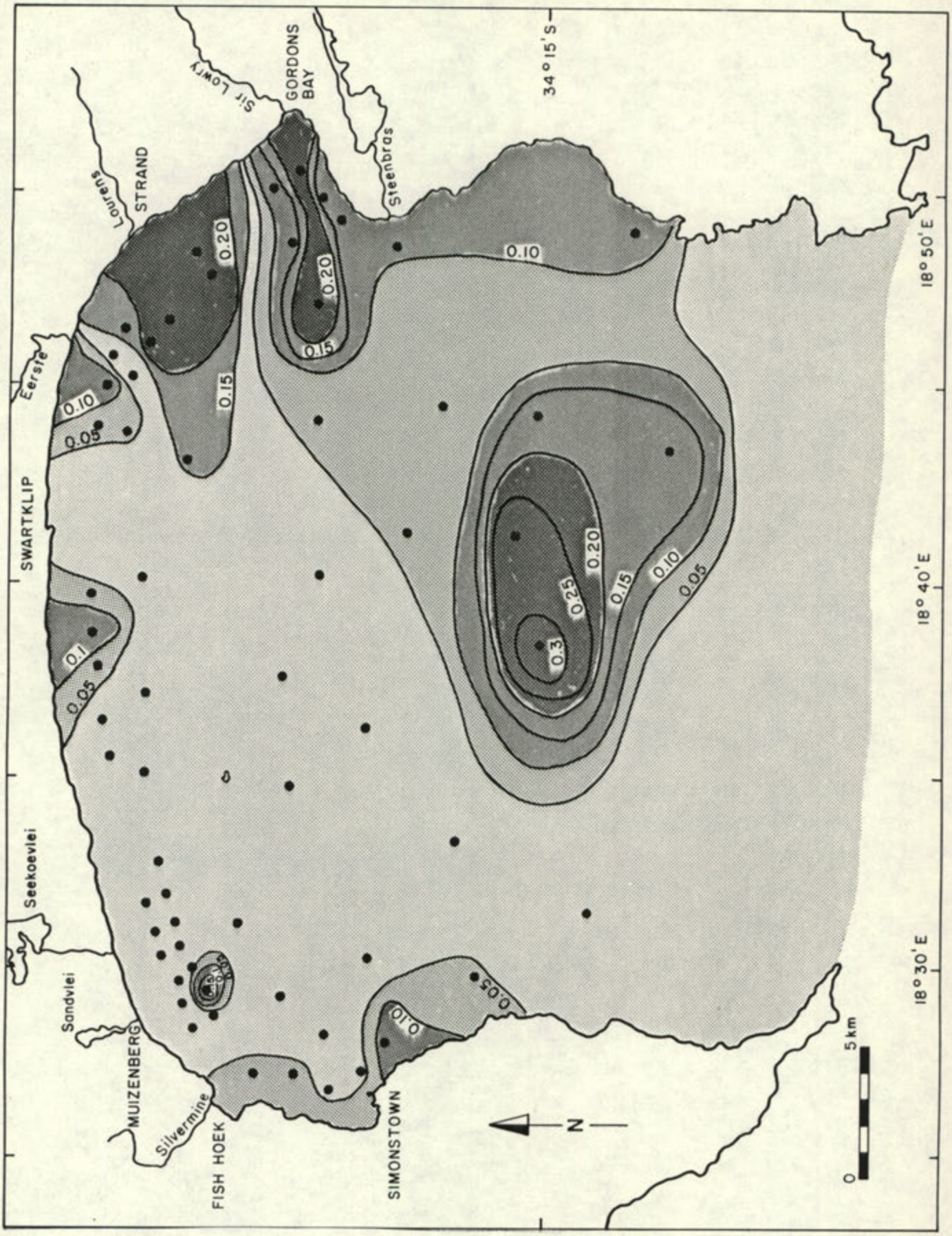


Fig. 21. Distribution of Cu in residual fraction of False Bay sediments (μg/g)

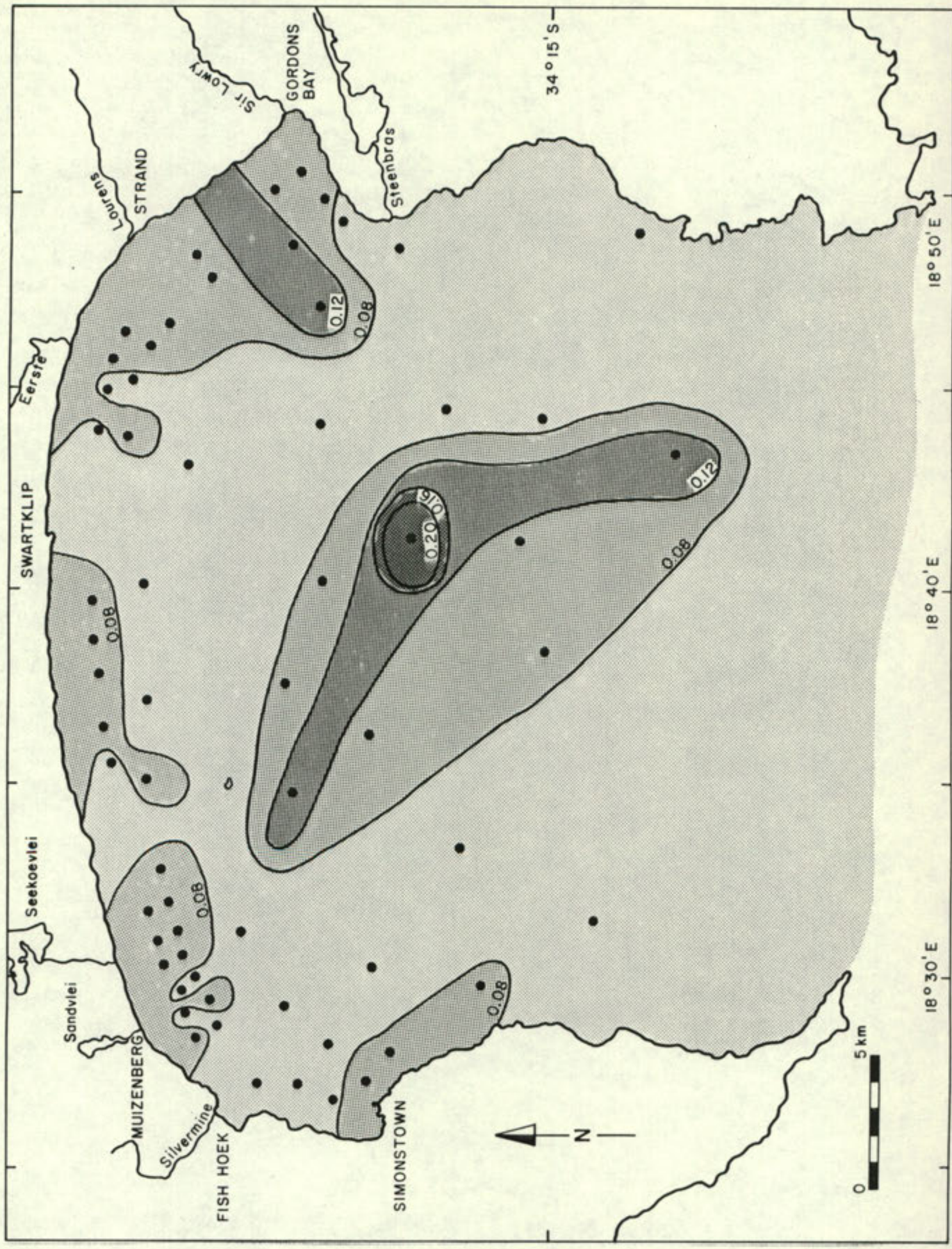


Fig. 22. Distribution of Cd in carbonate and reducible fraction of False Bay sediments (μg/g)

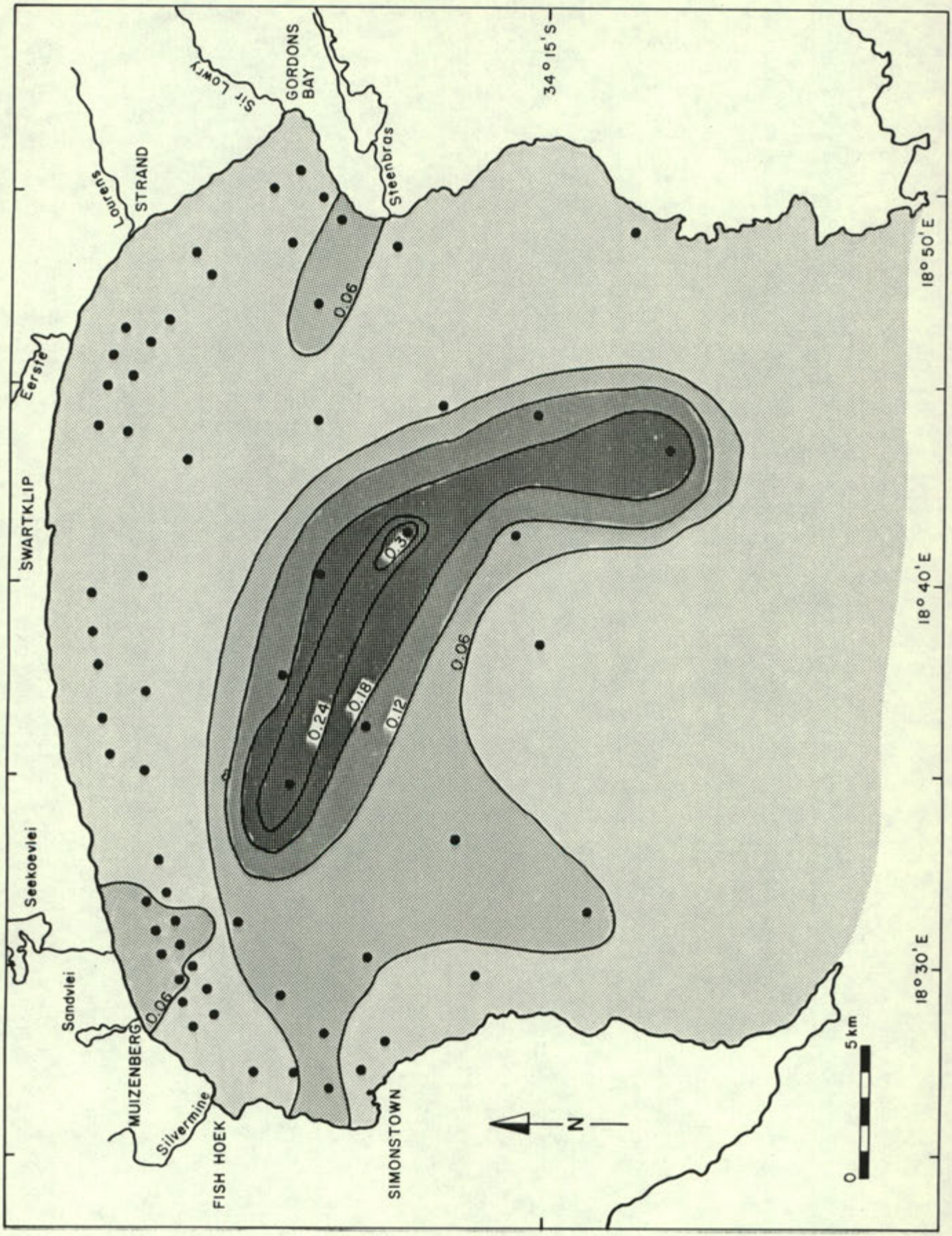


Fig. 23. Distribution of Cd in organic and sulphide fraction of False Bay sediments (µg/g)

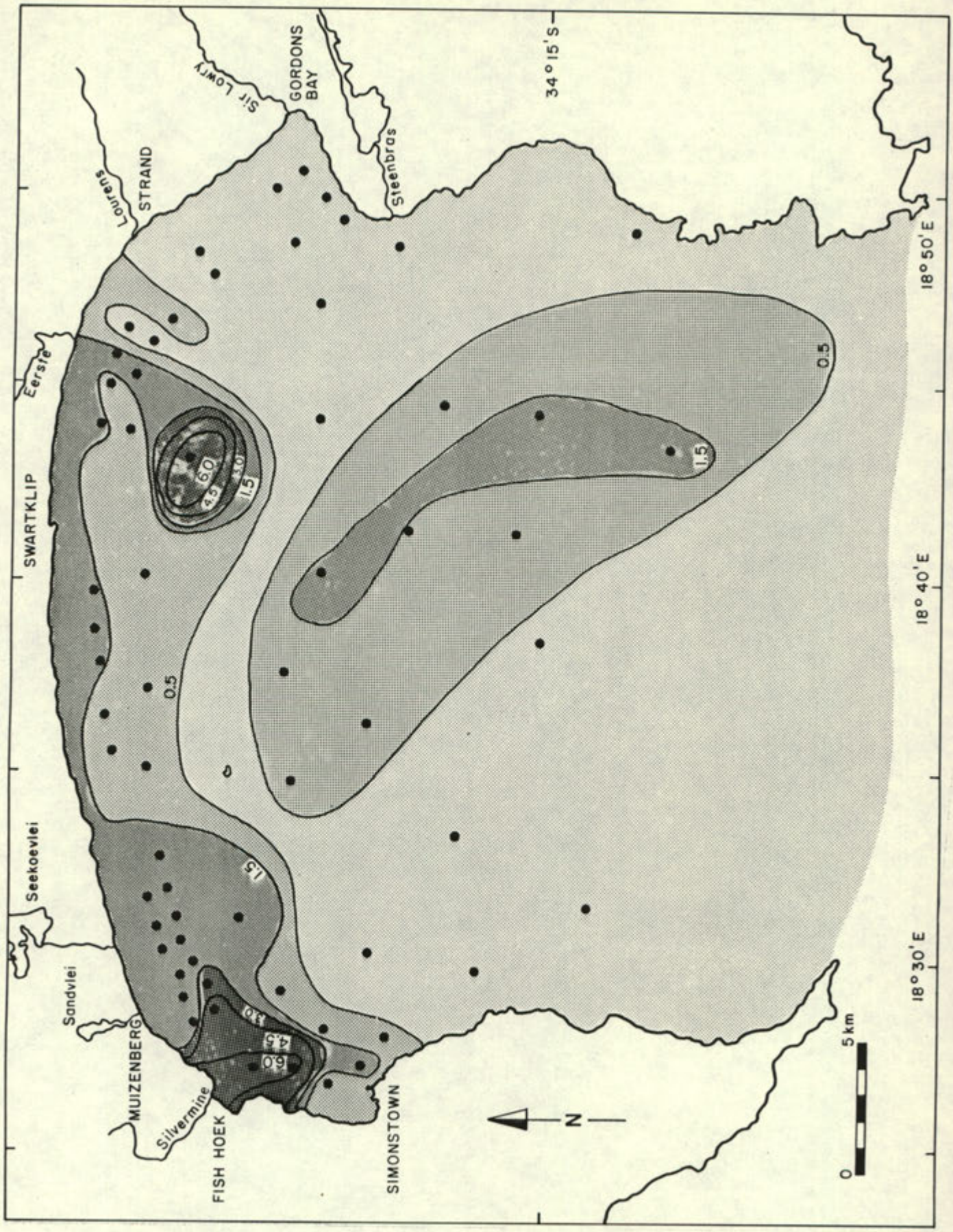


Fig. 24. Distribution of Cr in carbonate and reducible fraction of False Bay sediments (μg/g)

Fig. 25. Distribution of Cr in organic and sulphide fraction of False Bay sediments (μg/g)

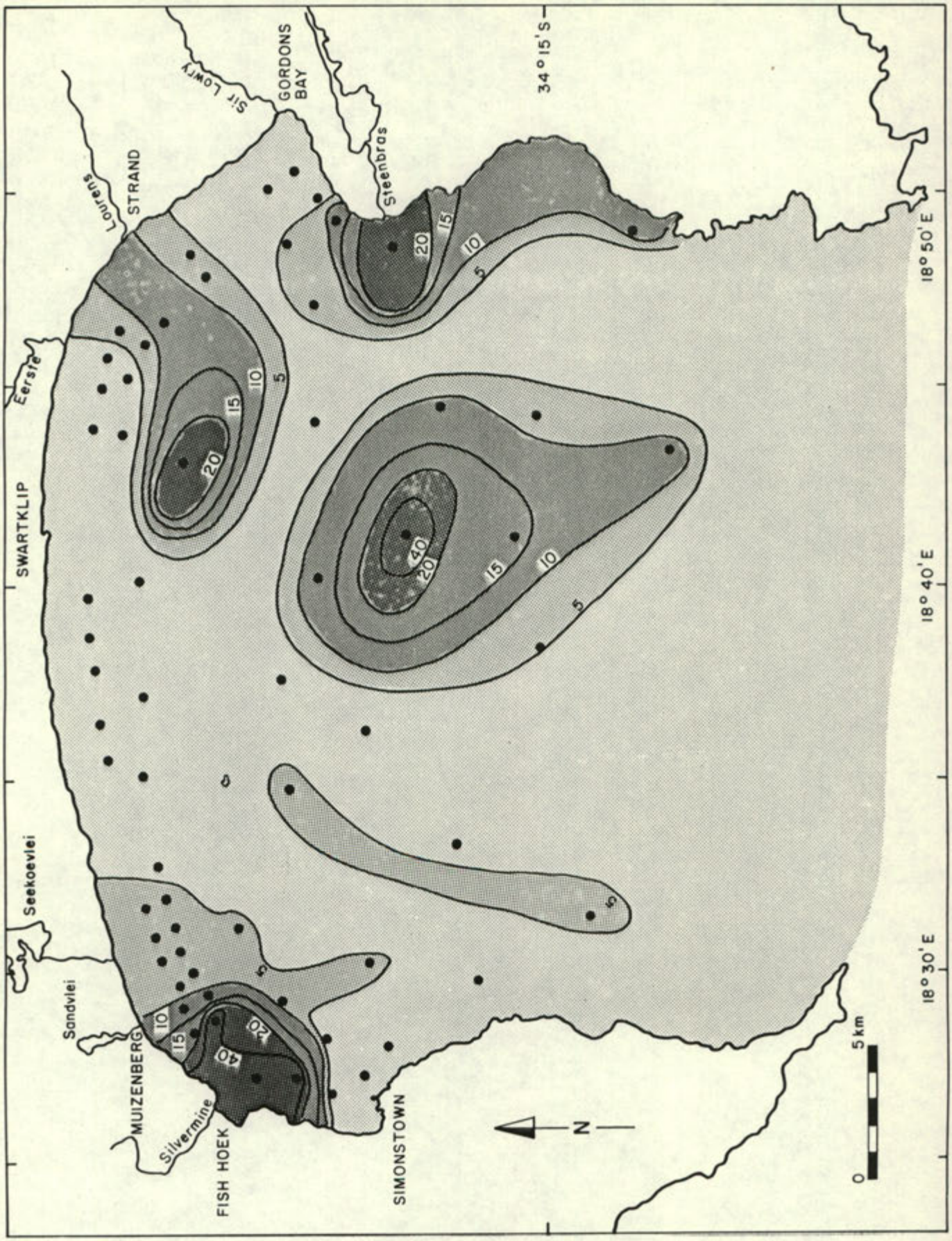


Fig. 26 Distribution of Cr residual fraction

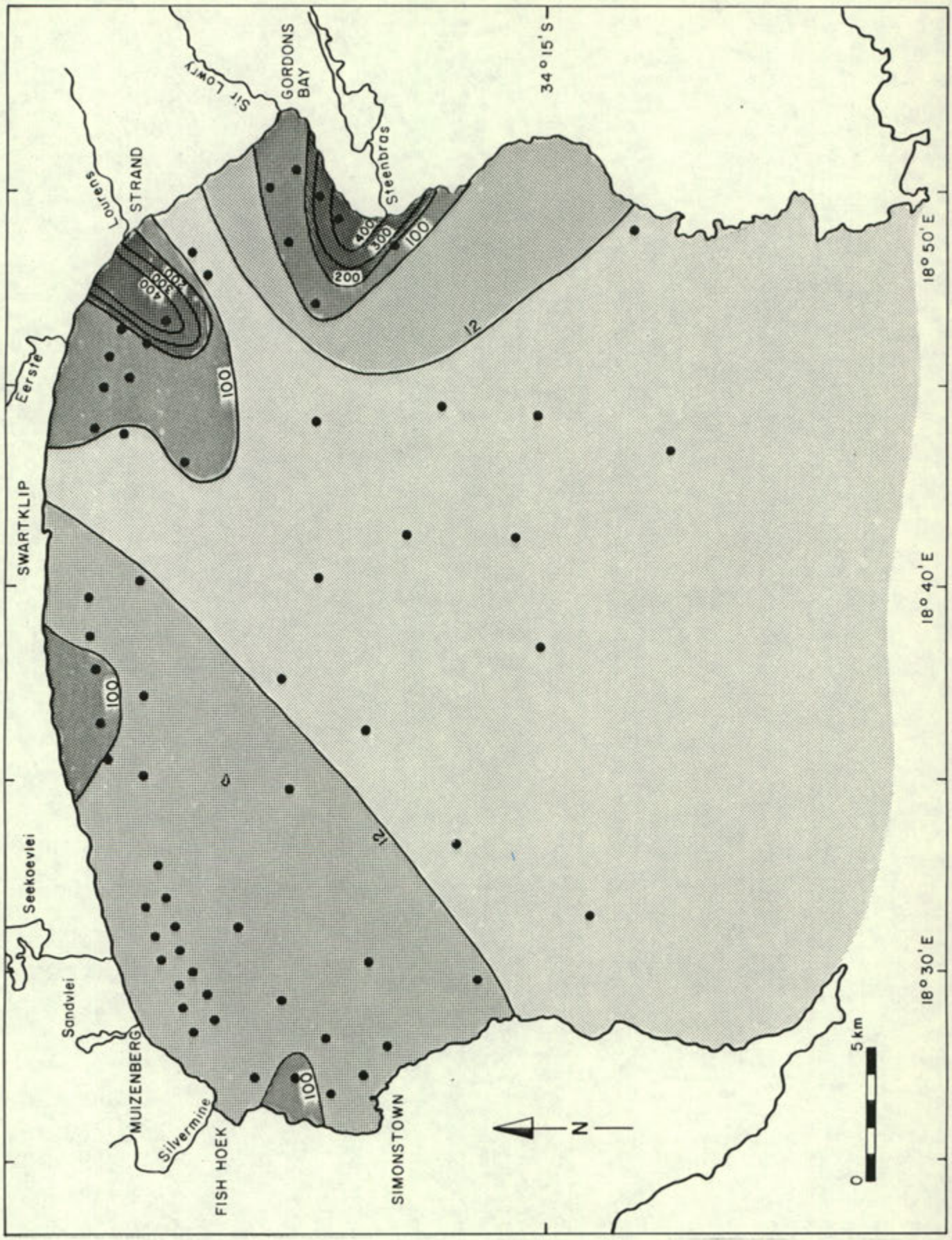


Fig. 27. Distribution of Fe in carbonate and reducible fraction of False Bay sediments (μg/g)

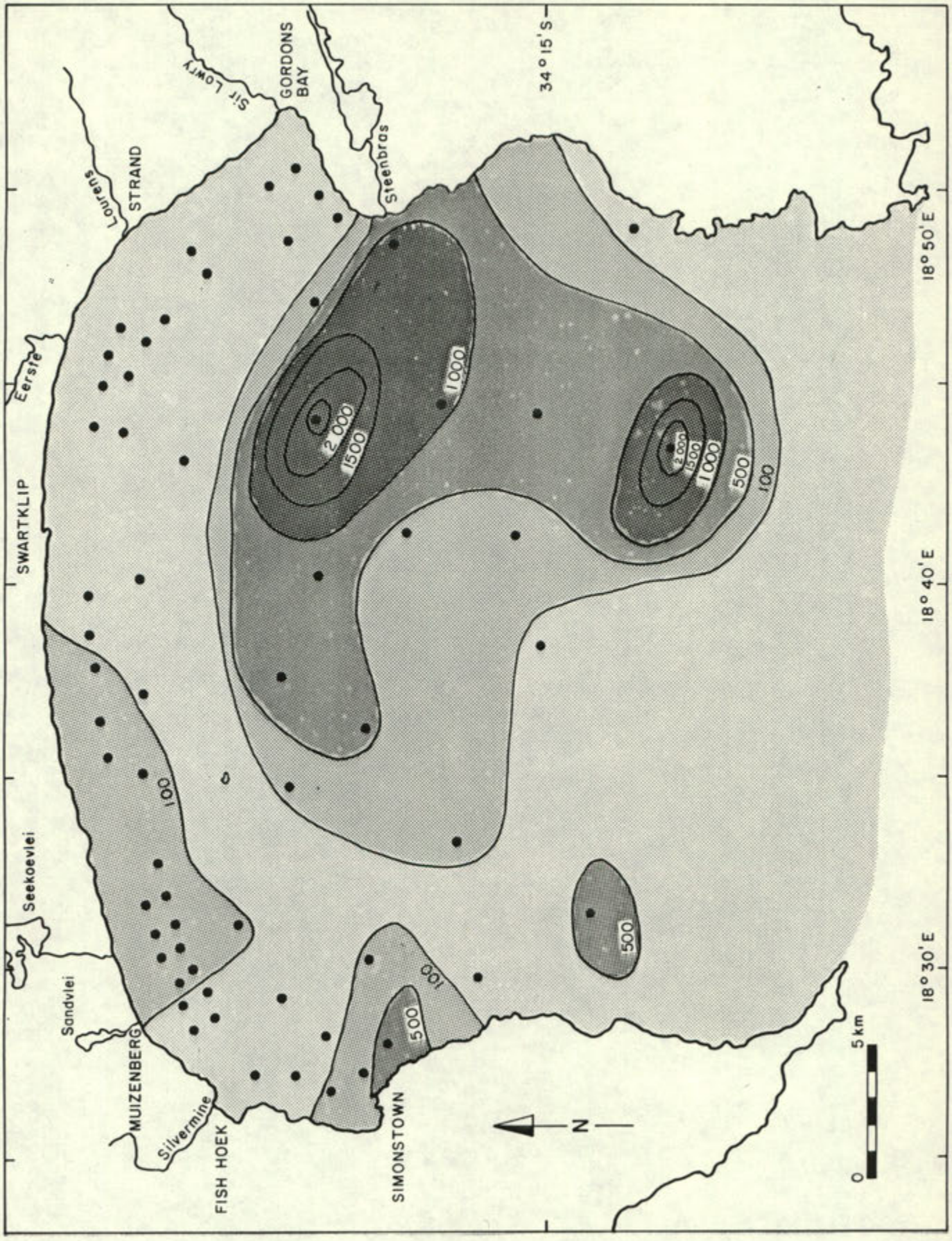


Fig. 28. Distribution of Fe in organic and sulphide fraction of False Bay sediments (µg/g)

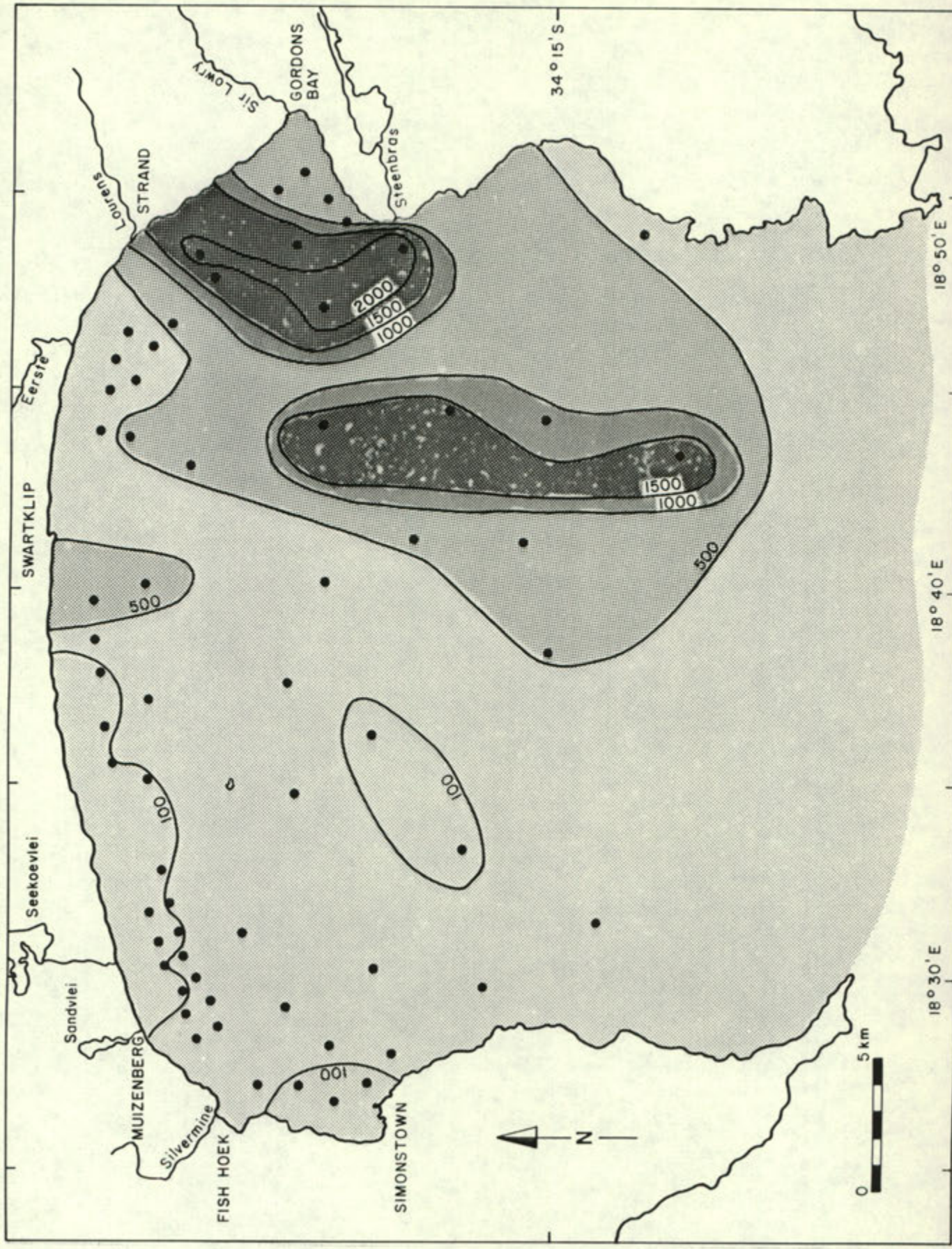


Fig. 29. Distribution of Fe in residual fraction of False Bay sediments (μg/g)

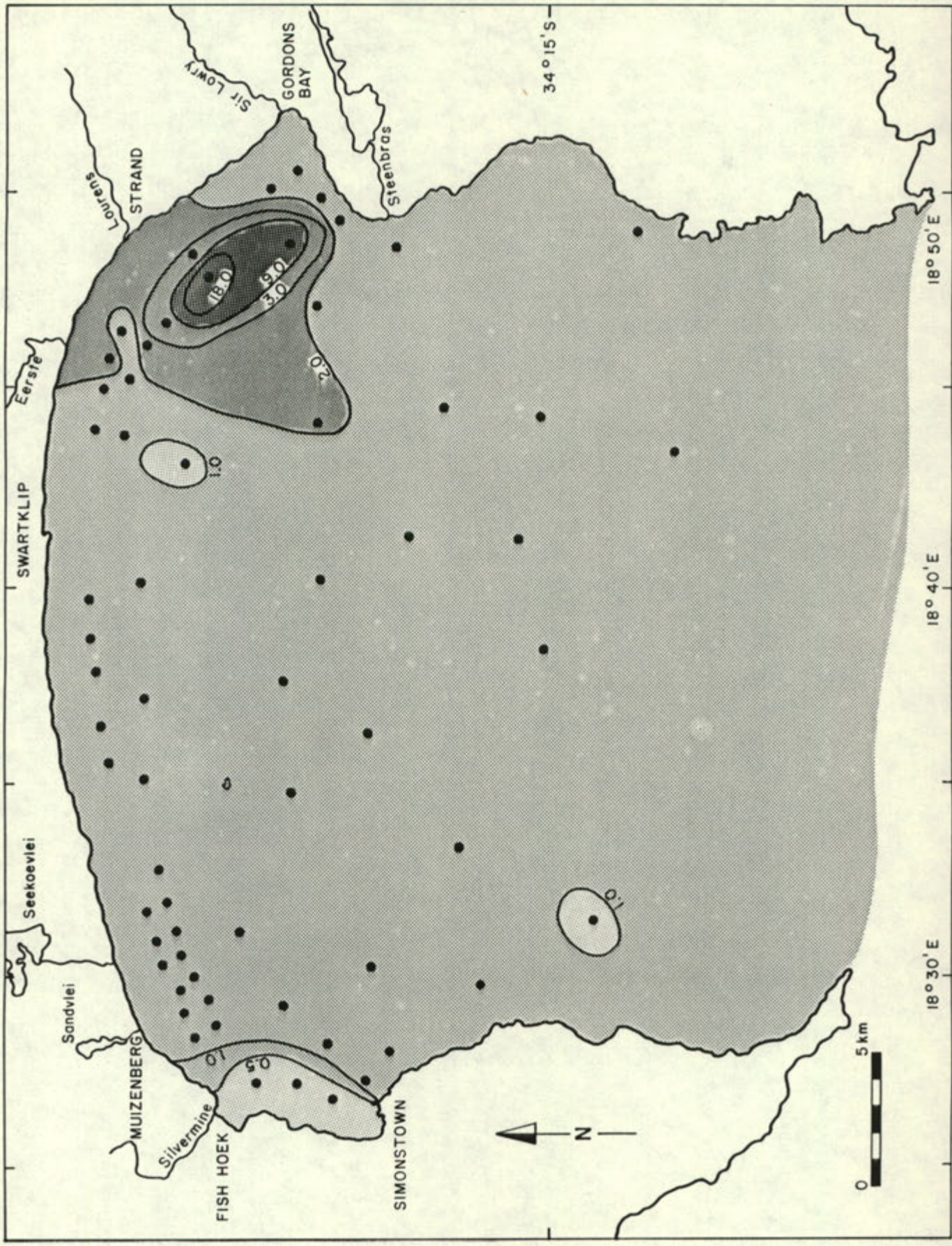


Fig. 30. Distribution of Mn in carbonate and reducible fraction of False Bay sediments (µg/g).

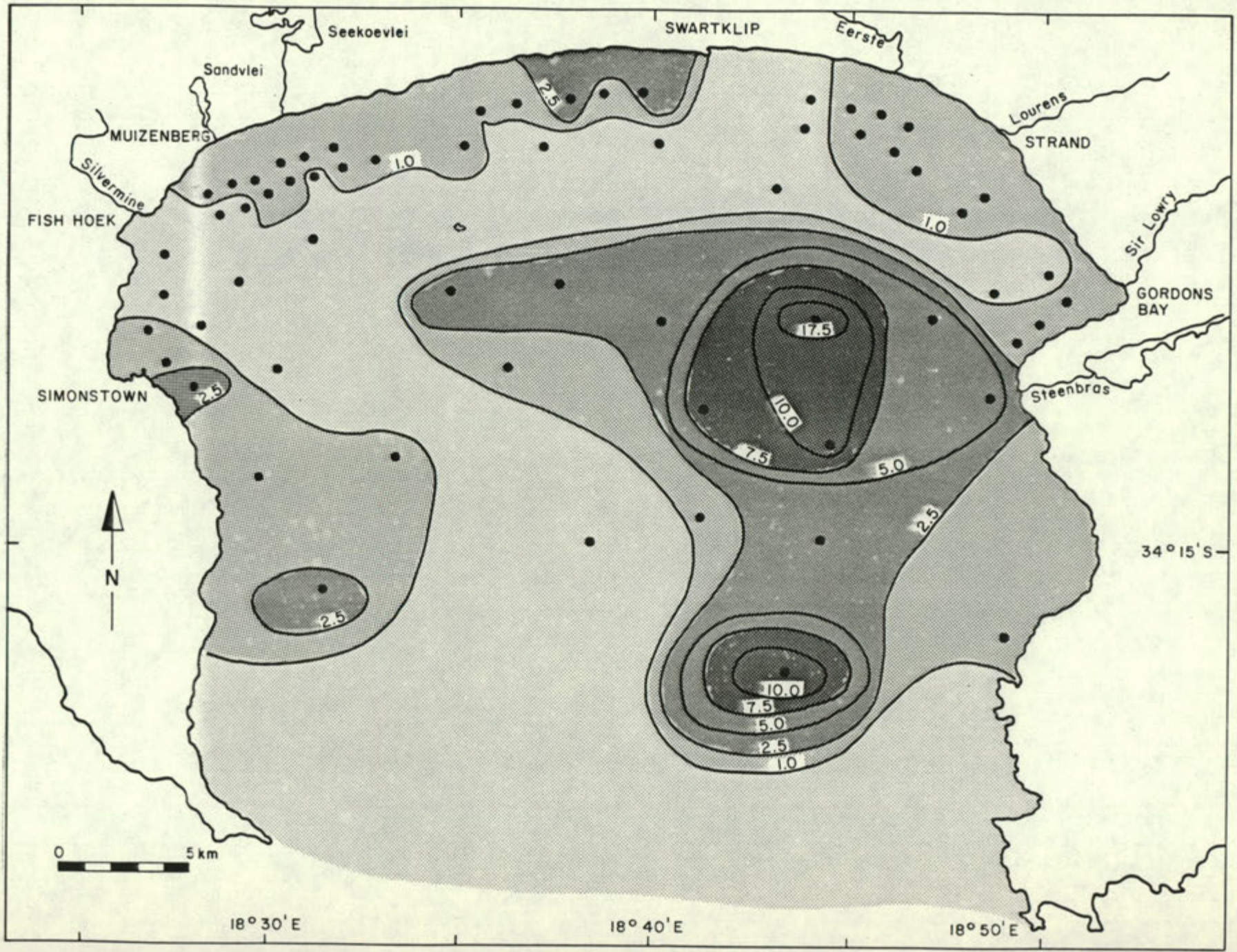


Fig. 31. Distribution of Mn in organic and sulphide fraction of False Bay sediments (µg/g)

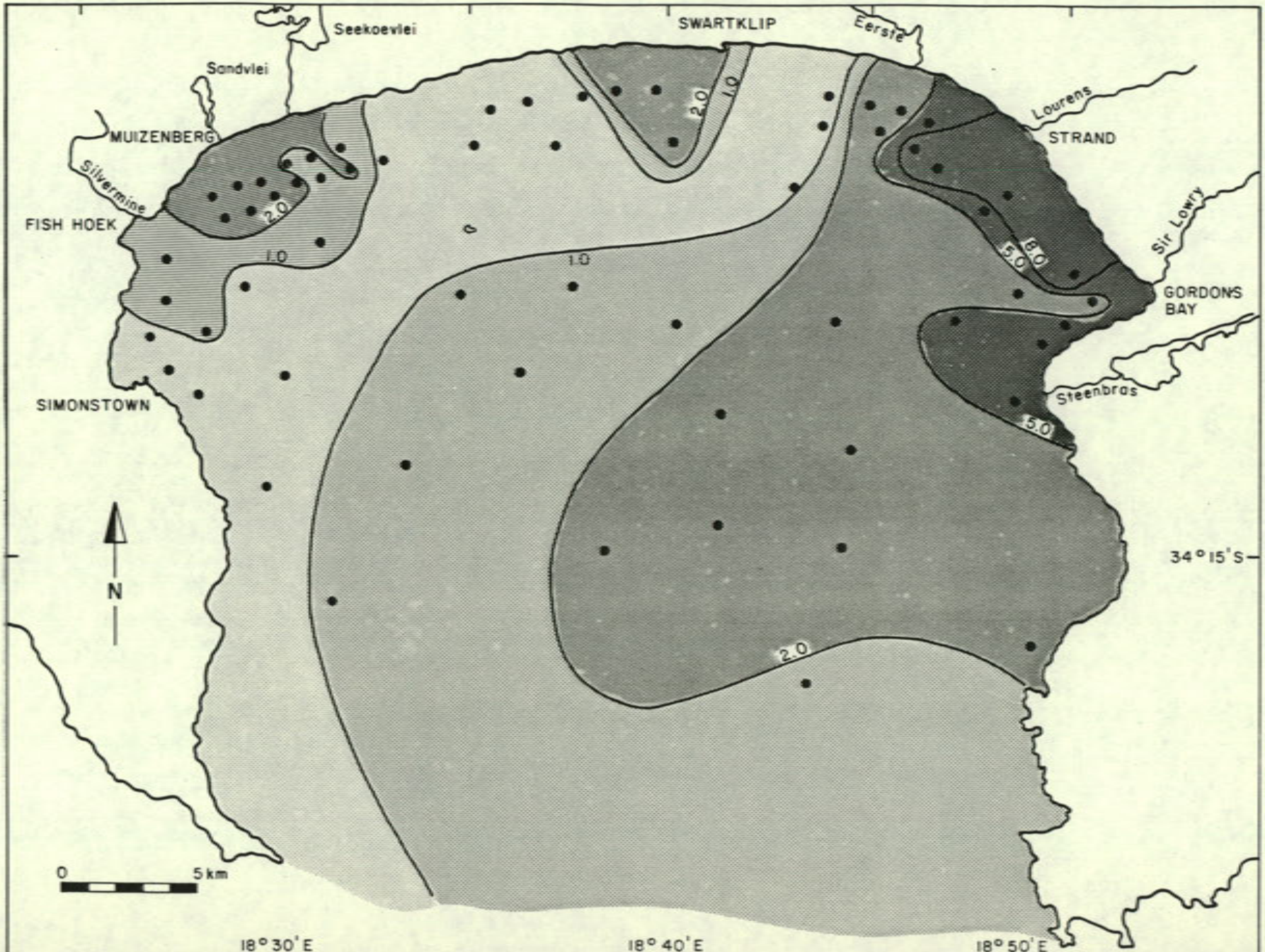


Fig. 32. Distribution of Mn in residual fraction of False Bay sediments (µg/g)

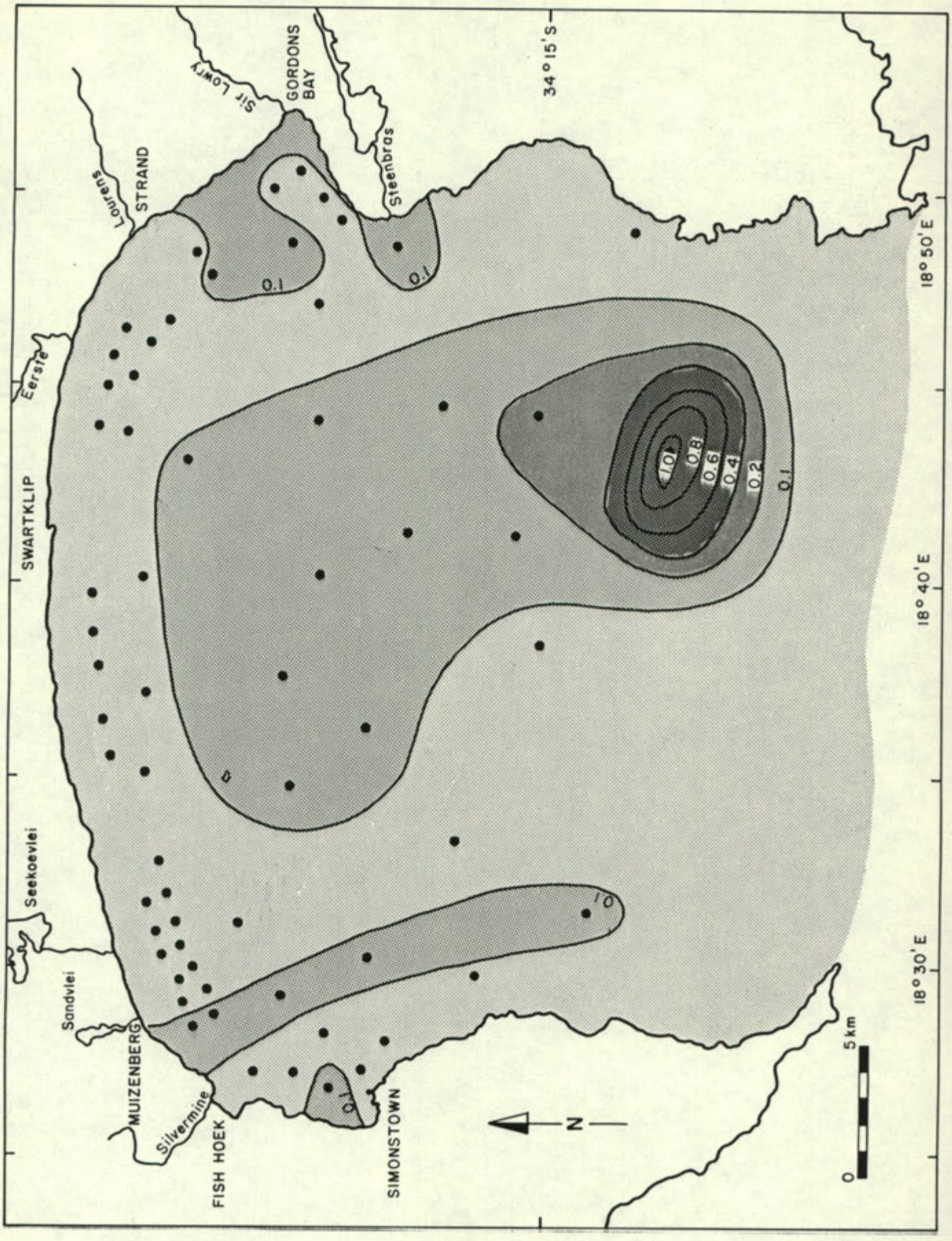


Fig. 33. Distribution of Ni in carbonate and reducible fraction of False Bay sediments (μg/g)

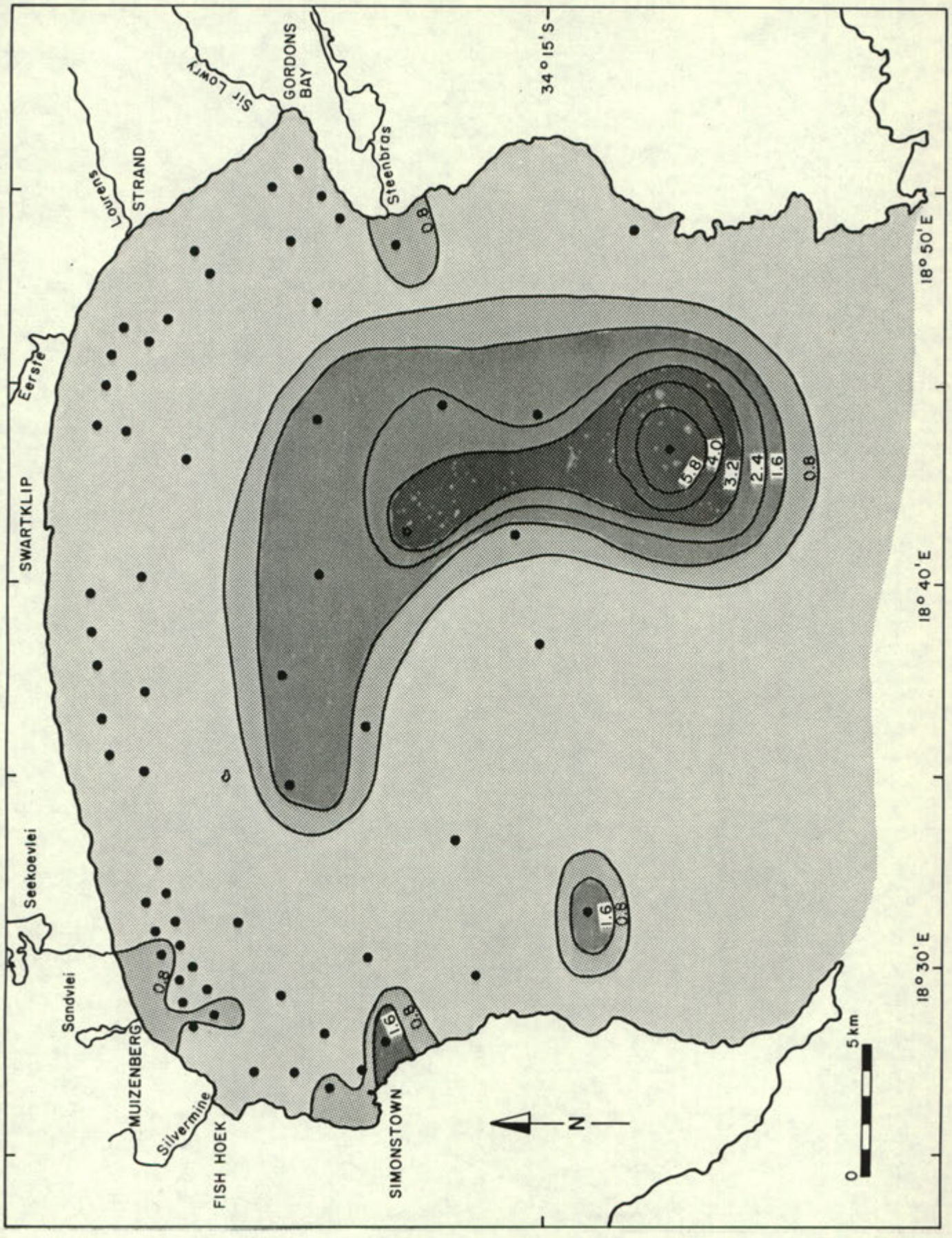


Fig. 34. Distribution of Ni in organic and sulphide fraction of False Bay sediments (µg/g)

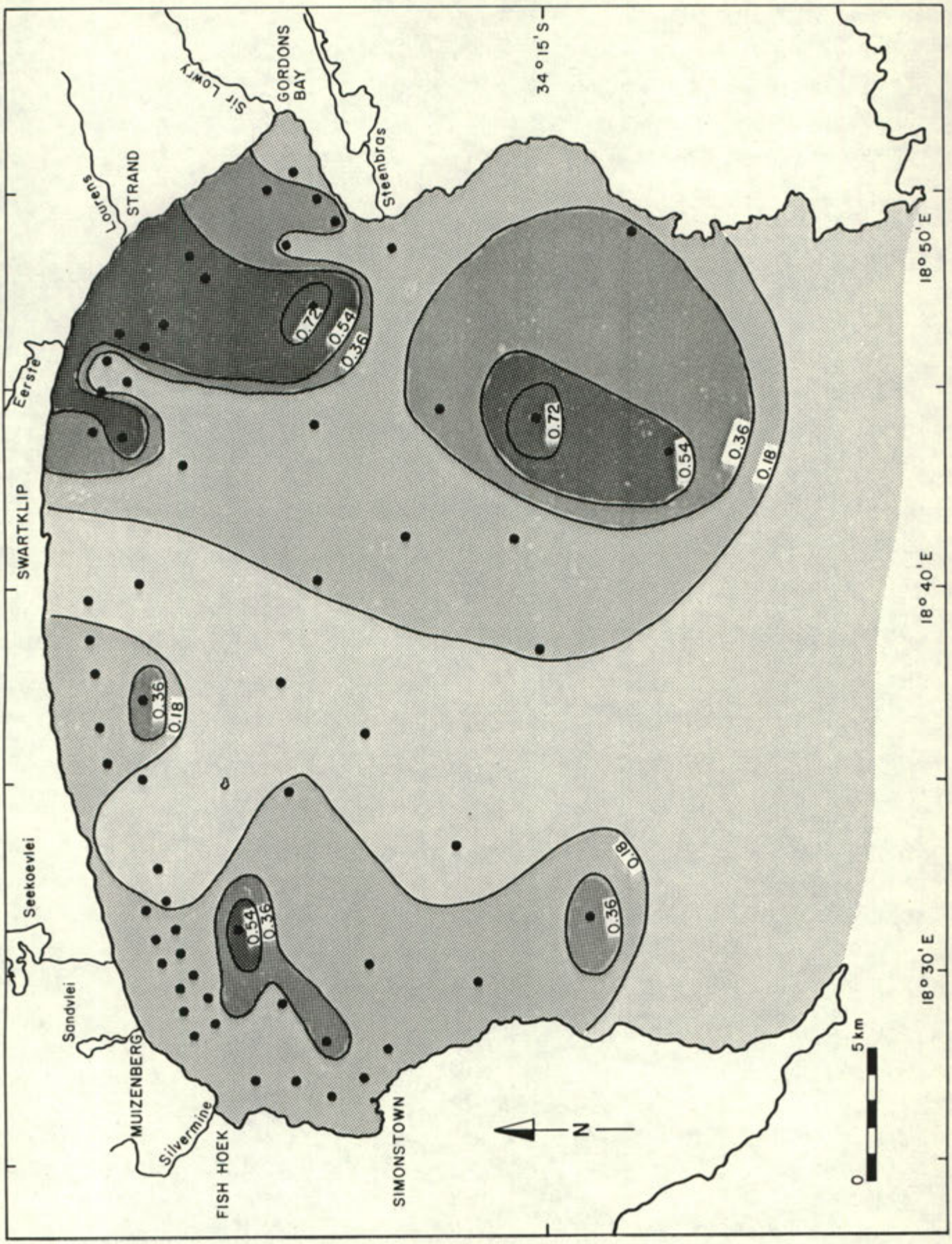


Fig. 35. Distribution of Ni in residual fraction of False Bay sediments (µg/g)

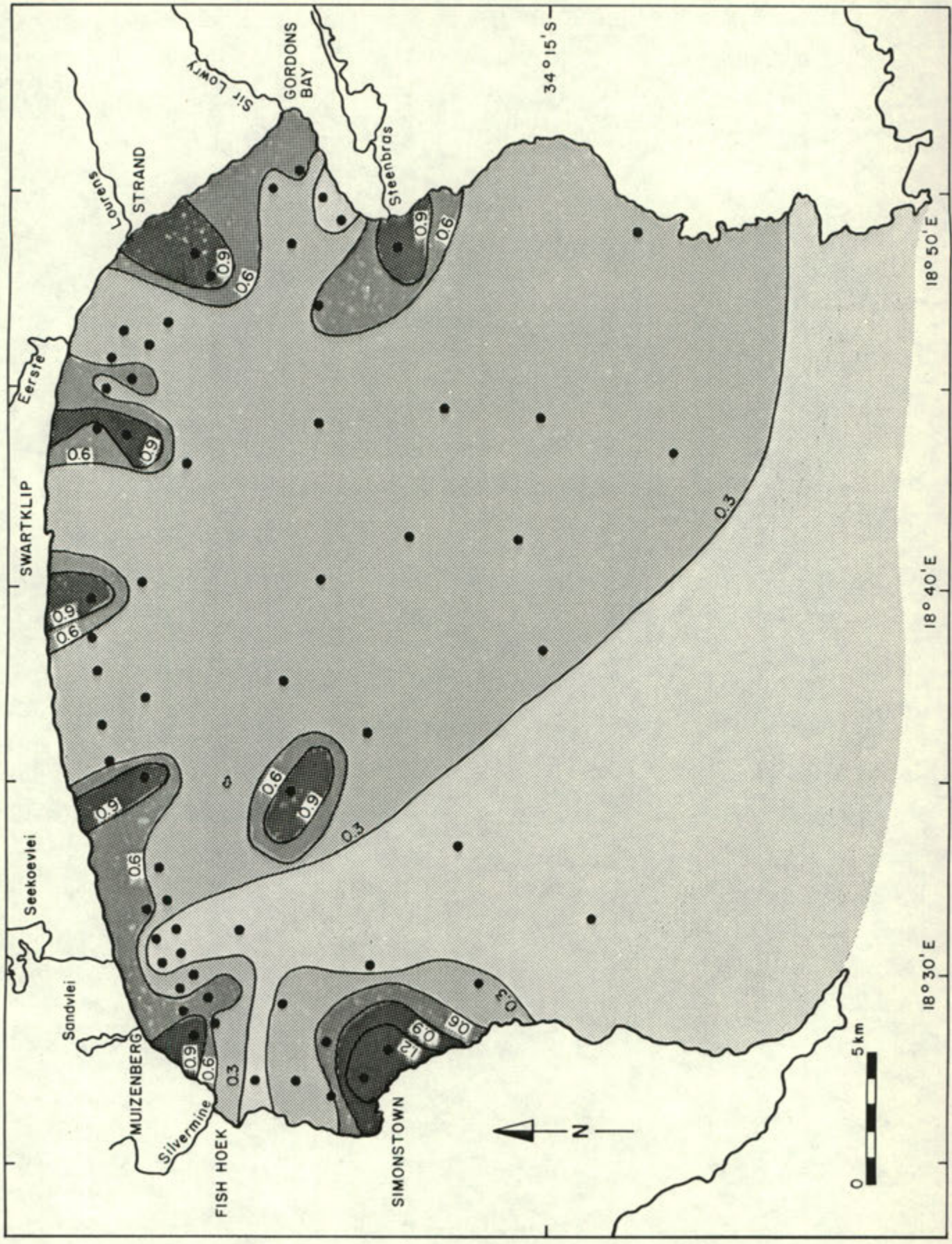


Fig. 36. Distribution of Pb in carbonate and reducible fraction of False Bay sediments (µg/g)

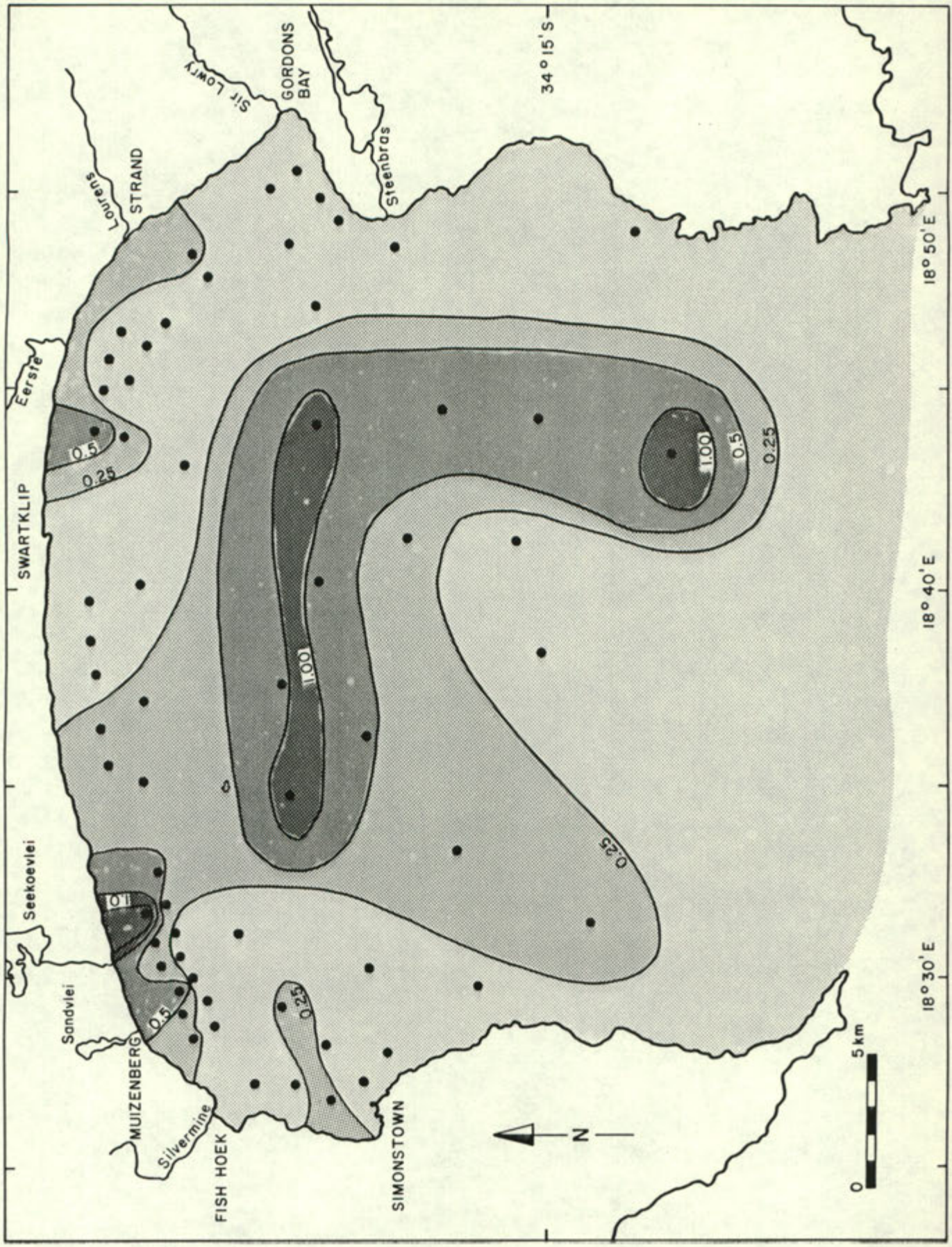


Fig. 37. Distribution of Pb in organic and sulphide fraction of False Bay sediments (µg/g)

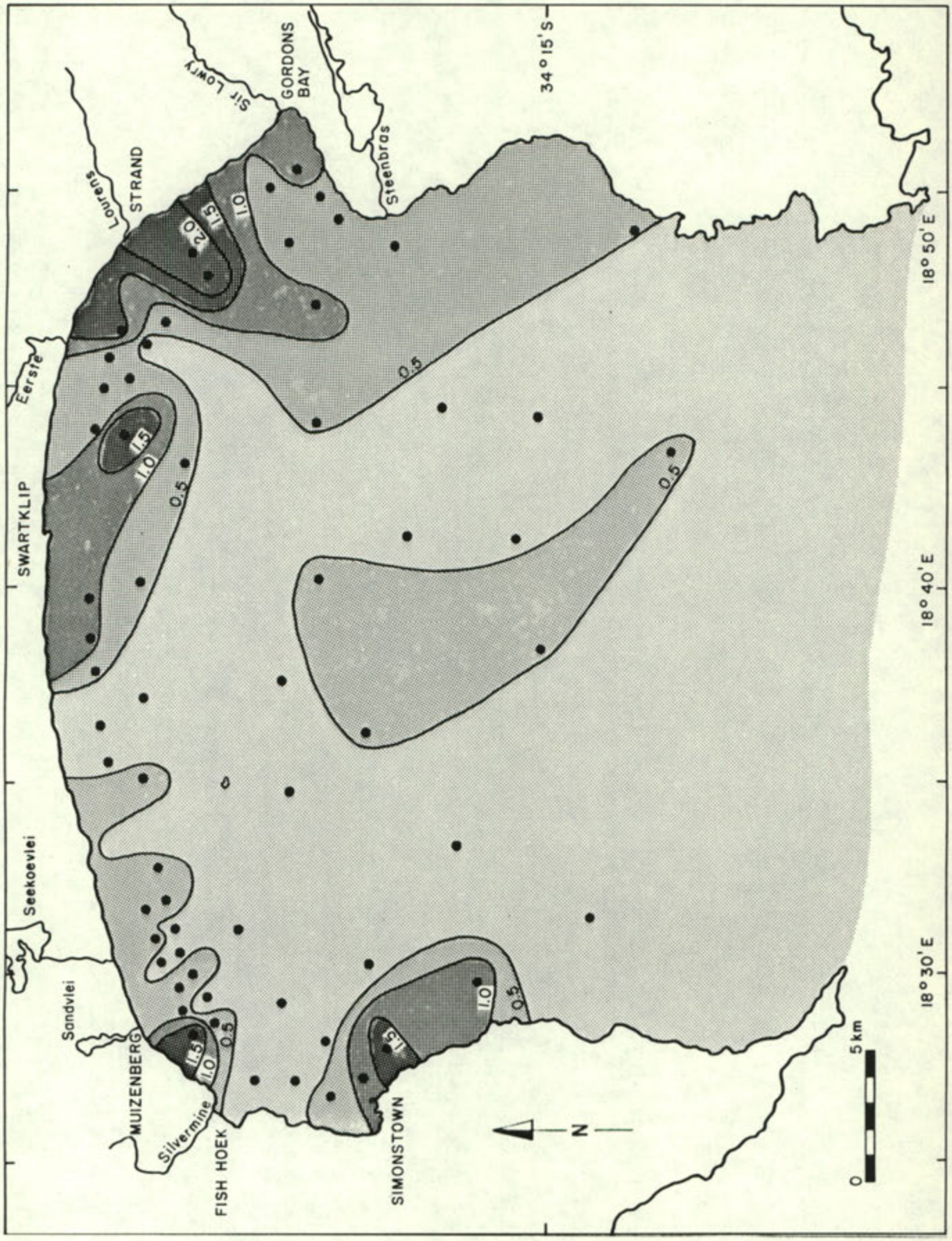


Fig. 38. Distribution of Pb in residual fraction of False Bay sediments (μg/g)

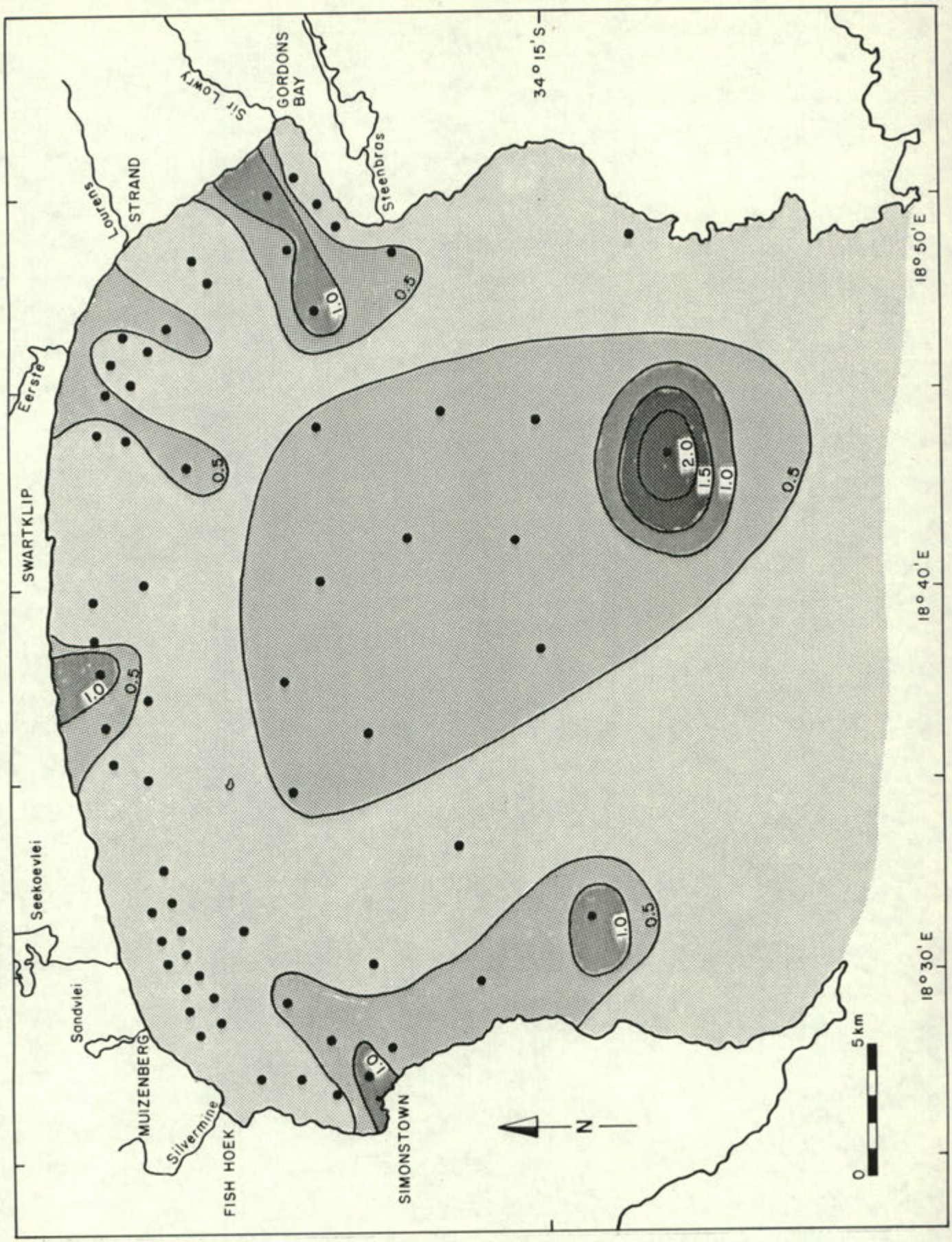


Fig. 39. Distribution of Zn in carbonate and reducible fraction of False Bay sediments (μg/g).

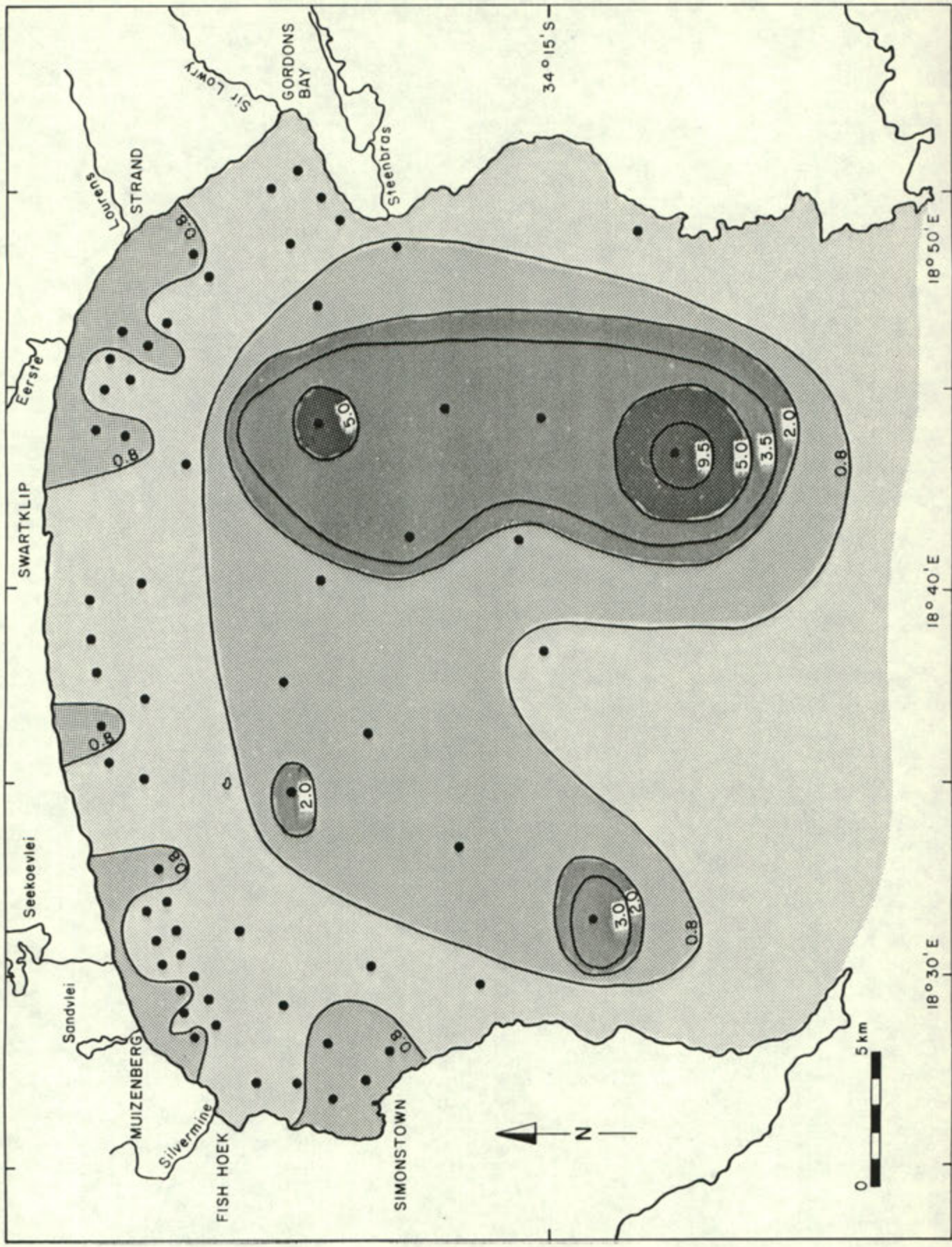


Fig. 40. Distribution of Zn in organic and sulphide fraction of False Bay sediments (μg/g)

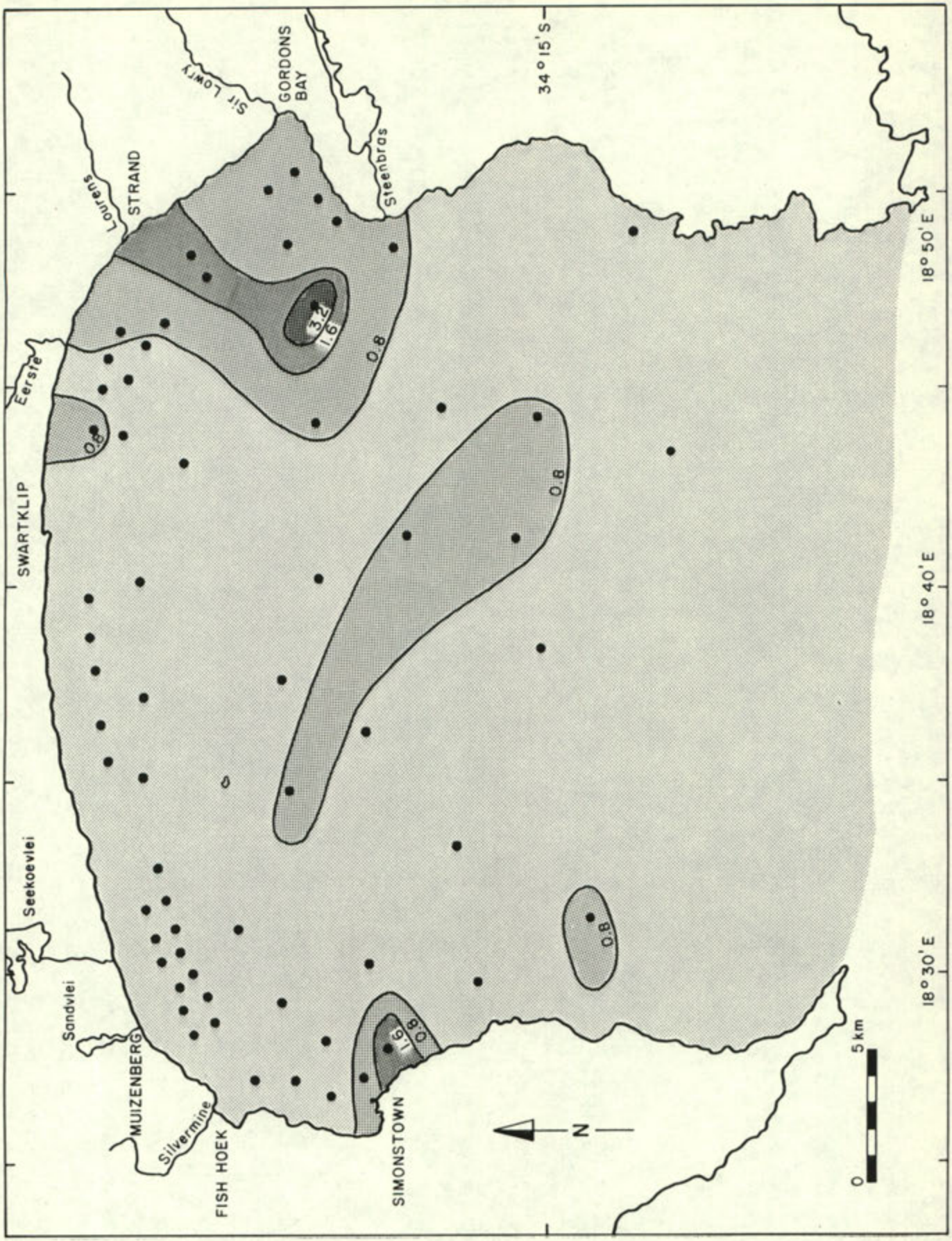


Fig. 41. Distribution of Zn in residual fraction of False Bay sediments (μg/g)

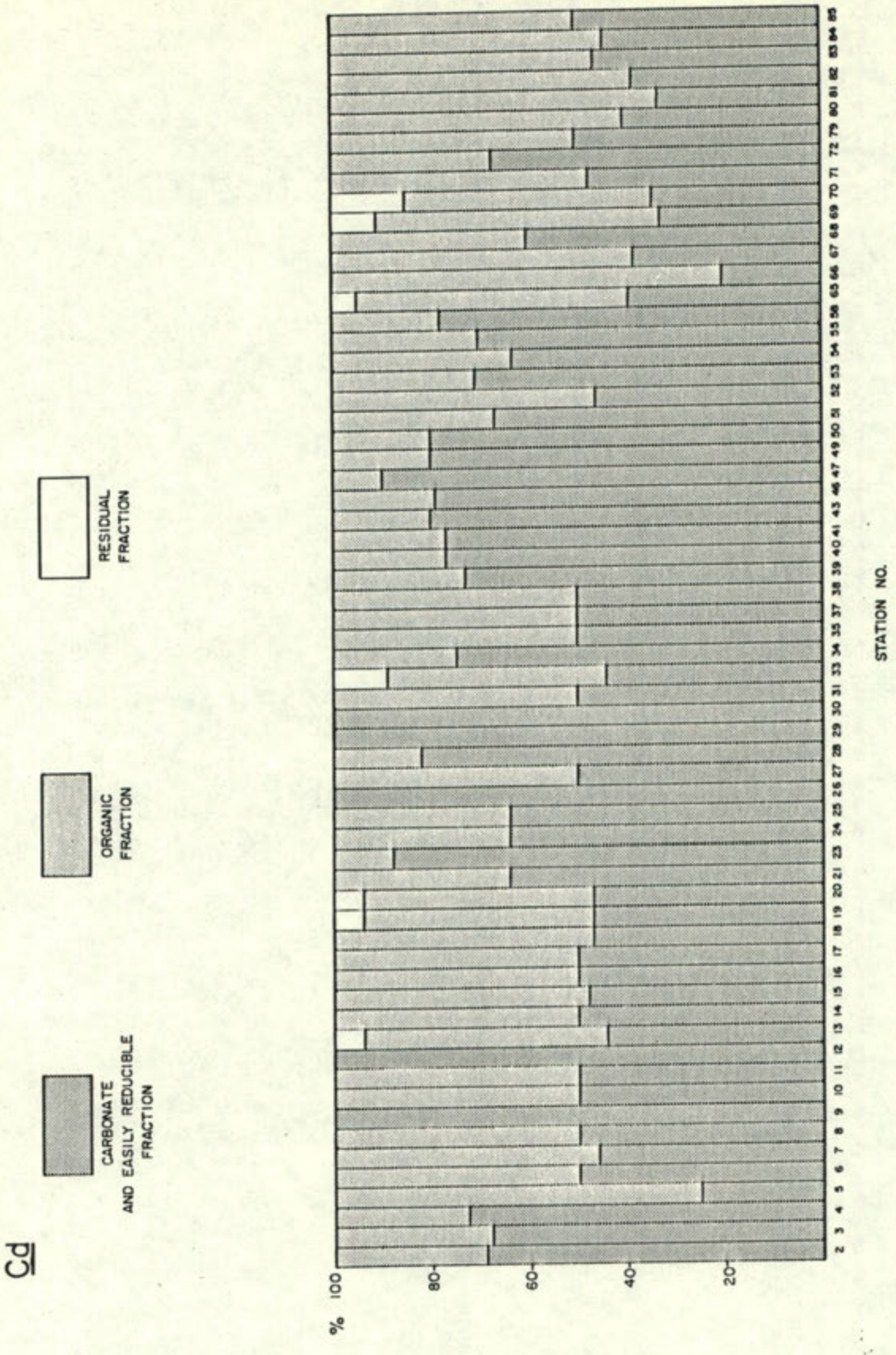


Fig. 42. Partitioning of Cd between different fractions in False Bay sediments (%)

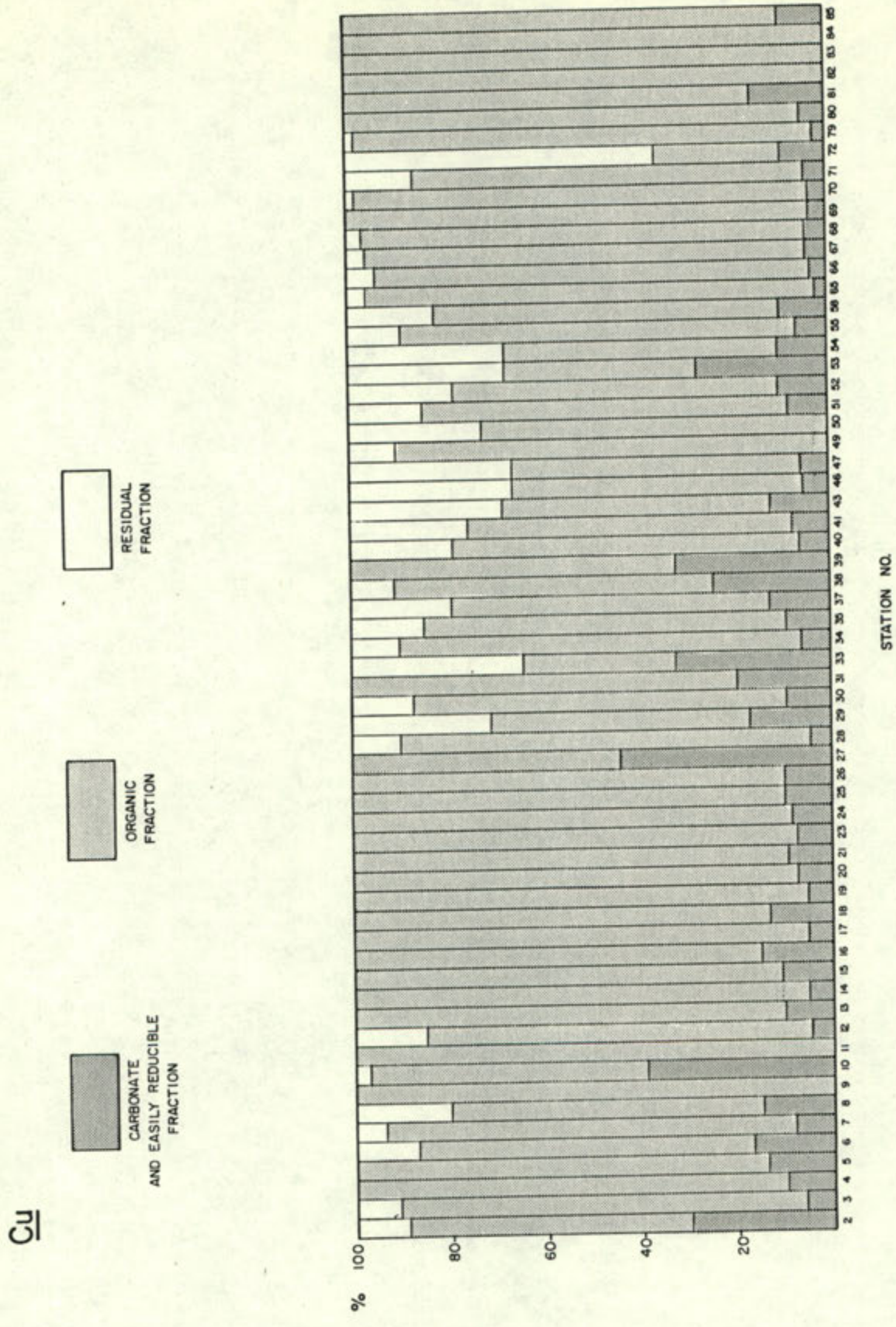


Fig. 43. Partitioning of Cu between different fractions in False Bay sediments (%)

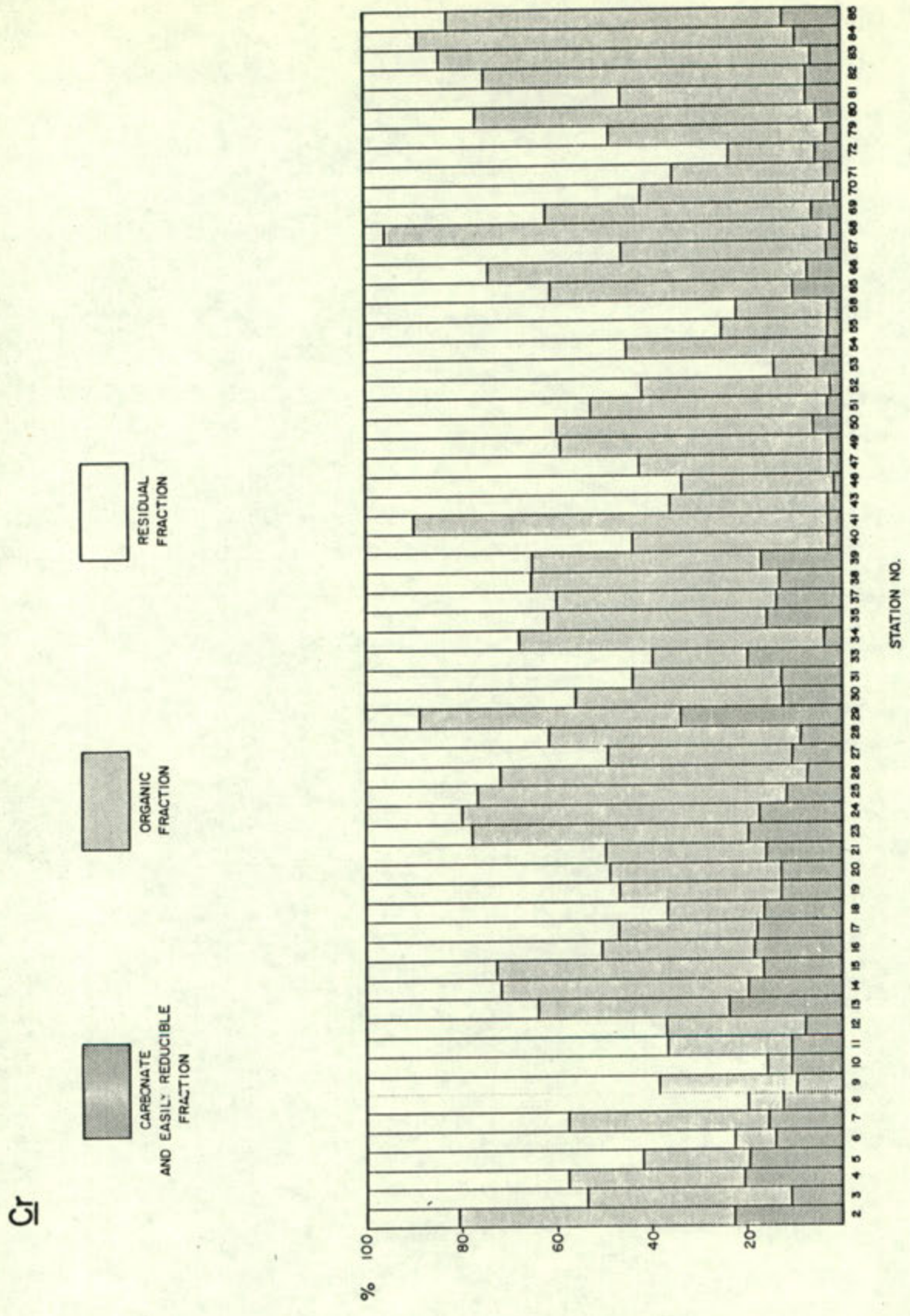


Fig. 44. Partitioning of Cr between different fractions in False Bay sediments (%)

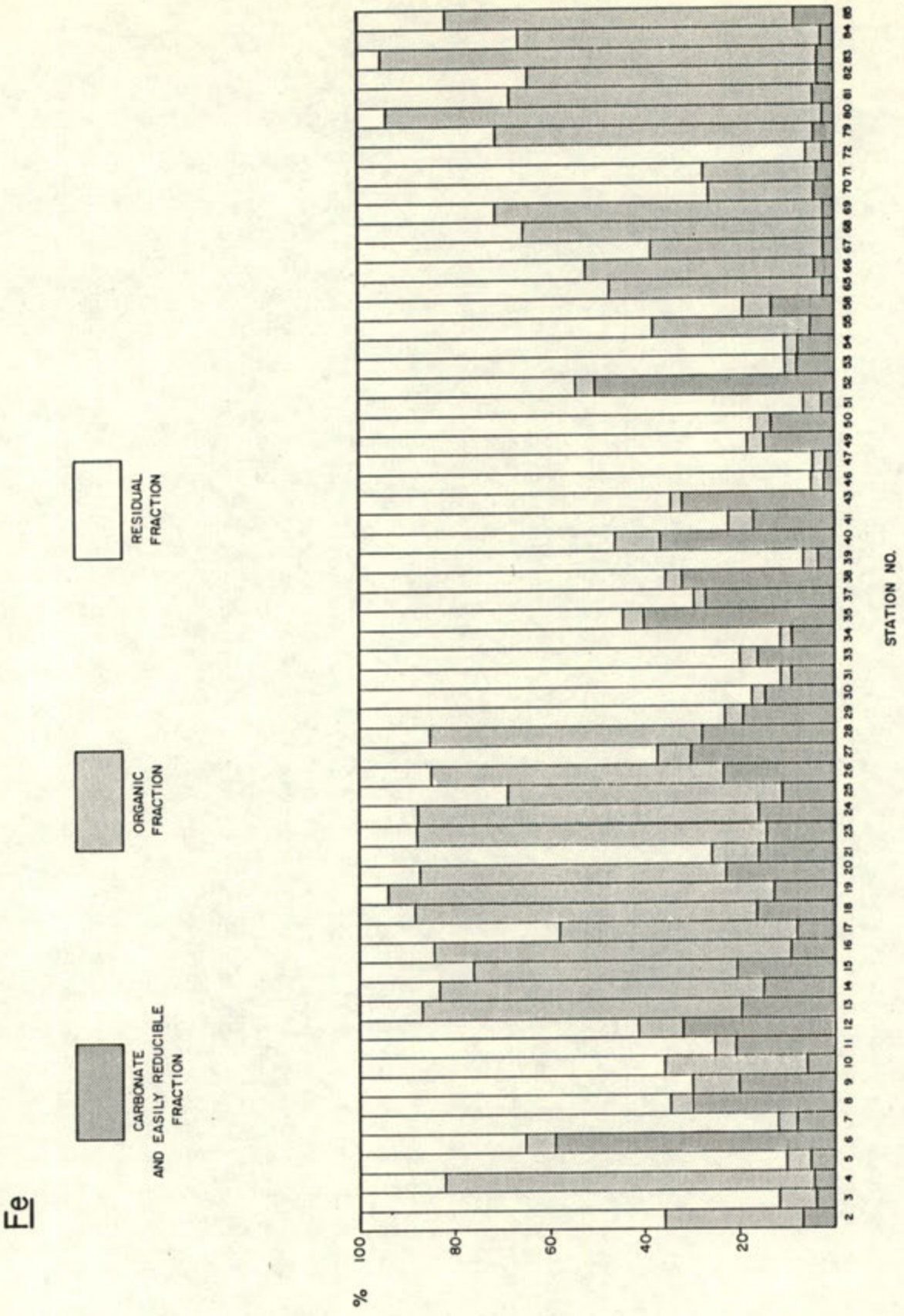


Fig. 45. Partitioning of Fe between different fractions of False Bay sediments (%)

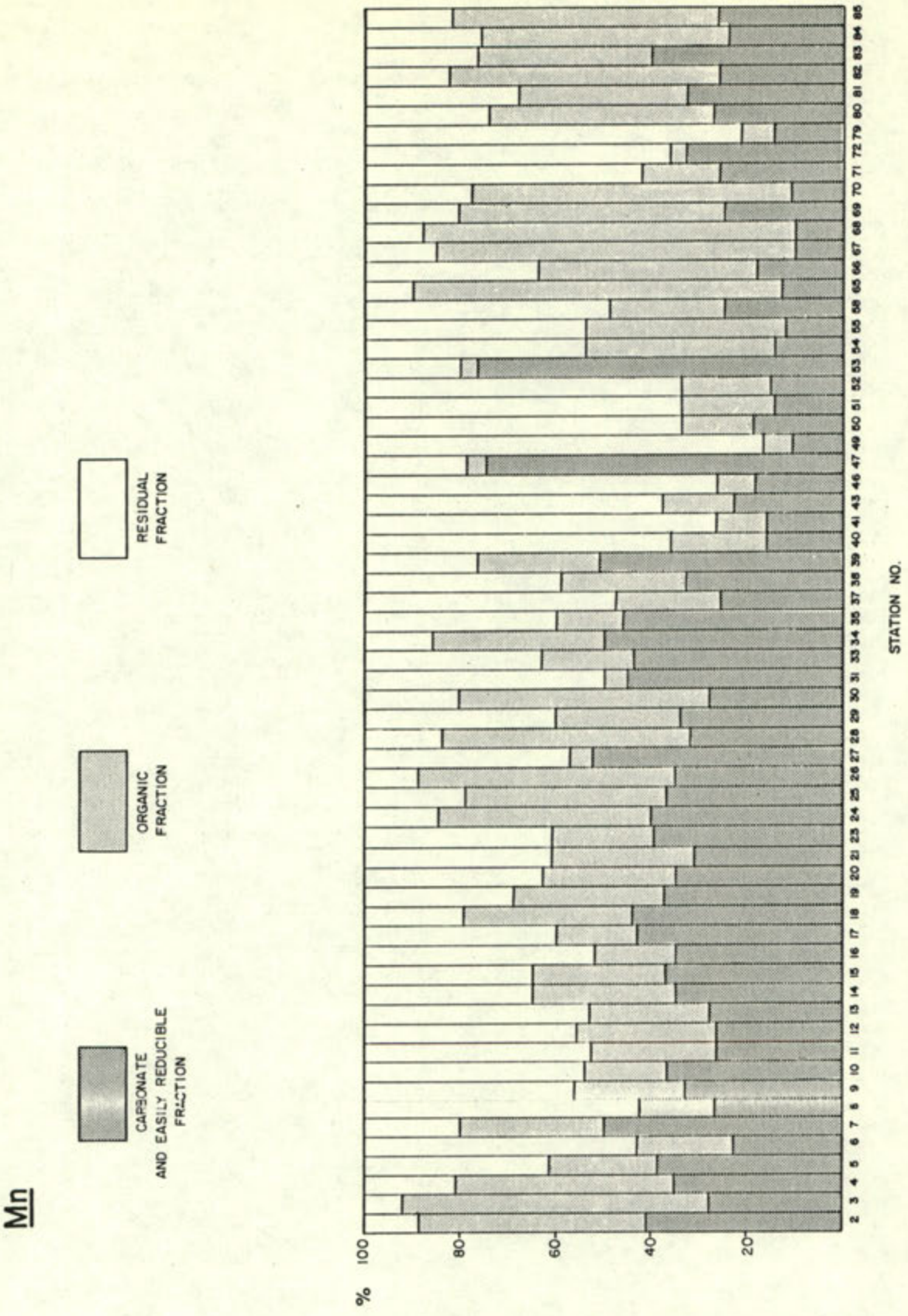


Fig. 46. Partitioning of Mn between different fractions in False Bay sediments (%)

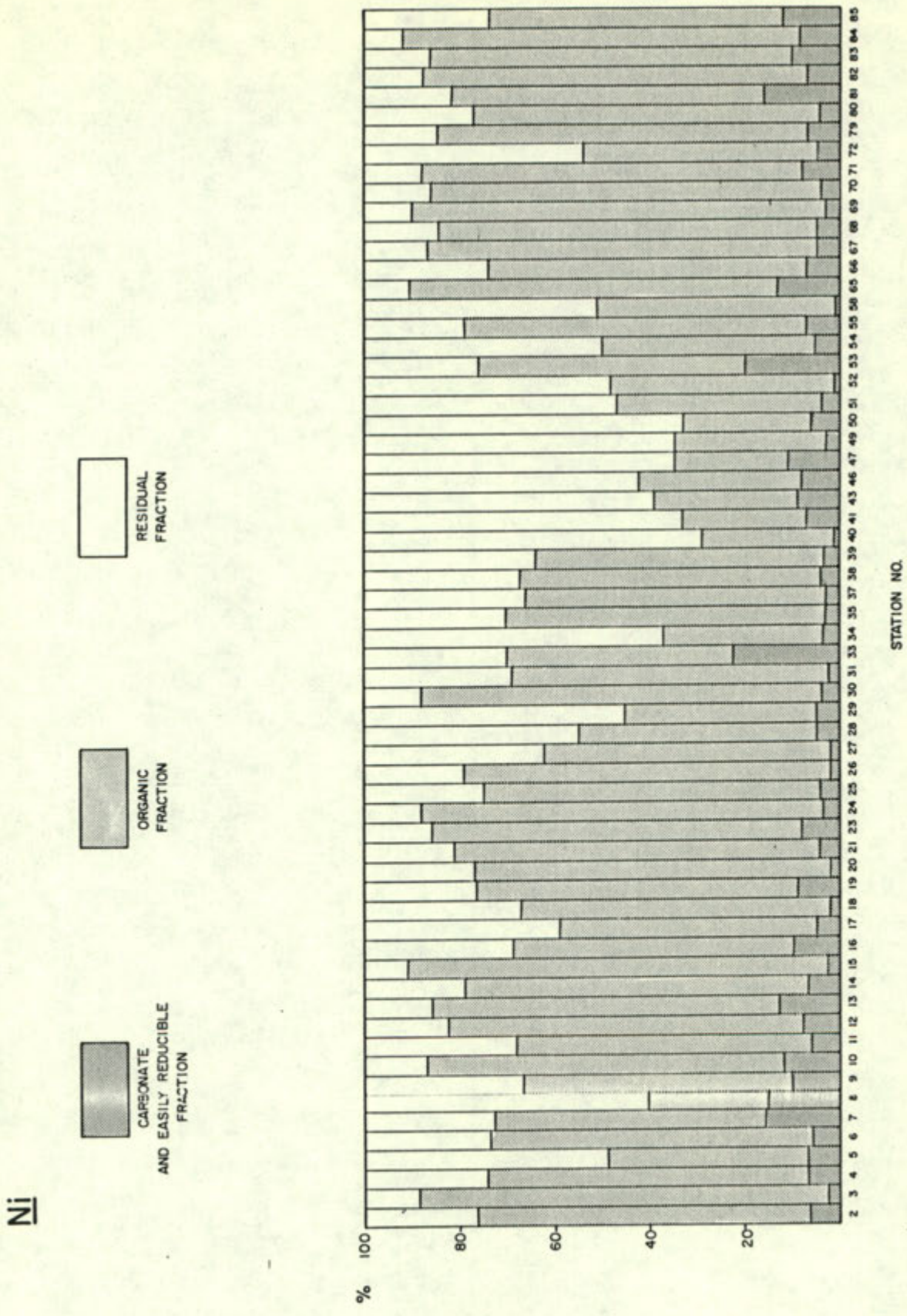


Fig. 47. Partitioning of Ni between different fractions in False Bay sediments (%)

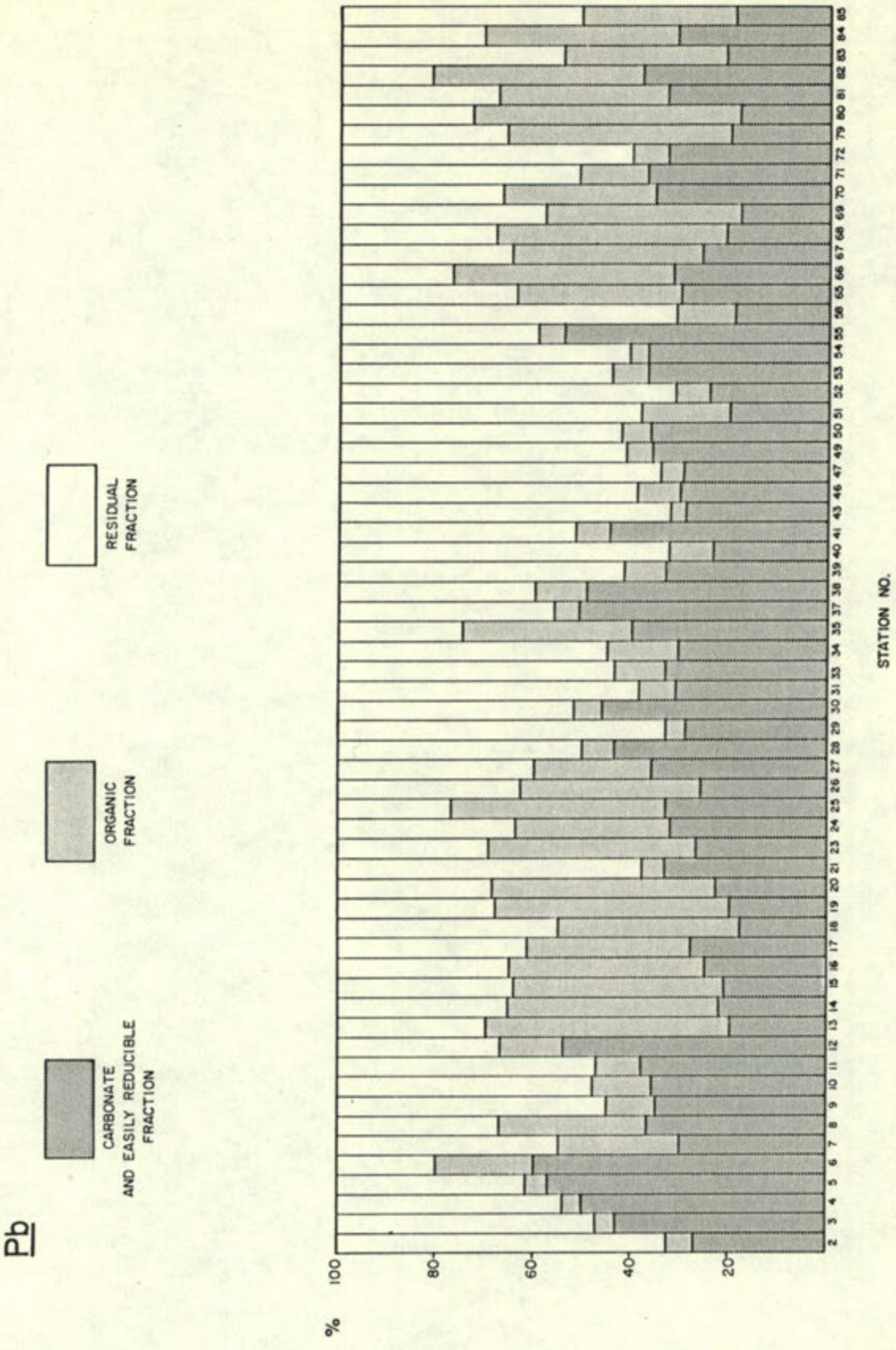


Fig. 48. Partitioning of Pb between different fractions in False Bay sediments (%)

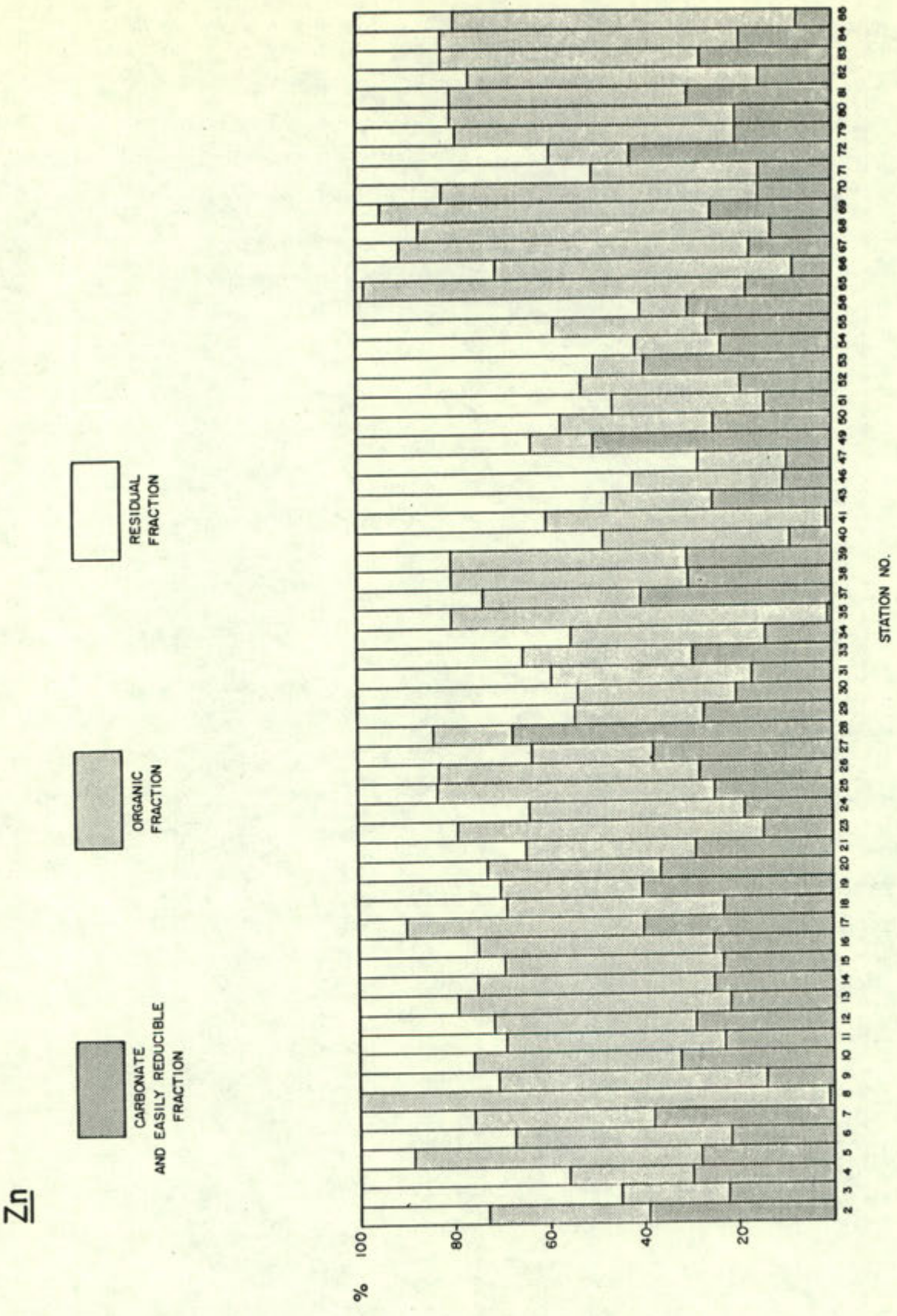


Fig. 49. Partitioning of Zn between different fractions in False Bay sediments (%)

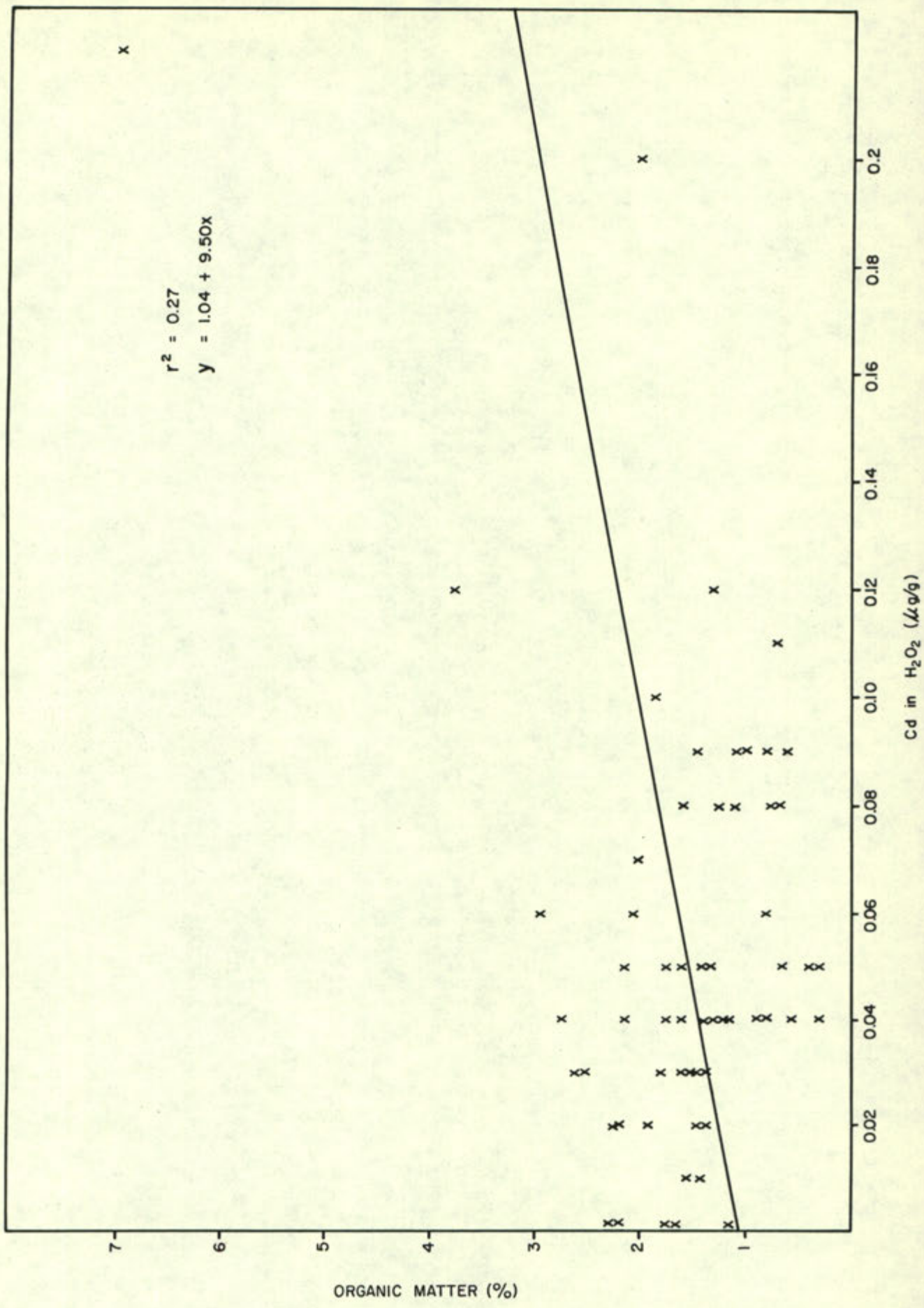


Fig. 50. Correlation between Cd (H_2O_2) and organic matter in oxidizable fraction

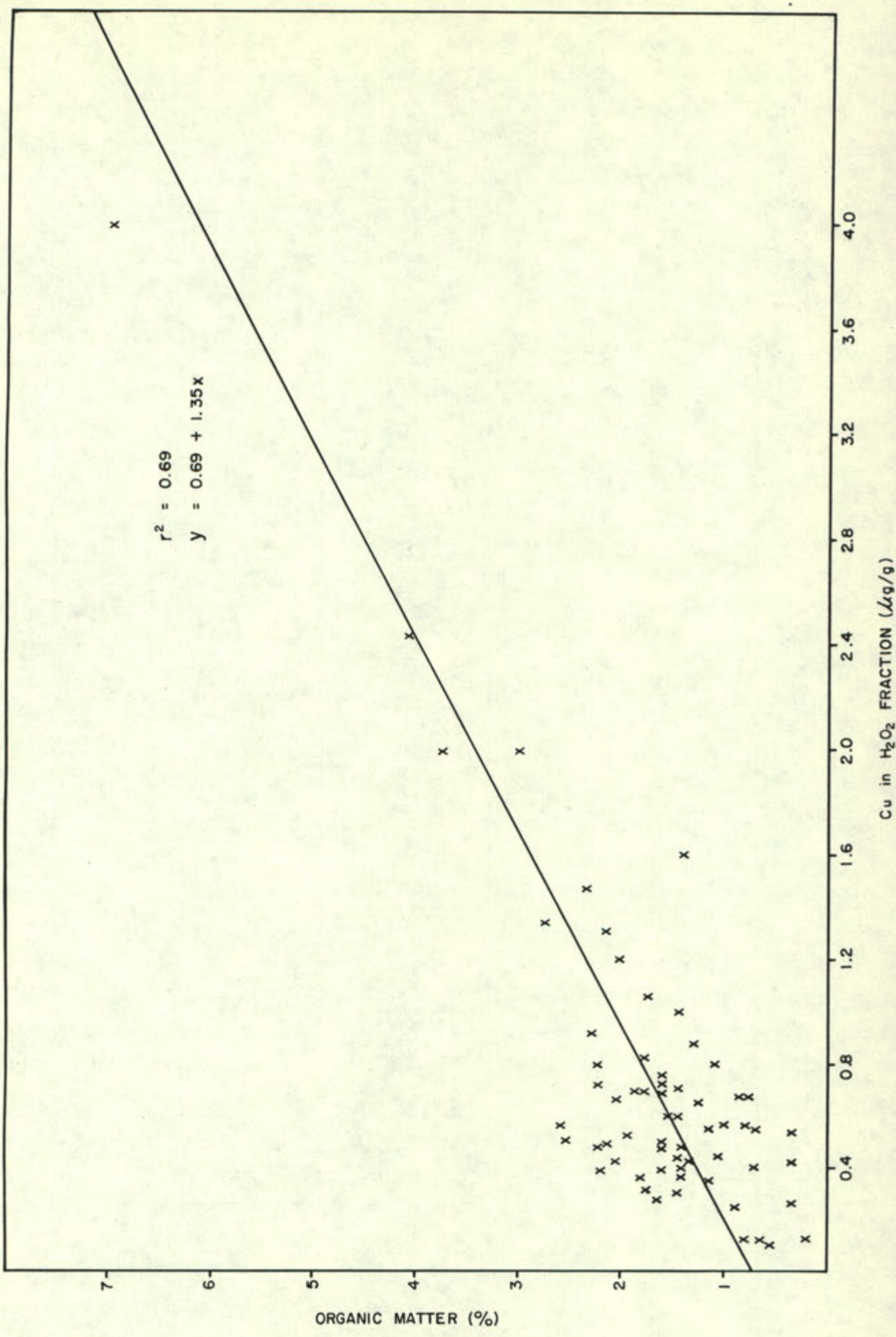


Fig. 51. Correlation between Cu (H_2O_2) and organic matter in oxidizable fraction

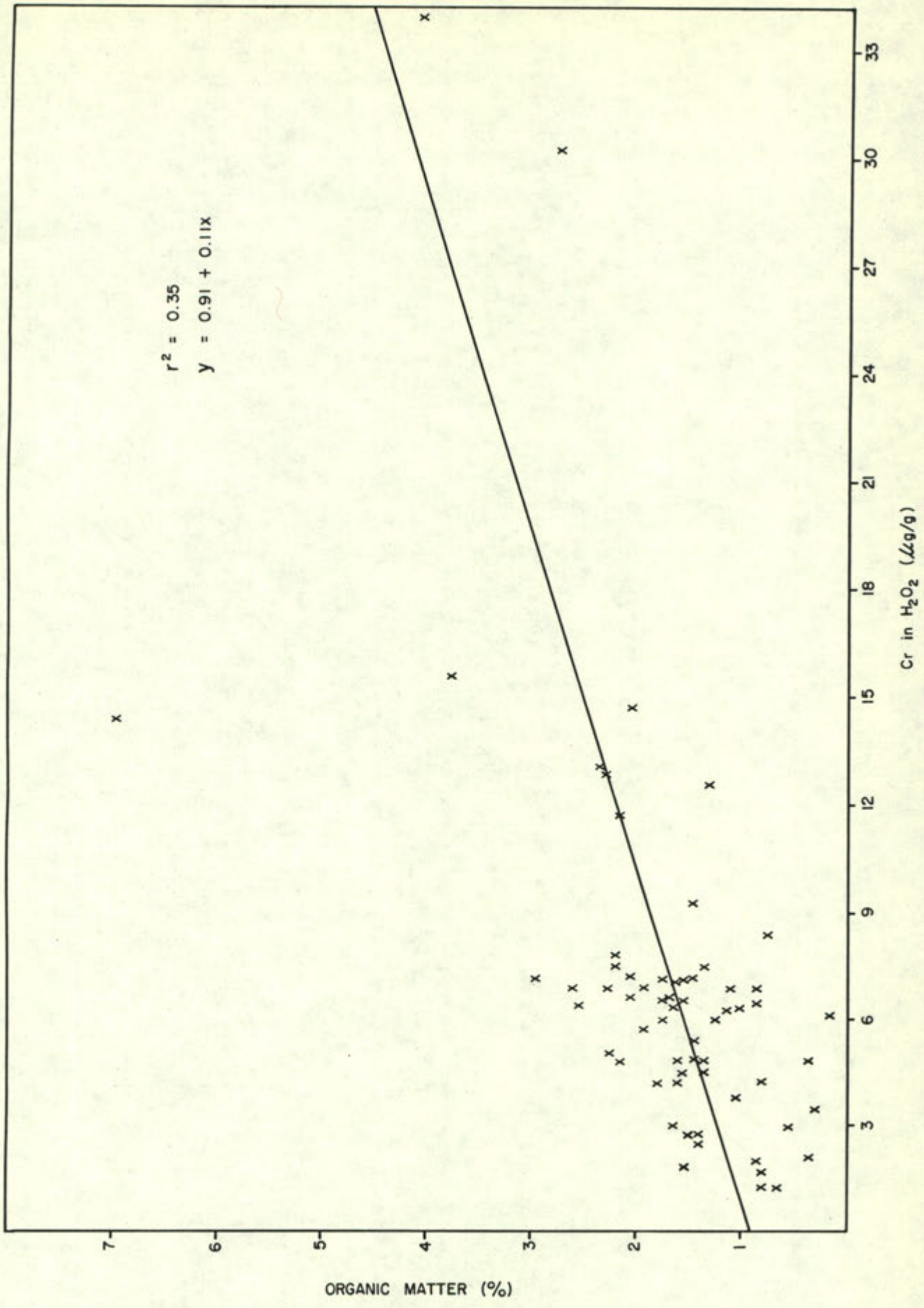


Fig. 52. Correlation between Cr (H_2O_2) and organic matter in oxidizable fraction

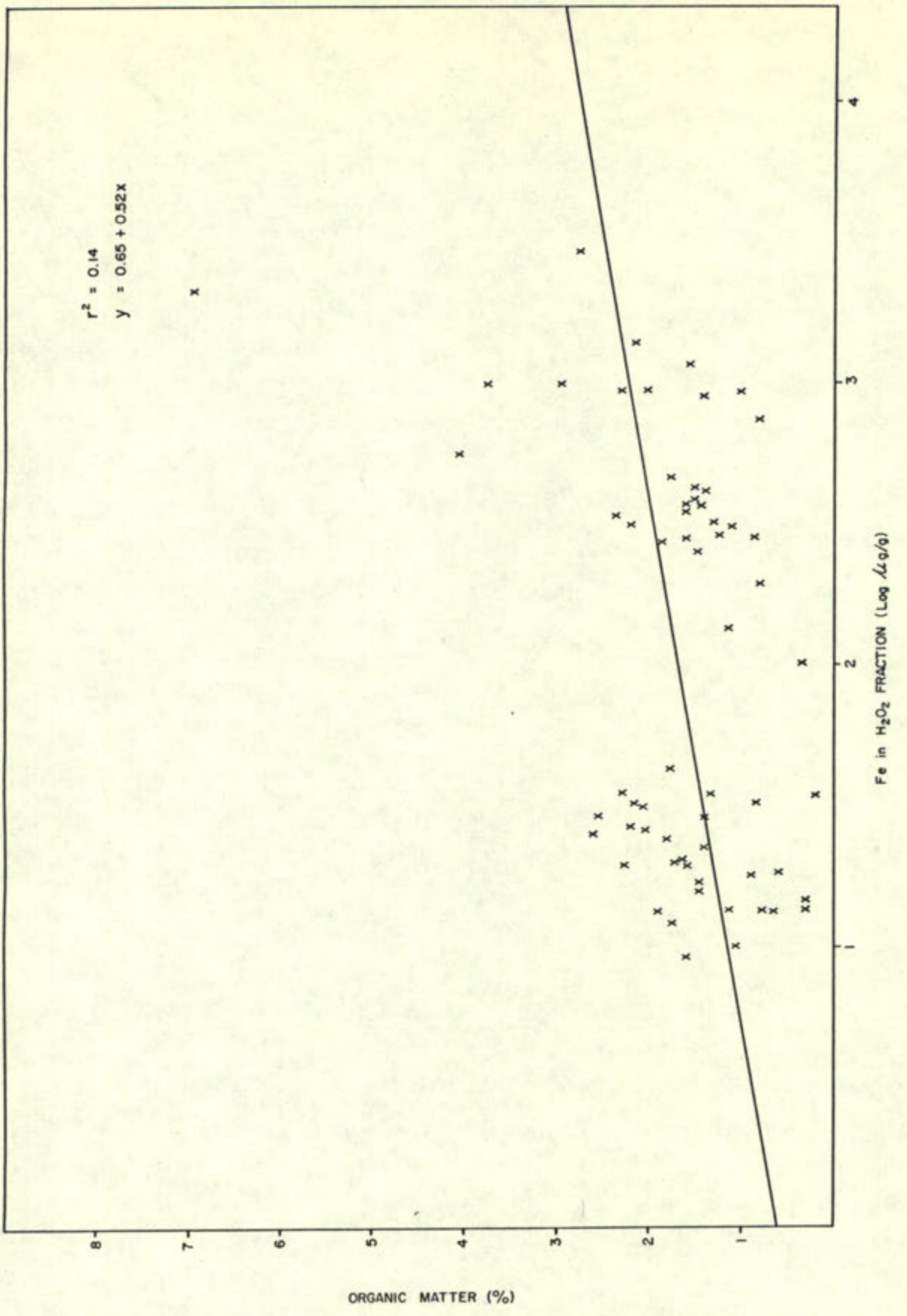


Fig. 53. Correlation between Fe (H_2O_2) and organic matter in oxidizable fraction

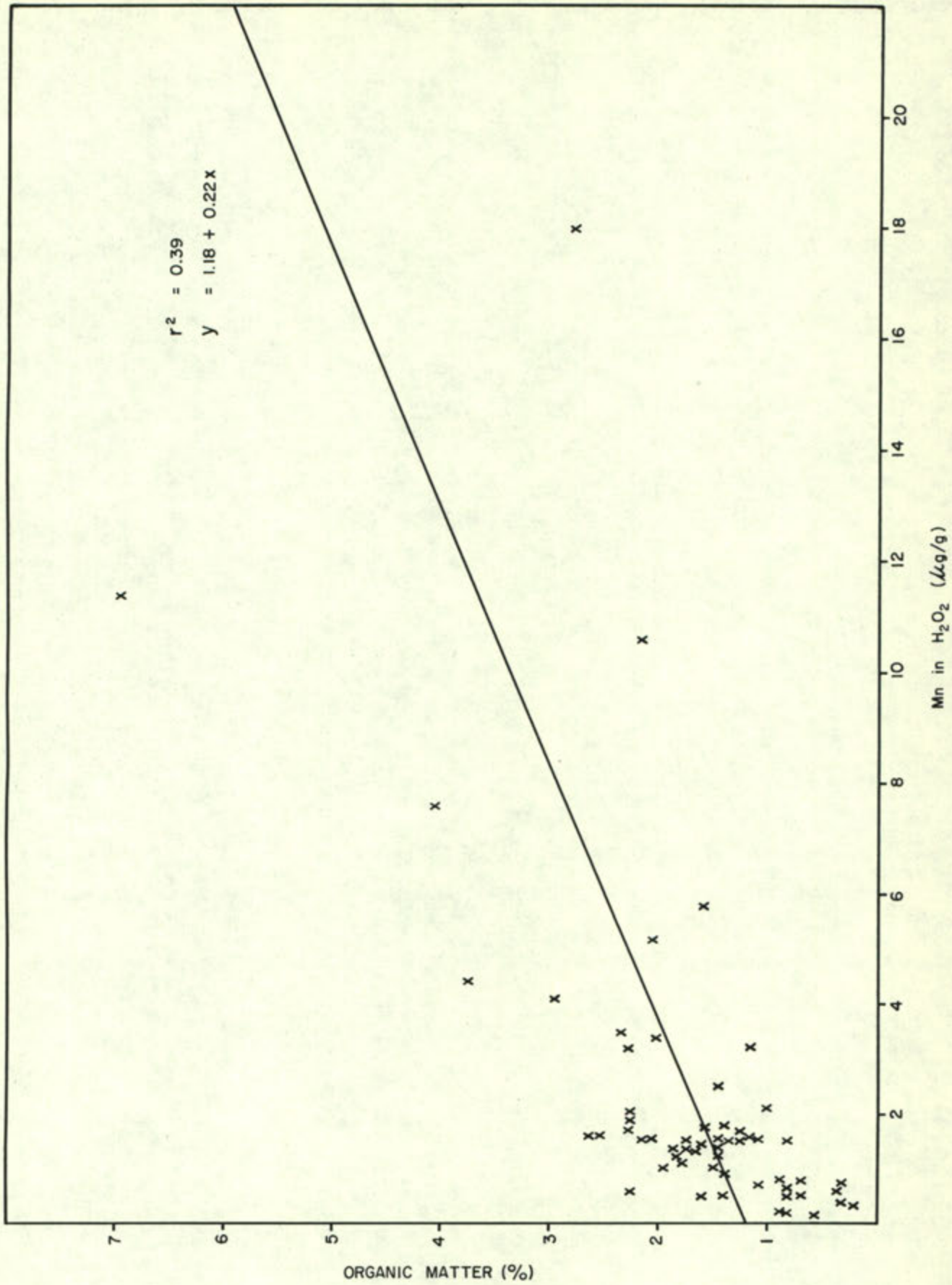


Fig. 54. Correlation between Mn (H_2O_2) and organic matter in oxidizable fraction

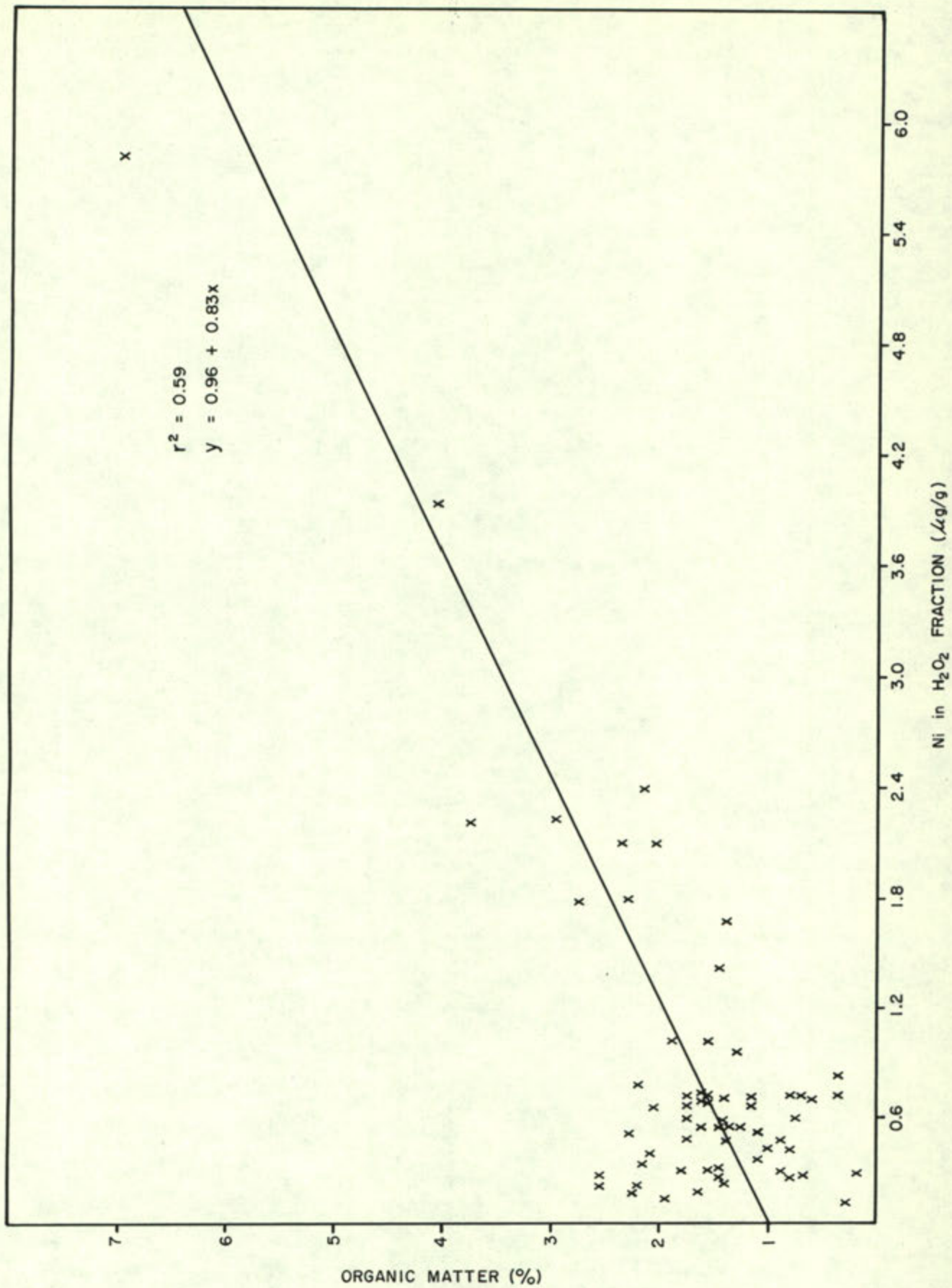


Fig. 55. Correlation between Ni (H_2O_2) and organic matter in oxidizable fraction

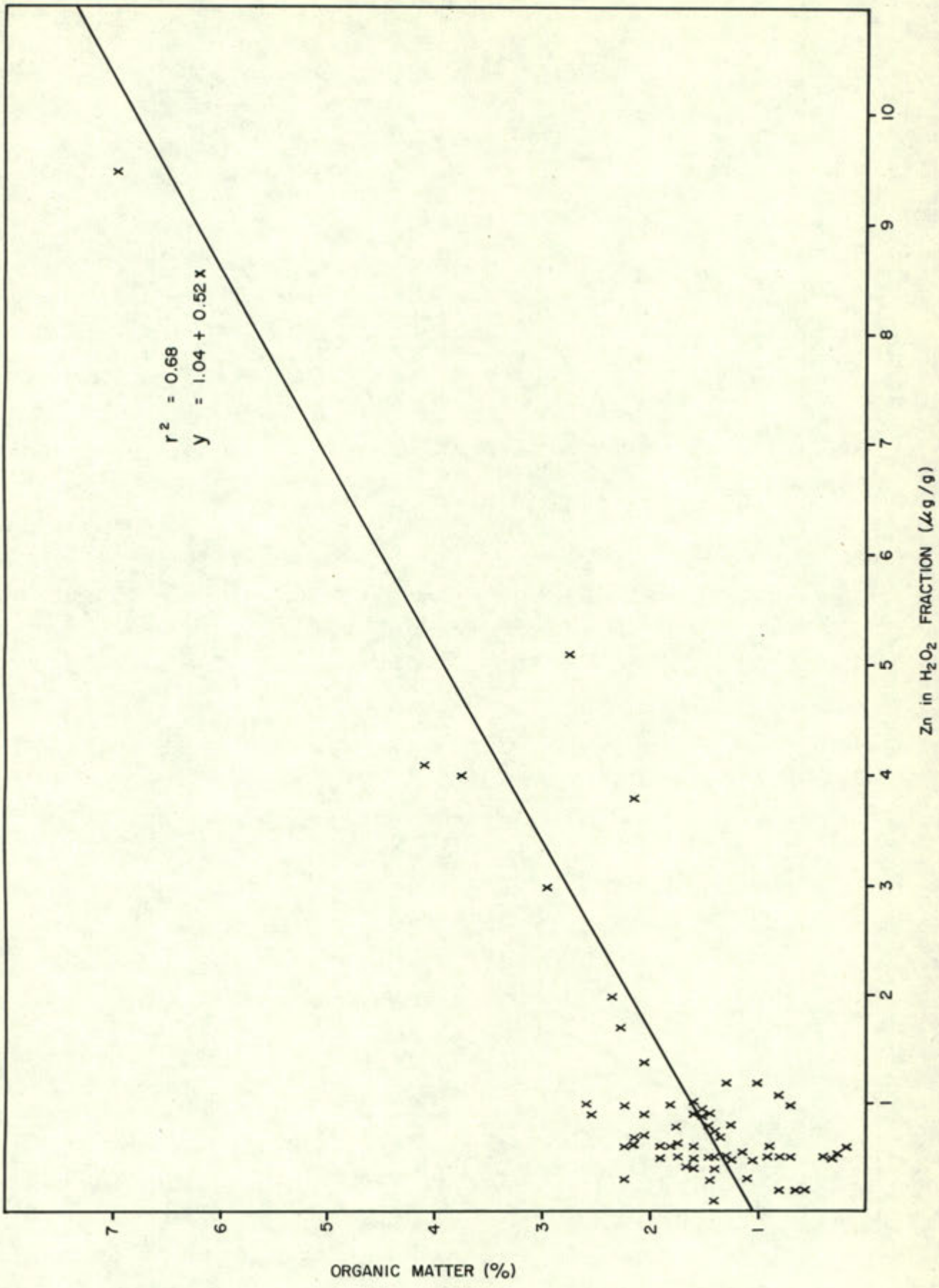
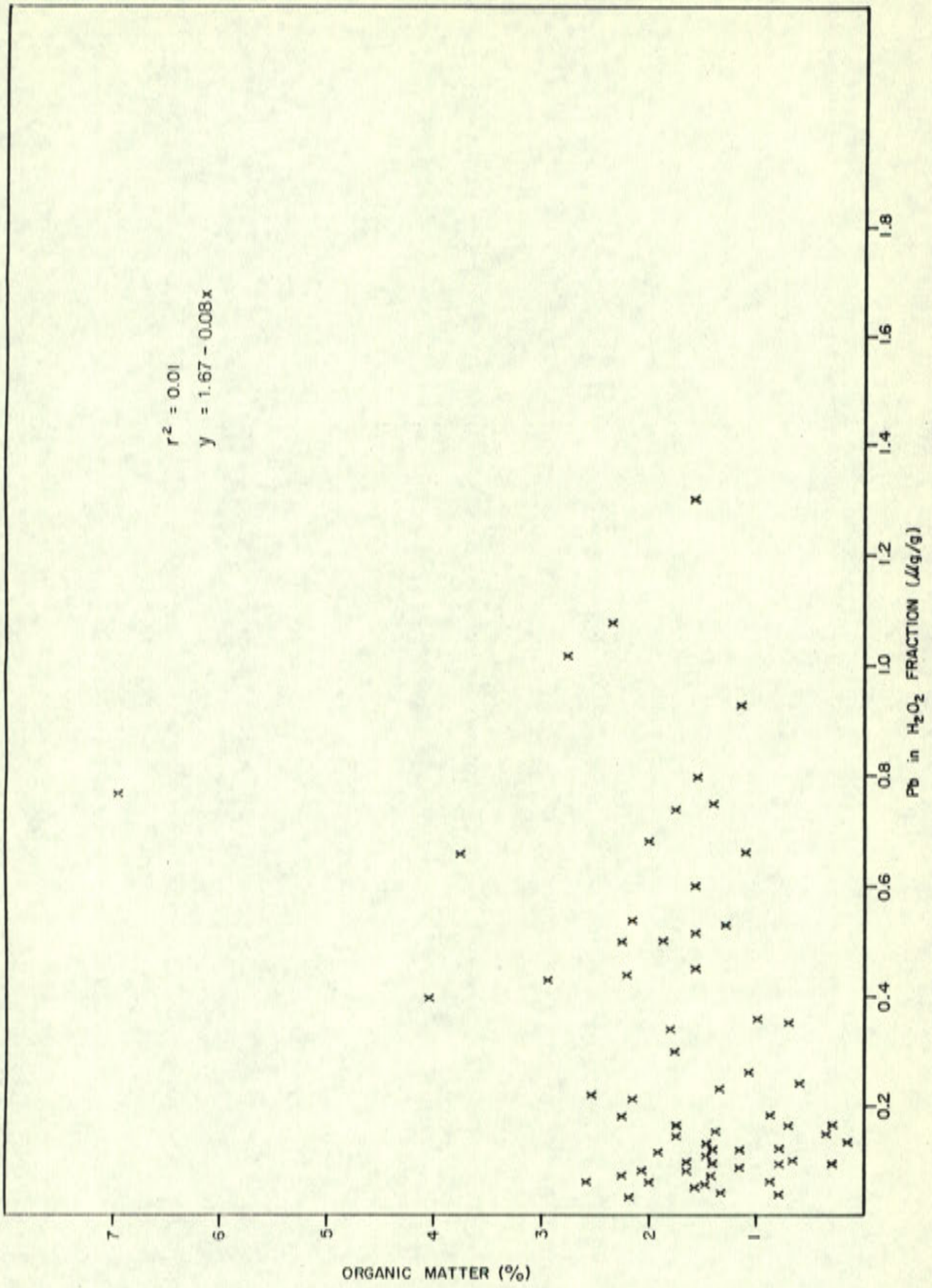


Fig. 56. Correlation between Zn (H_2O_2) and organic matter in oxidizable fraction



. 57. Correlation between Pb (H_2O_2) and organic matter in oxidizable fraction

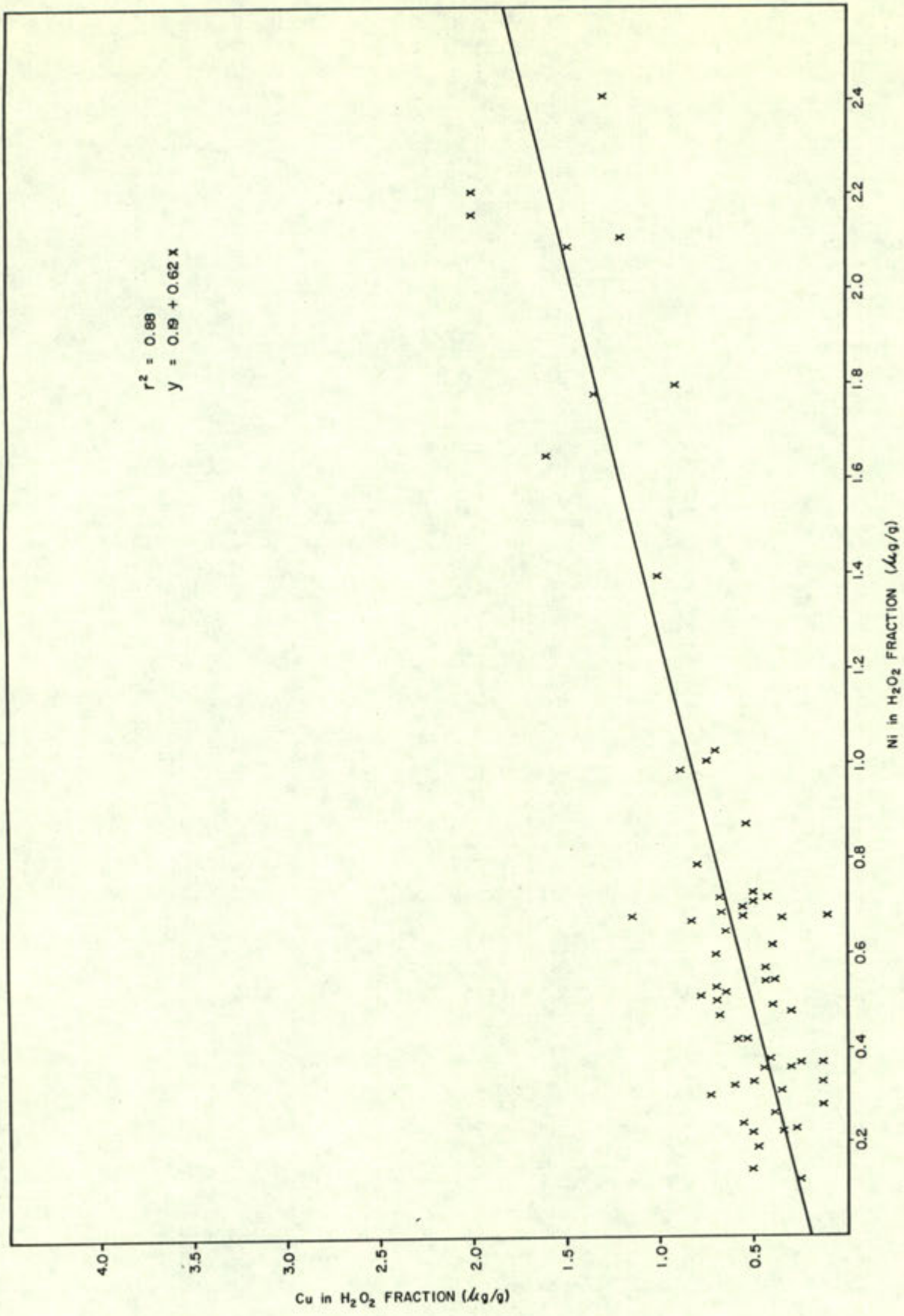


Fig. 58. Correlation between Ni and Cu in oxidizable fraction

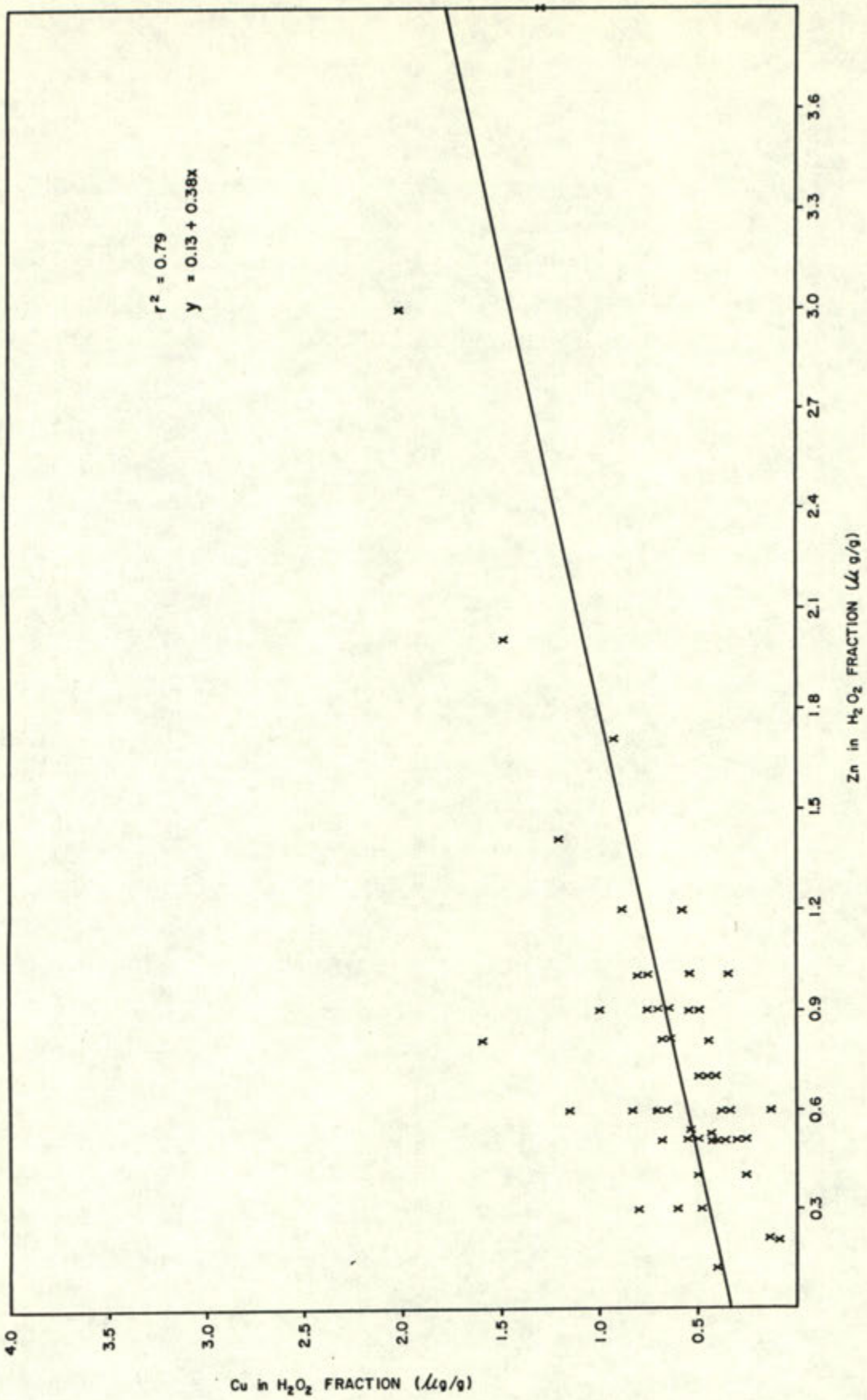


Fig. 59. Correlation between Zn and Cu in oxidizable fraction

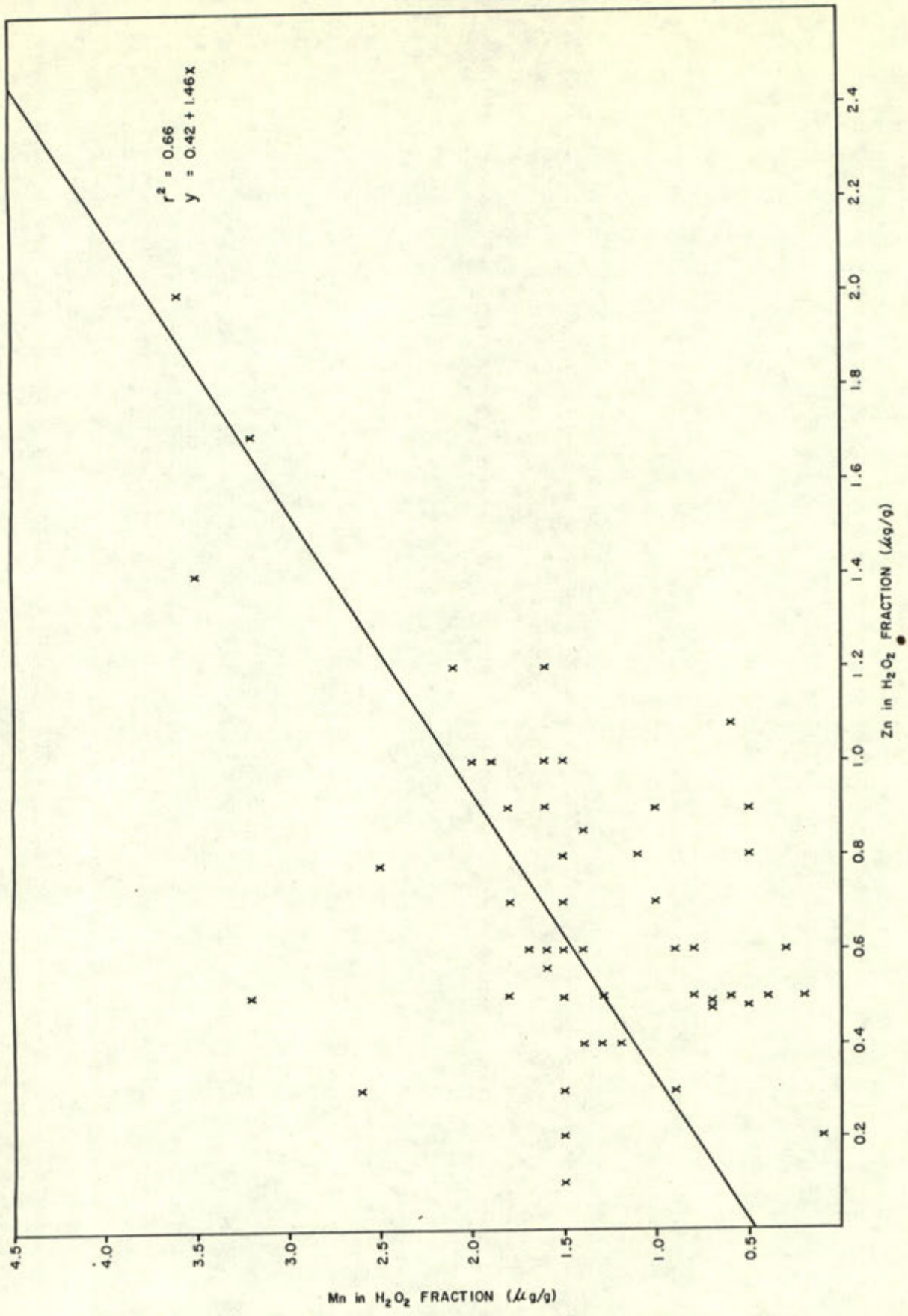


Fig. 60. Correlation between Zn and Mn in oxidizable fraction

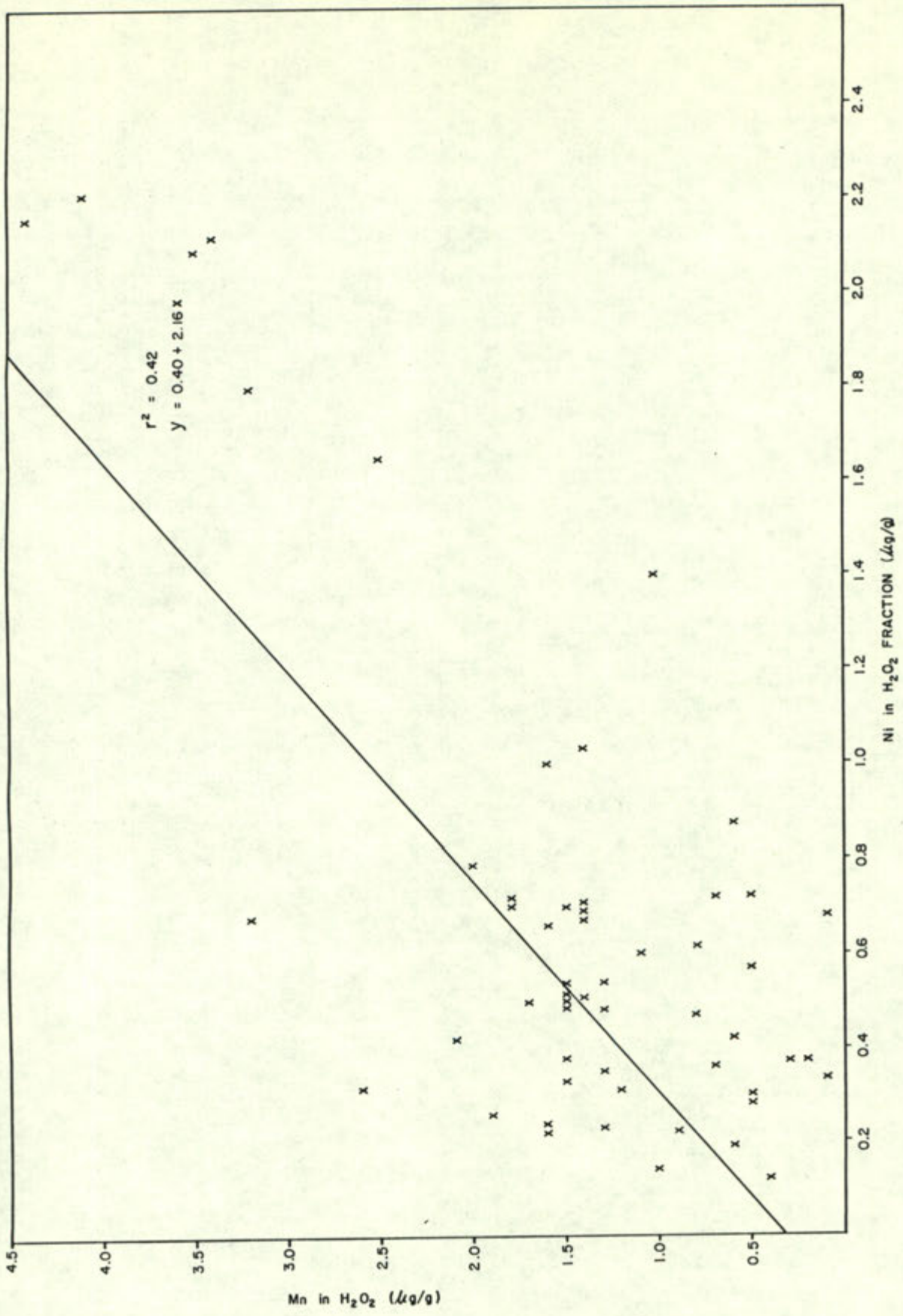


Fig. 61. Correlation between Ni and Mn in oxidizable fraction

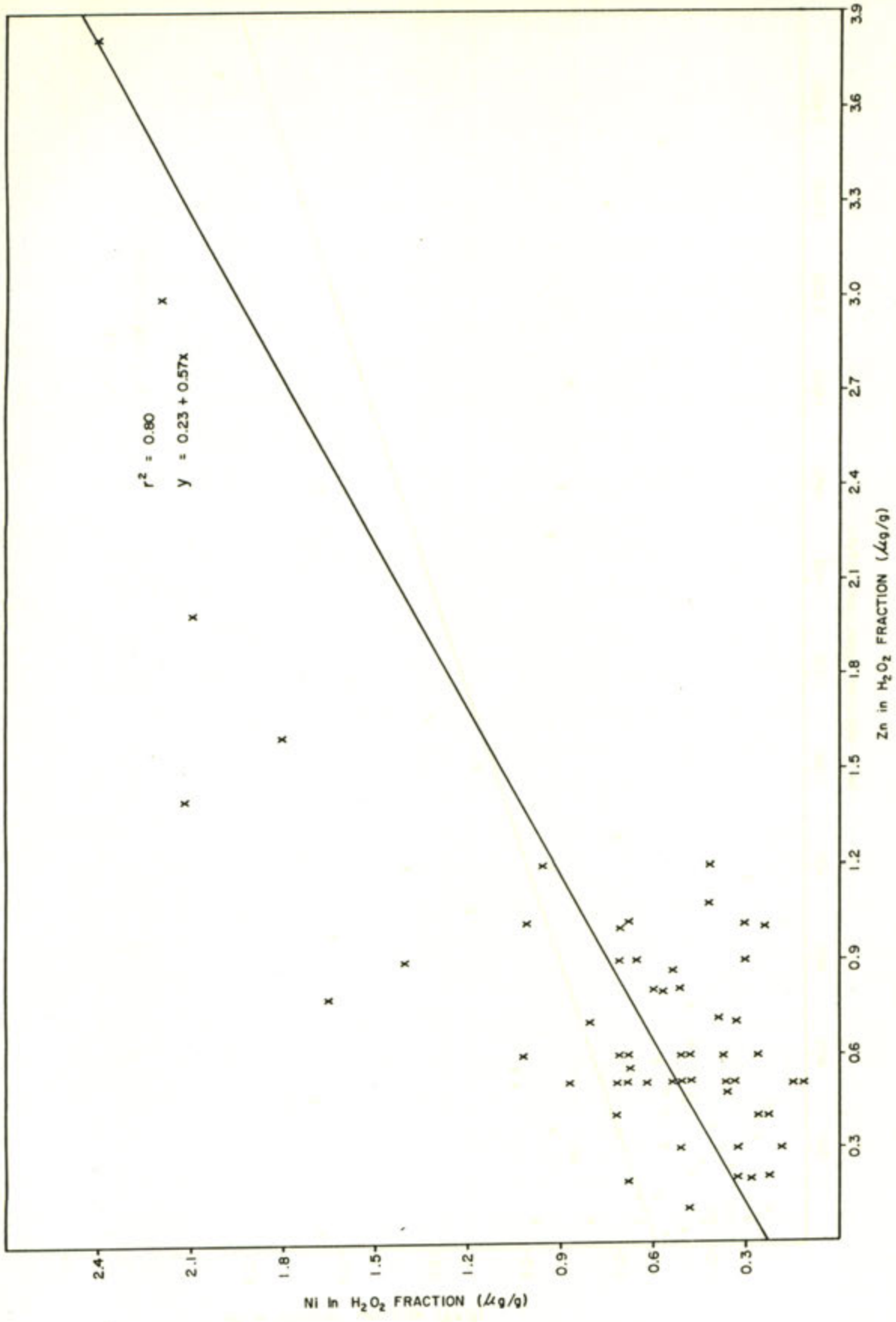


Fig. 62. Correlation between Zn and Ni in oxidizable fraction