COMMONWEALTH DEPARTMENT OF HEALTH

Australian Radiation Laboratory

Residual Radioactive Contamination of the Monte Bello Islands from Nuclear Weapons Tests Conducted in 1952 and 1956

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M. B. Cooper (Australian Radiation Laboratory)

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ABSTRACT

Distributions of long-lived radionuclides remaining from nuclear weapons trials conducted at the Monte Bello Islands in 1952 and 1956 are presented. These data are derived from a field survey carried out in 1978 and augmented with earlier data from a survey in 1972.

Significant radiation levels arising from neutron activation of soil constituents at the time of detonation are confined to the immediate environs of the ground zeros on Alpha and Trimouille Islands. These levels still exceed maximum recommended dose limits for continuous occupancy.

The range of concentrations of fallout products in the soil, including fission products and weapons material is similar to that observed at Marelinga (Cooper et al 1978). Levels of contamination are below those which would constitute a health hazard to occupants of the area.

Trace quantities of the radionuclide, ^{60}Co, were detected in several samples of marine organisms. Samples of vegetation taken from the vicinity of the ground zeros showed low concentrations of several radionuclides.

Introduction

In 1952, in an operation code - named HURRICANE, the Monte Bello Islands in Western Australia became the site of the first full-scale field trial in the British program for developing nuclear weapons. The Islands and their location off the coast of Western Australia are shown in the maps of Figure 1.

In all, three full-scale tests of nuclear weapons were carried out at the Islands - one in Operation HURRICANE and two, in 1956, in Operation MOSAIC - and details are given in Table 1. No other trials related to weapons development were conducted at the Islands.

In their execution, both HURRICANE and MOSAIC relied heavily on support from seaborne facilities provided by the Royal Navy, the ships being withdrawn from the Islands before the weapons were exploded. Hermite Island was the main logistic and land support base and, although it was used for this purpose throughout both operations, no permanent facilities were developed.

As at other nuclear weapon test sites (Cooper et al 1978), the residual radioactive contamination at the Islands comprises activation products in soil that was irradiated by neutrons from the explosions and close-in fallout around and downwind of the explosion ground zeros.

For the weapon trial mounted on HMS PLYM, activation products in soil are now evident only in the central region of Trimouille Island, along and above Main Beach, whereas, for MOSAIC G1 and G2, the activation products describe the usual circular pattern around each of the ground zeros, extending to radial distances of several hundred metres (Cooper et al 1978). For all three trials, the fallout plumes left the Islands in generally north-westerly directions, depositing close-in fallout on Trimouille Island, Alpha Island and North West Island and on the minor islands between them. Radionuclides in the close-in fallout derive from fission products, neutron activation of platform material and weapon hardware and unconsumed fissile material and its activation products. Thus the areas contaminated with radioactive material released to the environment in the three nuclear explosions are confined to the north-western region of the Islands, and the radionuclides remaining of potential significance as hazards to health are listed in Table 2.

In the years following the trials, major radiation surveys were made of the Islands in 1962, 1968, 1972 and 1978. This report presents the results of the two most recent surveys and consolidates all radiological data available for the Islands for assessment in terms of the potential hazards to health.

The Environment of the Monte Bello Islands

The hundred or so islands constituting the group loosely enclose a series of lagoons and channels, navigation of which is impeded by many submerged reefs and rocky outcrops. Only about fifteen islands can be considered to be of significant size, the largest being Trimouille Island and Hermite Island, of 500 and 950 hectare respectivaly. All of the islands are low lying and devoid of protective physical features - the highest hillocks extend only 40 m above sea level - so that the entire group presents an exposed, windswept terrain heavily affected by the cyclonic conditions which occur in the area several times each year. At these times, many of the smaller islands may become awash and all islands become inaccessible.

The geological structure of the Islands has been described in detail elsewhere (Smith, 1965). Pleistocene coastal limestone is dominant throughout and is expressed as a buff or red-coloured, highly calcareous and ferruginous cross-bedded sandstone. Alpha Island and Trimouille Island reflect the extreme in terrain and soil structure occurring in the group. Thus, the northern half of Trimouille Island consists of loose, sandy soil derived from the coastal limestone, with more consolidated dunes and sandhills in inland areas. Alpha Island has a barren rocky terrain with outcrops and hills of coastal limestone and few areas with substantial soil cover. Of the other main islands, North West Island is similar in terrain and soil type to that of Trimouille Island while Hermite Island has a rocky terrain like Alpha Island.

There have been several surveys of the flora and fauna of the Islands (Hill (1965), Burbridge (1971)). The vegetation on Trimouille Island consists mainly of grasses and low shrubs with spinifex and launea being dominant on the beaches, dunes and less consolidated areas and sorghum and sporobolus grasses characterising the inland areas. Alpha Island has much less coverage of vegetation, the main region being to the west of Burgundy Bay where spinifex and launea grasses predominate.

Burbridge (1971) lists a wide variety of mammals, birds and reptiles that have been observed on the islands during the past 100 years. Evidently, native marsupials became extinct many years ago and introduced species, such as domestic cats and ship rats (Rattus rattus), are now the main terrestrial mammals. Marine life abounds in the area but few documented studies have been made of the many edible species of mollusca, crustacea and fish.

The climate of the Islands - and of the nearby coastal region of the mainland - is characterised by an annual cycle of hot, wet, humid summer (average maximum and minimum temperatures 38°C and 24°C, respectively) and warm dry winter (25°C and 11°C) (Bureau of Meteorology, 1972). The winter climate is described as equable and especially comfortable, whereas the summer period is dominated by tropical cyclones and incipient cyclones. The tropical cyclones occur mainly between November and April and reach extreme severity on an average of two days each year. The annual rainfall of some 300 mm occurs mainly during these summer months.

The use made of the Islands in HURRICANE and MOSAIC is now evident only in buildings and debris of the base camp on Hermite Island, the trials hardware around the ground zeros and the instrument stations and the target response material on Trimouille Island. The concrete bases of the towers at G1 and G2 still remain and identify the ground zeros of these explosions.

In the early 1950's, when the Islands were selected as test sites, they offered extreme remoteness from populated areas and were regarded as a barren region with no productive potential. More recently the discovery of oil at Barrow Island and the development of the iron ore industry have introduced many more people to the region and it can no longer be considered as isolated.

Previous Surveys

The first comprehensive set of data on residual radioactive contamination of the Islands was obtained in May-June 1962 in an extensive survey executed for the Atomic Weapons Tests Safety Committee (AWTSC) by the Royal Australian Navy (R.A.N.) (Moroney, 1964). This was followed by two further surveys executed for the AWTSC, the first, by the R.A.N., in February 1968 (AWTSC, 1968) and the second, by the National Mapping Division of the Department of National Development, in October 1972 (AWTSC, 1972).

The surveys in 1962 and 1968 defined the regions of the Islands for which the external radiation dose-rate remained above background levels, but, did not provide data on the radionuclide content of the soil.

The survey in 1972 yielded a full set of field material, comprising

- radiation dose-rates at 139 survey points on Trimouille Island and Alpha Island.
- soil samples from 53 survey points on Trimouille Island and Alpha Island, each from four horizons, namely, 0 to 80 mm, 80 to 160 mm, 160 to 240 mm and 240 to 320 mm.

Details of the field program executed in 1972 are given elsewhere (AWTSC, 1972). Further visits were made to the Islands in 1974 and 1977 by the W.A. State X-ray Laboratory (Hartley et al, 1978).

The Present Survey

The most recent field survey was undertaken in October 1978 to collect further soil samples to augment those obtained in 1972, to collect samples of flora and fauna from the region, and to provide an updated set of meesurements of radiation exposure levels where they are still significant. In general, the field procedures followed closely those used at Maralinga in a similar study, and these have been described elsewhere (Cooper et al 1978). The positions of sampling sites surveyed either in 1972 or 1978 are illustrated in Figures 2, 3 and 4.

(i) Radiation Measurements

At each designated location radiation measurements were made at a height of 1 metre above the ground. Within the radial grids around G1 and G2 each measurement was an average reading taken over an area of 5 metre diameter. In the broad-scale survey and within the Main Beach Grid the γ-radiation field was measured over an area of approximately 10 metre diameter at each point.

Measurements were made using two instruments, an energy-compensated Geiger-Muller detector (Berthold LB1200) giving a reading of dose rate in microroentgen per hour and a scintillation detector (Scintrex count rate meter Type BGS-ISL) which measured the radiation field in counts per second. Except at locations where the radiation levels were too high (> 1000 μR/h)

both instruments were used at each point to enable cross-calibration and comparison. Both instruments were calibrated in the Laboratory before and after the field survey and daily checks were made for satisfactory operation of each detector.

Results obtained in the regions about the ground zeros for 1972 and 1978 are illustrated in Figures 5 and 6, and for the Main Beach area on Trimouille Island for 1972 only in Figure 7. In the latter case the 1978 levels were sufficiently low that they did not warrant a detailed survey. Similarly, broad scale measurements made on the 'minor' islands north and north west of the trials areas showed no significant radiation levels above background.

(ii) Radioactivity in Soil

Soil samples were collected at locations indicated in Figures 2, 3 and 4 using a simple hand corer ~40 mm in diameter, and ~80 mm deep. Each sample had a mass in the range 250-350 g. At each point the soil profile was described by samples taken at the same horizons which were selected for the 1972 survey. These were

- surface to 80 mm,
- 80 mm to 160 mm,
- 160 mm to 240 mm and
- 240 mm to 320 mm

Data from the survey of the nuclear weapons test range at Maralinga (Cooper et al 1978) had revealed that, in many instances, considerable variation in radionuclide concentrations existed between surface samples taken from an individual survey point. This arises in part from the discrete particulate nature of close-in fallout. To assess this variability around a survey point two surface samples (0-80 mm) were taken at each site in addition to the soil profiles described above. The rocky terrain in some areas of Alpha Island, made it impossible to collect profile samples and only surface samples exist for these sites.

During the broad scale survey of the 'minor' islands to the north and north-west of the ground zeros G1 and G2, surface samples were collected at various points to supplement the radiation measurements.

A total of 204 samples were taken from 58 sites and submitted for analysis along with the 1972 samples already in hand. In order to preserve

information on point-to-point variability of the radioactive contaminants in soil, all 410 soil samples were analysed separately. However, once the nature and distribution of the contaminants was adequately established, procedures were introduced which economised on laboratory effort without loss of information.

All samples of soil from the 1972 survey of the Islands were thoroughly homogenised by grinding and mixing. Aliquots of 60 g were enclosed in standard P.V.C. packs (70 mm diameter, 10 mm deep) and presented for γ-ray spectrometric analysis. The sample preparation and analysis procedures have been described in detail elsewhere (Cooper et al 1978). For a set of 107 samples, measured for periods between 10000 seconds and 60000 seconds, spectra were recorded and analysed over the energy range of 40 keV to 2000 keV to identify the γ-emitting nuclides present in the soil and to give the activity concentrations of the main contaminants to a precision generally better than ± 15%. For the remaining soil samples from the survey, spectrometric data were recorded only for the principal γ-ray emitted by each of the five main contaminants - ^{60}Co (1332.5 keV), ^{137}Cs (661.6 keV), ^{152}Eu (121.8 keV), ^{155}Eu (105.3 keV) and ^{241}Am (59.5 keV) - and for four other nuclides of possible interest, known to be present - ^{133}Ba (355.9 keV), ^{154}Eu (723.3 keV), ^{226}Ra (186.1 keV) and ^{235}U (185.7 keV). Measurement periods ranged from 1000 seconds to 4000 seconds. At activity concentrations of 1 nCi/kg or more, the measurement uncertainties (one standard deviation) were no greater than ± 30% of the recorded activity for any of the nine radionuclides. The lower limit for reporting a result is set at two standard deviations above zero activity - that is, where the measurement uncertainty exceeded 50% of the recorded activity. This was no greater than 0.5 nCi/kg for any of the nine nuclides.

The soil samples from the 1978 survey were presented for γ-ray spectrometric analysis without laboratory preparation. The complete field sample was contained in a standard polypropylene jar (85 mm diameter, 500 ml volume) and located centrally on the end cap of the spectrometer detector. Otherwise, the analysis routines followed the procedure developed for the shorter period measurements on samples from the 1972 survey, described above; a measurement period of 1000 seconds was used throughout. Measurement uncertainties at 1 nCi/kg did not exceed ± 30% of the recorded activities of ^{60}Co, ^{137}Cs and ^{152}Eu and the lower limit for reporting, as determined by 50% uncertainty, remained below 0.5 nCi/kg. For ^{155}Eu and ^{241}Am uncertainties at 1 nCi/kg were generally below 50%.

γ-ray spectrometry on the 1978 survey samples utilized a 60 cm^3 ORTEC model VIP-10 lithium drifted germanium detector with pulse-height analysis by Nuclear Data ND 2400 multichannel analyser or Nuclear Data ND 6600 data acquisition system. The spectrometer was calibrated for soil masses up to 600 g, in the polypropylene jar geometry, to cover the range of masses of the field samples. Calibration sources previously prepared for the P.V.C. pack geometry (Cooper et al 1976) were recontained to suit the larger diameter of the jar. The absolute sensitivity of the spectrometer for the energy range 40 to 1600 keV was then derived from a set of measurements made with the calibration sources above known masses of inactive soil in the jar. Numerical integrations covering the full range of masses enabled smooth relationships to be developed between sensitivity and mass of sample for each of the principal γ-rays of the nine radionuclides of interest.

The results from the γ-ray spectrometry on the surface soil and horizon soil samples, from both the 1972 and 1978 surveys, are presented in detail elsewhere (Cooper et al, 1979) together with their measurement uncertainties. The data on ^{152}Eu, ^{60}Co, ^{137}Cs and ^{241}Am in surface soil are summarised in Figures 8 to 15 as geographical distributions of activity concentration in the environs of the two ground zeros.

Data obtained from the analysis of soil from the 1977 survey of major trial sites at the Maralinga range had indicated that for a particular weapons trial the ratio of ^{90}Sr activity to ^{137}Cs activity in the soil close to ground zero is constant within the limits of overall measurement uncertainties (Cooper et al, 1978). This observation is consistent with studies of isotopic ratios in fallout extremely close to trials sites at the Neveda Range in USA (Heft, 1968). It was therefore considered that adequate information on the distribution of ^{90}Sr in the more radioactive areas of the Monte Bello Islands could be derived from measurements of ^{137}Cs concentrations throughout the regions of close-in fallout and the determination of the ratio ($^{90}Sr/^{137}Cs$) for a selection of soil samples for each of the trial sites.

The highly calcareous (up to 75% CaO) nature of the soil necessitated the same techniques and modified procedures that were used for ^{90}Sr

analysis in the Maralinga survey (Cooper et al, 1978). After chemical separation of ^{90}Sr (plus added Strontium carrier) from the other constituents of the soil, the ^{90}Y daughter product was allowed to grow-in over a suitable period of time. The ^{90}Y was separated with the aid of carrier and planchets of an yttrium oxalate precipitate were prepared. The activity of ^{90}Y was determined by β-counting and the ^{90}Sr content of each sample was then calculated after correction factors for chemical yield, counter efficiency, and decay time had been applied. Each sample for analysis consisted of 90 g of soil. They were presented in batches of six field samples and two quality control samples according to procedures described elsewhere (Cooper et al 1978).

Table 3 presents the results for ^{90}Sr activity for selected field samples. Radioactive concentrations are given as nCi/kg soil. From these measurements and the ^{137}Cs concentrations, determined by γ-spectrometry, the ratios $^{90}Sr/^{137}Cs$ are calculated and are presented in the same Table.

(iii) Plutonium in Soil

Two additional isotopes of plutonium ^{240}Pu and ^{241}Pu, are produced by neutron capture during the manufacture of ^{239}Pu for nuclear weapons material. Consequently these two isotopes will be present along with ^{239}Pu in the close-in fallout from a nuclear weapons test. They may also occur by neutron activation of the weapons material during the test itself. Americium (^{241}Am), the decay product of ^{241}Pu, becomes the means for determining the presence of plutonium because of its accessible γ-ray spectrum (Cooper et al 1978; Ellis 1978). By measuring the ratio $^{239}Pu/^{241}Am$ (or $^{239,240}Pu/^{241}Am$) in a selected number of samples it becomes possible to determine soil concentrations of plutonium in any sample (^{239}Pu, ^{240}Pu) from the concentration of ^{241}Am because of the constancy of the plutonium/americium (^{241}Am) abundances for any particular trial site (Cooper et al, 1978).

Because ^{239}Pu could not be detected directly by γ-ray spectrometry, alternative analytical techniques and α-particle counting were used to measure the plutonium concentration in selected soil samples and so calculate the ratio for each close-in fallout region. Plutonium was separated from the other soil constituents by a series of ion exchange processes after an initial acid digestion. A source for radioactive measurement was prepared by co-precipitation of the plutonium on praseodymium hydroxide. The two principle α-emitting nuclides present after the purification procedure

are ^{239}Pu and ^{240}Pu so the measured concentrations are quoted as $^{239,240}Pu$. The α-counter was calibrated using a series of standard $^{239,240}Pu$ sources prepared by the same method. Linearity of total count rate with plutonium activity was achieved over a wide range with a fixed (5 mg) mass of precipitate.

The $^{239,240}Pu$ concentration was determined in a total of 11 samples. The samples were selected from the three areas of concern on Alpha Island and Trimouille Island and included samples from both the 1972 and 1978 surveys. Table 4 lists the activities of $^{239,240}Pu$ and ^{241}Am from which the ratio $^{239/240}Pu/^{241}Am$ has been calculated, and demonstrates that ^{241}Am serves as a good index of plutonium concentration in this case.

(iv) Marine Samples

The collection of marine samples was limited to two or three species using the criteria that they should be

- an obvious part of the human food chain,
- likely to concentrate contaminants and
- resident in one locality for long periods.

Available species of marine animals which fulfilled these criteria were identified and collected by an officer of the W.A. Museum. Three main organisms were sampled, namely, giant clam, rock oysters and painted crayfish. Samples were taken from accessible locations throughout the Islands including the coastlines in the vicinity of the ground zeros G1 and G2. Teble 5 records the species sampled and the approximate locations from which they were taken. Flesh from each sample was removed, placed in bags, deep frozen and returned to the Laboratory for further preparation and analysis.

The frozen flesh from each of the oyster samples was reduced in bulk by freeze-drying prior to analysis. This enabled the sample to be powdered and encapsulated in the standard P.V.C. packs and submitted for γ-ray spectrometry. The samples of the giant clam and crayfish were treated in the same manner except that the volume of material remaining after freeze-drying and crushing was too large to use the standard P.V.C. containers and samples were placed in 500 ml polypropylene containers for analysis by γ-spectrometry. The results obtained for concentrations of radionuclides observed in marine samples are presented in Table 5.

(v) Terrestrial Flora and Fauna

Previous botanical studies of the Monte Bello Islands had revealed that the vegetation on the Islands could not be considered to be part of the human food chain (Hill 1965). Nor did there exist herbivorous fauna which are edible species in a normal human diet (Burbridge 1971). Nevertheless a sample of vegetation was taken from the area around each of the ground zeros, G1 and G2 and analysed for radionuclide content. The results are presented in Table 6.

Discussion

The only areas remaining at the Monte Bello Islands where the external radiation exposure levels are significantly above background are the immediate vicinity of the ground zeros on Alpha and Trimouille Islands. The data on soil contamination indicate that in the region within 100 m of G1 and G2 the external gamma field is produced mainly by neutron activation products, ^{152}Eu and ^{60}Co. The range of external gamma dose rates are similar to those encountered at the major trials sites at Maralinga although G2 ground zero has a significantly higher dose rate than any other site (Cooper et al, 1978). Likewise, the concentration range of the various soil contaminants are of a similar magnitude to those determined at Maralinga. A comparison of radionuclide concentrations at both Maralinga and Monte Bello trials sites is displayed in Table 7.

The region of Main Beach on Trimouille Island, where close-in fallout was deposited as a result of the test on the HMS PLYM, had maximum levels of external gamma dose in 1978 in the range of 100-150 $\mu R/h$. This is a factor of 10 less than the levels at the ground zero on G1 and shows a consistent decline when compared with data from the more detailed survey of that area in 1972.

Radiation levels throughout the 'minor' islands have decreased to levels slightly above background and this confirms previous trends from the survey of these islands in 1968. Trace amounts of fission products were detected on these islands; however, these represent no hazard to health.

Relative abundances of activation products in soil can be calculated from the data in Table 7. There is good agreement between the ratios for the trials sites at Maralinga and Monte Bello Islands. Consequently a dose rate decay curve for this distribution of activation products can be

generated in order to predict the future dose rate levels in the vicinities of the ground zeros on Alpha and Trimouille Islands. This curve is illustrated in Figure 16, normalised to unity at October 1978. Measured dose rates obtained during previous surveys normalised to unity for 1978 are also plotted in Figure 16 and there is good agreement with predicted levels. It can be seen that the maximum dose rates will have diminished to 57 μR/h, the dose limit recommended for continuous exposure for members of the public (NHMRC, 1967), by 2044 AD for Alpha ground zero and 2034 AD for Trimouille ground zero.

Because there are no terrestrial flora and fauna on the Islands which form part of the human food chain, the only significant path for intake of a radionuclide is by inhalation of airborne contaminants. Under normal conditions, dust loadings in the atmosphere are not likely to exceed 1 mg/m^3, although it is possible that higher loadings may be raised from time to time under adverse conditions (Trefry 1978).

Table 8 presents surface soil concentrations of contaminants obtained by averaging over all data points within 200 m of G2 on Alpha Island. This includes, as illustrated in Figures 5, 8-11, all areas remaining contaminated significantly with radioactivity. Included in Table 8 are the corresponding airborne concentrations based upon a dust loading of 10 mg/m^3, together with the maximum recommended limits for continuous exposure to these isotopes (ICRP, 1959). It is apparent from this Table that plutonium is the only contaminant of significance in this context. The assumptions used in the calculations relate to extreme dusty conditions resulting from a vigorous disturbance of the surface soil and it is most unlikely that these conditions would be approached in an open working environment. Soil concentrations in the vicinity of G1 on Trimouille Island and elsewhere are considerably lower and consequently the hazard to health in the contaminated areas is even less than that on Alpha Island.

From the distribution of the neutron activation nuclide ^{152}Eu it appears that there has been no significant dispersal of material by either wind or water from the sites where it was originally deposited. Some of the soil profiles, however, taken from sand dunes indicate that fresh soil has covered and diluted the original contamination.

The trace quantities of contaminants which were detected in some samples of oysters and clams represent no hazard to health if eaten. The concentration of ^{60}Co measured in the samples (Table 5) is of the same order of magnitude as environmental levels of ^{60}Co in molluscs reported for other regions (IAEA, 1976).

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Table 1 : Nuclear Weapons Tests Conducted at the Monte Bello Islands.

Code name	Date	Platform	Location	Yield
HURRICANE	3 Oct '52	HMS PLYM	moored off Main Beach Trimouille I.	kiloton range
MOSAIC G1	16 May '56	tower	north western Trimouille I.	kiloton range
MOSAIC G2	19 Jun '56	tower	north western Alpha I.	kiloton range

Table 2 : Radionuclides remaining at the Monte Bello Islands of Potential Significance as Hazards to Health

Nuclide (radiation and half-life)*	Origin	Principal organ at risk	Pathway
ACTIVATION PRODUCT IN SOIL			
^{60}Co β, γ; 5.3 yr	^{59}Co (n, γ)	whole body	external radiation
^{152}Eu β, γ; 12.4 yr	^{151}Eu (n, γ)	whole body	" "
^{154}Eu β, γ; 7.8 yr	^{153}Eu (n, γ)	whole body	" "
CLOSE-IN FALLOUT			
^{60}Co β, γ; 5.3 yr	^{59}Co (n, γ)	whole body	external radiation
^{90}Sr–^{90}Y β; 27.7 yr	fission products	bone	ingestion
^{137}Cs–^{137m}Ba β, γ; 30 yr	fission products	whole body	external radiation
^{155}Eu β, γ; 4.6 yr	fission products	whole body	external radiation
^{239}Pu α; 24390 yr	fissile material	lung & bone	inhalation
^{240}Pu α; 6580 yr	^{239}Pu (n, γ)	" " "	inhalation
^{241}Pu–^{241}Am α, β, γ; 13.2,458 yr	^{240}Pu (n, γ)	" " "	inhalation

*Lederer et al (1967); Blachot and Fiche (1977)

Table 3 : Radioactive Concentration of ^{90}Sr and $^{90}Sr/^{137}Cs$ ratio in selected soil samples

Sample Code	Location (Survey date)	Activity (nCi/kg) ^{90}Sr	Activity (nCi/kg) ^{137}Cs	Ratio $^{90}Sr/^{137}Cs$
	Main Beach			
015 A0	survey pt. 23 (1972)	255.2	165.8	1.54
015 A2	" " " (1972)	24.2	28.4	0.85
016 A0	survey pt. 24 (1972)	78.0	165.2	0.50
191 B0	survey pt. 28 (1978)	14.2	31.8	0.45
023 A0	survey pt. 31 (1972)	30.3	18.4	1.96
024 A2	survey pt. 32 (1972)	39.5	20.2	1.64
	Trimouille G1			
048 A0	50 m N (1972)	13.4	23.9	0.56
160 C0	50 m NE (1978)	42.0	45.3	0.93
052 A0	50 m E (1972)	9.1	17.2	0.53
162 A0	50 m SW (1978)	13.6	22.7	0.60
164 A0	50 m NW (1978)	17.5	23.5	0.74
	Alpha G2			
108 A0	50 m E (1972)	46.4	314.6	0.15
110 A2	50 m SE (1972)	28.1	305.1	0.09
211 B0	50 m SE (1978)	33.7	1000.0	0.03
107 A0	50 m SW (1972)	16.7	391.3	0.04
213 C0	50 m SW (1978)	116	425.0	0.27
214 C0	50 m NW (1978)	35.9	101.9	0.35
218 A0	125 m W (1978)	28.9	238.0	0.12
217 B0	150 m NWW (1978)	1.6	23.4	0.07

Table 4 : Concentrations of Plutonium ($^{239,240}Pu$) in selected soil samples and ratios of ($^{239,240}Pu/^{241}Am$)

Sample Code	Location (Survey)	Activity (nCi/kg) $^{239,240}Pu$	Activity (nCi/kg) ^{241}Am	Ratio ($^{239,240}Pu/^{241}Am$)
	Trimouille G.Z.			
051A2	50 m S.W.	341	29.8	11.4
053A0	50 m W	401	20.3	19.8
055A2	50 m N.W.	331	51.0	6.5
	Main Beach			
015A0	survey pt. 23	70.8	4.6	15.4
016A0	" " 24	43.7	3.8	11.5
020A4	" " 28	43.7	6.1	7.2
024A0	" " 32	38.0	5.5	6.9
025A6	" " 33	48.4	8.4	5.8
	Alpha G.Z.			
107A0	50 m S.W.	602	31.8	18.9
108A0	50 m W	275	11.4	24.1
111A2	50 m N.W.	454	45.2	10.1

Table 5 : Radioactivity in Marine Organisms

Species (sample code)	Location of sample	Activity (nCi/kg wet tissue)				
		^{241}Am	^{155}Eu	^{152}Eu	^{137}Cs	^{60}Co
Oyster (390)	Trimouille I.	-	-	-	0.02 ± 0.01	0.10 ± 0.02
Oyster (391)	Trimouille I.	-	-	-	-	0.06 ± 0.02
Oyster (392)	Trimouille I.	-	-	-	-	0.32 ± 0.10
Oyster (393)	Alpha I.	-	-	-	-	0.42 ± 0.20
Oyster (394)	Alpha I.	-	0.36 ± 0.04	0.42 ± 0.04	-	0.15 ± 0.03
Oyster (395)	Alpha I.	-	0.30 ± 0.07	0.09 ± 0.05	-	0.15 ± 0.04
Oyster (396)	Trimouille I. (s. of G1)	-	-	-	-	0.13 ± 0.06
Oyster (397)	Trimouille I.	-	-	-	-	0.52 ± 0.10
Clam (398)	North West I. (No. 1 Landing site)	-	-	-	0.13 ± 0.05	22.7 ± 0.3
Clam (399)	North West I. (north side)	-	-	-	-	0.47 ± 0.02
Crayfish (400)	Trimouille I. (north)	-	-	-	0.02 ± 0.01	0.02 ± 0.01
Clam (401)	Hermite I.	-	-	-	-	0.24 ± 0.01
Oysters (403)	Trimouille I. (Tidepole Bay)	-	0.40 ± 0.10	-	0.21 ± 0.10	0.26 ± 0.08
Oyster (404)	Alpha I.	-	-	0.30 ± 0.10	-	0.12 ± 0.06
Oyster (405)	Alpha I.	-	-	0.08 ± 0.03	-	0.06 ± 0.02
Oyster (406)	Hermite I.	-	-	-	-	0.02 ± 0.05

Table 6 : Radioactivity in Vegetation

Region Sampled	Activity (nCi/kg tissue)							
	^{241}Am	^{155}Eu	^{152}Eu	^{226}Ra	^{133}Ba	^{137}Cs	^{154}Eu	^{60}Co
Alpha G.Z.	0.36	0.82	8.0	-	0.32	12.3	0.5	3.4
Trimouille G.Z.	-	0.14	1.05	-	1.22	128.2	-	0.31

Table 7 : Comparison of Radionuclide Concentrations measured at the nuclear weapons sites at Monte Bello Islands and Maralinga.

Test Site	Activity in soil sampled within 100 m G.Z. (mCi/kg)							
	^{239}Pu [1]	^{241}Am	^{60}Co	^{152}Eu	^{154}Eu	^{137}Cs	^{90}Sr	^{155}Eu
Maralinga								
One Tree	- (4)	2.6	44.4	186.0	17.2	12.6	1.2	5.6
Marcoo	- (4)	1.1	0.6	1.6	-	7.8	5.5	3.0
Breakaway	- (4)	6.1	256	8.28	74.3	43.1	16.7	11.8
Tadje	3087	56.1	2.8	7.5	0.7	22.1	18.4	7.8
Biak	- (4)	0.5	20.0	109.2	9.4	1.7	0.8	1.1
Monte Bello Islands								
Trimouille	53	4.2	3.7	42.3	3.6	31.6	15.8(2)	8.6
Alpha I.	245	13.6	149	1082	74.5	315	158(2)	40.6

NOTE:
1. Obtained by ratio $^{239}Pu/^{241}Am$ (see text)
2. Obtained by ratio $^{90}Sr/^{137}Cs$
3. Includes ^{240}Pu concentration
4. Data not available.

Table 8 : Assessment of Hazard due to Airborne Contaminants.

Isotope	Average Observed Concentration (within 200 m of G.2 on Alpha I. (nCi/kg)	Corresponding Concentration in air ($\mu C/cm^3$)	Max. Recommended Limit ($\mu C/cm^3$)
^{60}Co	75	7.5×10^{-13}	1×10^{-7}
^{90}Sr	18	1.8×10^{-13}	4×10^{-10}
^{137}Cs	180	1.8×10^{-12}	2×10^{-8}
^{152}Eu	450	4.5×10^{-12}	2×10^{-7}
$^{239,240}Pu$*	470	4.7×10^{-12}	6×10^{-13}
^{241}Am	26	2.6×10^{-12}	2×10^{-12}

*obtained from ^{241}Am (see text).

FIGURE CAPTIONS

Figure 1. Map of Monte Bello Islands. (× Nuclear weapons test site).

Figure 2. Locations of sampling sites on Alpha Island surveyed in 1972 and 1978.

Figure 3. Locations of sampling sites in vicinity of ground zero G1, on Trimouille Island, surveyed in 1972 and 1978.

Figure 4. Locations of sampling sites on Trimouille Island surveyed in 1972 and 1978.

Figure 5. Gamma Ray dose distribution on Alpha Island from 1972 and 1978 surveys.

Figure 6. Gamma Ray dose distribution in vicinity of ground zero G1, on Trimouille Island, from 1972 and 1978 surveys.

Figure 7. Gamma Ray dose distribution in vicinity of Main Beach on Trimouille Island from 1972 survey.

Figure 8. Distribution of ^{152}Eu (nCi/kg) in surface soil in vicinity of ground zero on Alpha Island.

Figure 9. Distribution of ^{60}Co (nCi/kg) in surface soil in vicinity of ground zero on Alpha Island.

Figure 10. Distribution of ^{137}Cs (nCi/kg) in surface soil in vicinity of ground zero on Alpha Island.

Figure 11. Distribution of ^{241}Am (nCi/kg) in surface soil in vicinity of ground zero on Alpha Island.

Figure 12. Distribution of ^{152}Eu (nCi/kg) in surface soil in vicinity of ground zero on Trimouille Island.

Figure 13. Distribution of ^{60}Co (nCi/kg) in surface soil in vicinity of ground zero on Trimouille Island.

Figure 14. Distribution of ^{137}Cs (nCi/kg) in surface soil in vicinity of ground zero on Trimouille Island.

Figure 15. Distribution of ^{241}Am (nCi/kg) in surface soil in vicinity of ground zero on Trimouille Island.

Figure 16. Time distribution of γ-ray dose near ground zeros on Alpha Island and Trimouille Island, normalised to unity at October 1978. (⊙ measured dose rates from Alpha Island close to ground zero).

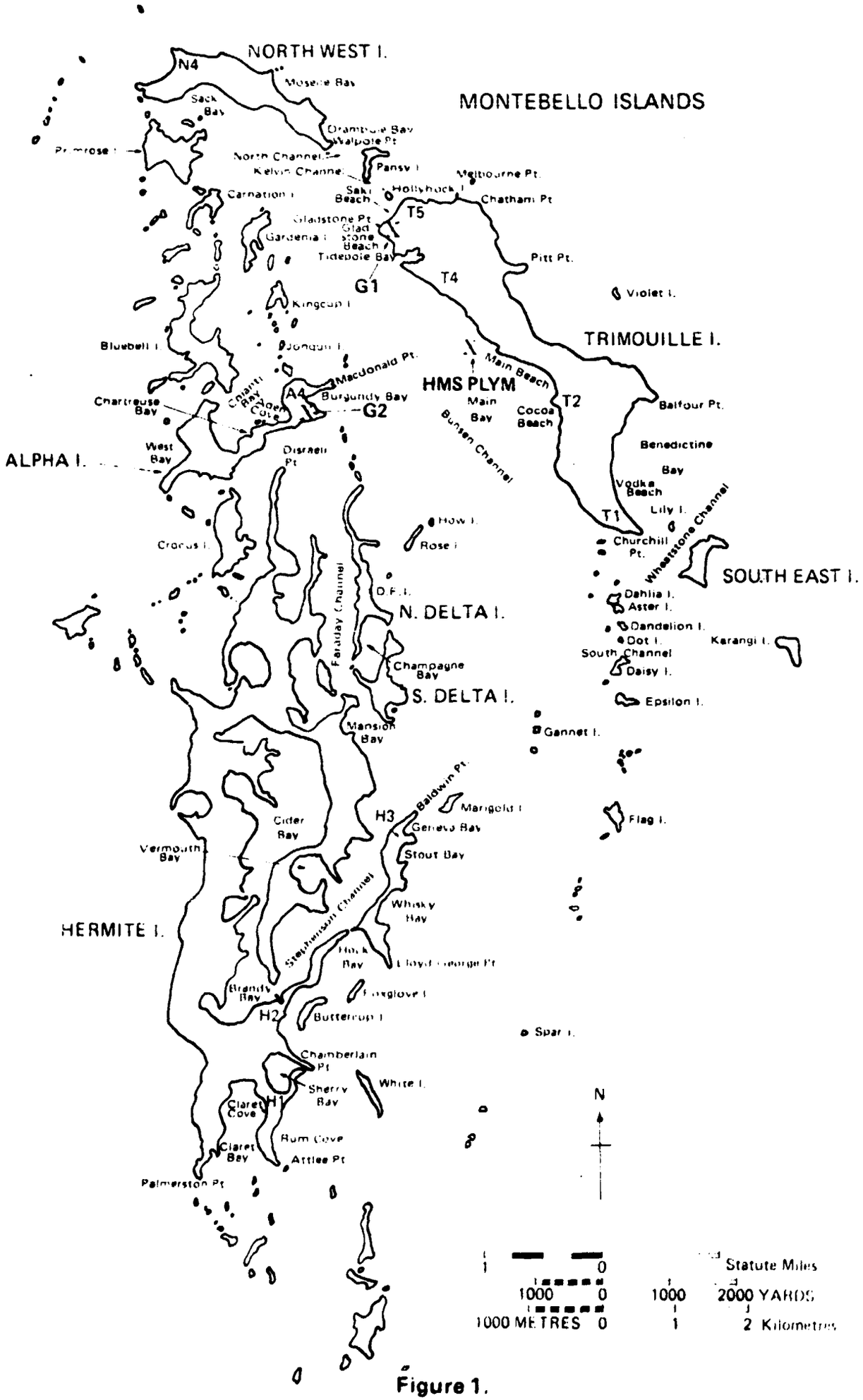

NORTH WEST I.
MONTEBELLO ISLANDS
N4
Mosele Bay
Sack Bay
Primrose I.
Dramboise Bay
Walpole Pt
North Channel
Kelvin Channel
Pansy I.
Melbourne Pt.
Carnation I.
Hollyhock I.
Chatham Pt
T5
Gladstone Pt
Gardenia I.
Tidepole Bay
Pitt Pt.
G1
T4
Violet I.
Kingcup I.
TRIMOUILLE I.
Bluebell I.
Main Beach
Macdonald Pt.
HMS PLYM
Main Bay
T2
Cocoa Beach
Balfour Pt.
Chartreuse Bay
A4
Burgundy Bay
G2
Bunsen Channel
ALPHA I.
West Bay
Disraeli Pt.
Benedictine Bay
Vodka Beach
Lily I.
T1
Churchill Pt.
Wheatstone Channel
SOUTH EAST I.
How I.
Crocus I.
Rose I.
Faraday Channel
D.F.I.
N. DELTA I.
Dahlia I.
Aster I.
Dandelion I.
Dot I.
Karangi I.
South Channel
Champagne Bay
Daisy I.
S. DELTA I.
Epsilon I.
Mansion Bay
Gannet I.
Baldwin Pt.
Marigold I.
Flag I.
H3
Cider Bay
Geneva Bay
Vermouth Bay
Stout Bay
Whisky Bay
HERMITE I.
Stephenson Channel
Brandy Bay
H2
Buttercup I.
Spar I.
Chamberlain Pt
White I.
Sherry Bay
H1
Claret Cove
Rum Cove
Claret Bay
Attlee Pt
Palmerston Pt
N
Statute Miles
1000 0 1000 2000 YARDS
1000 METRES 0 1 2 Kilometres

Figure 1.

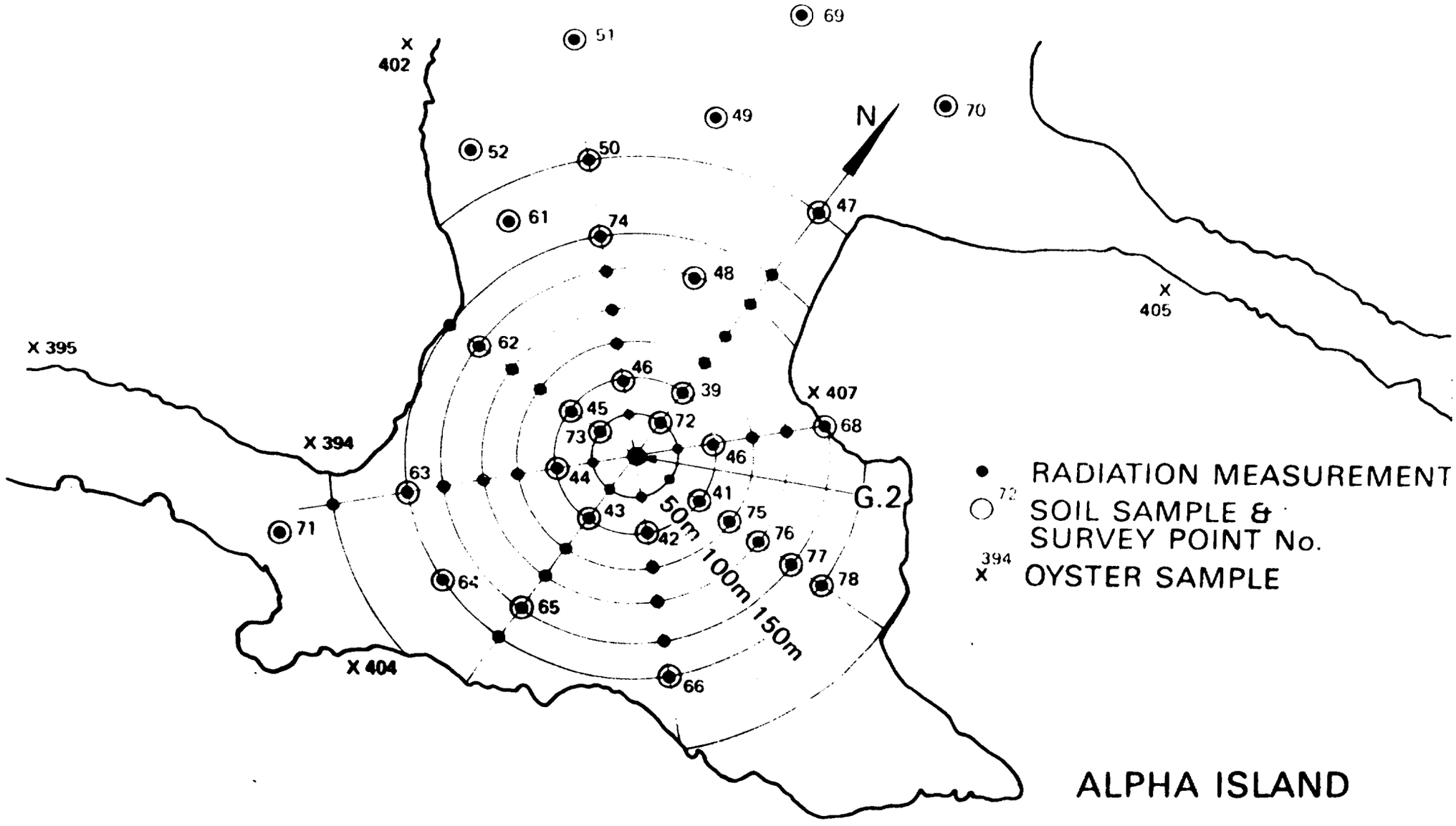

69
51
X 402
49
N
70
52
50
47
61
74
48
X 405
62
46
39
X 407
45
72
68
X 395
73
X 394
46
63
44
41
G.2
71
43
75
50m
42
76
100m
77
64
78
65
150m
X 404
66
RADIATION MEASUREMENT
SOIL SAMPLE & SURVEY POINT No.
OYSTER SAMPLE
ALPHA ISLAND

Figure 2.

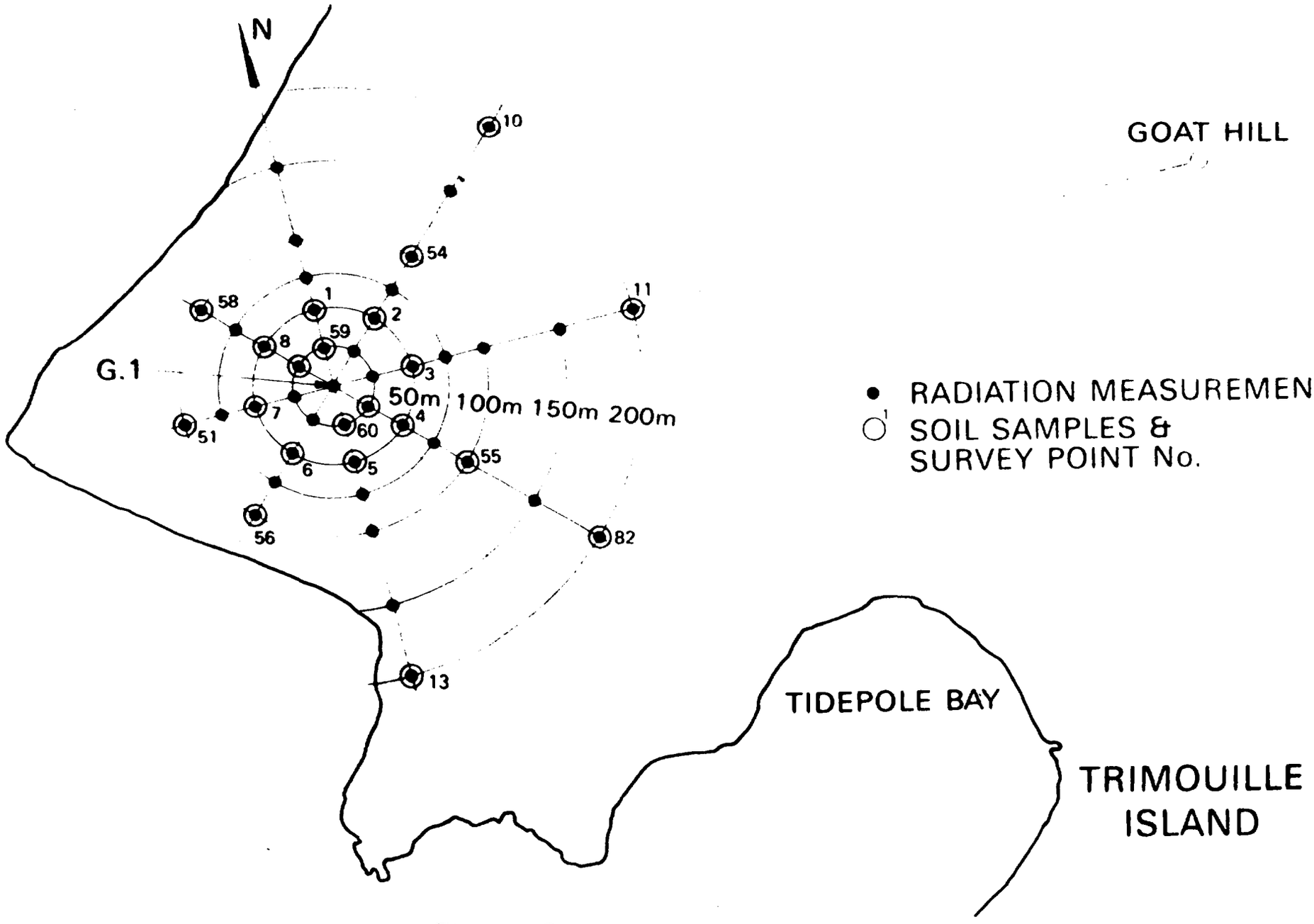

N
GOAT HILL
G.1
50m
100m
150m
200m
RADIATION MEASUREMENT
SOIL SAMPLES &
SURVEY POINT No.
TIDEPOLE BAY
TRIMOUILLE
ISLAND
10
54
58
1
2
11
59
8
3
7
4
51
60
6
5
55
56
82
13

Figure 3.

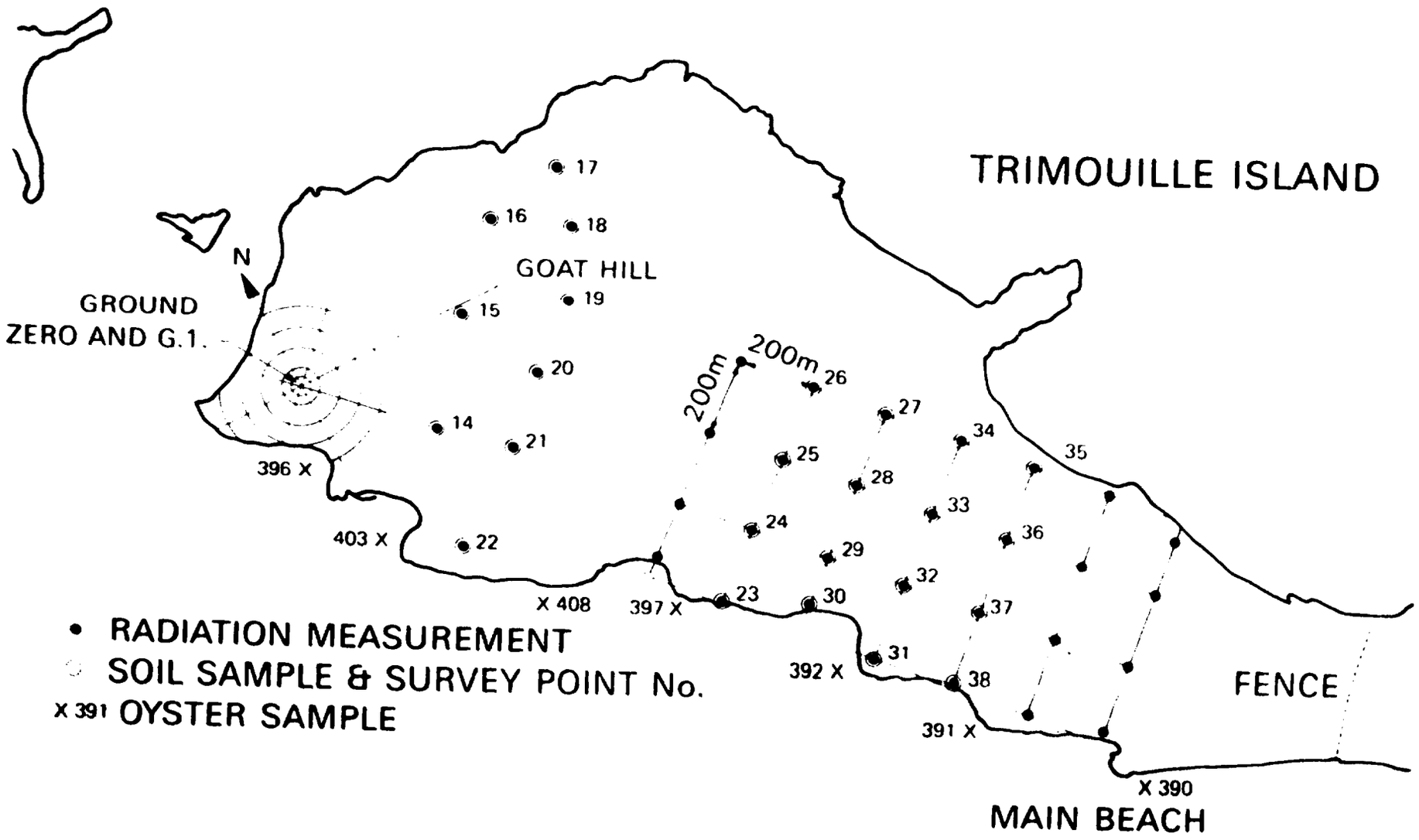
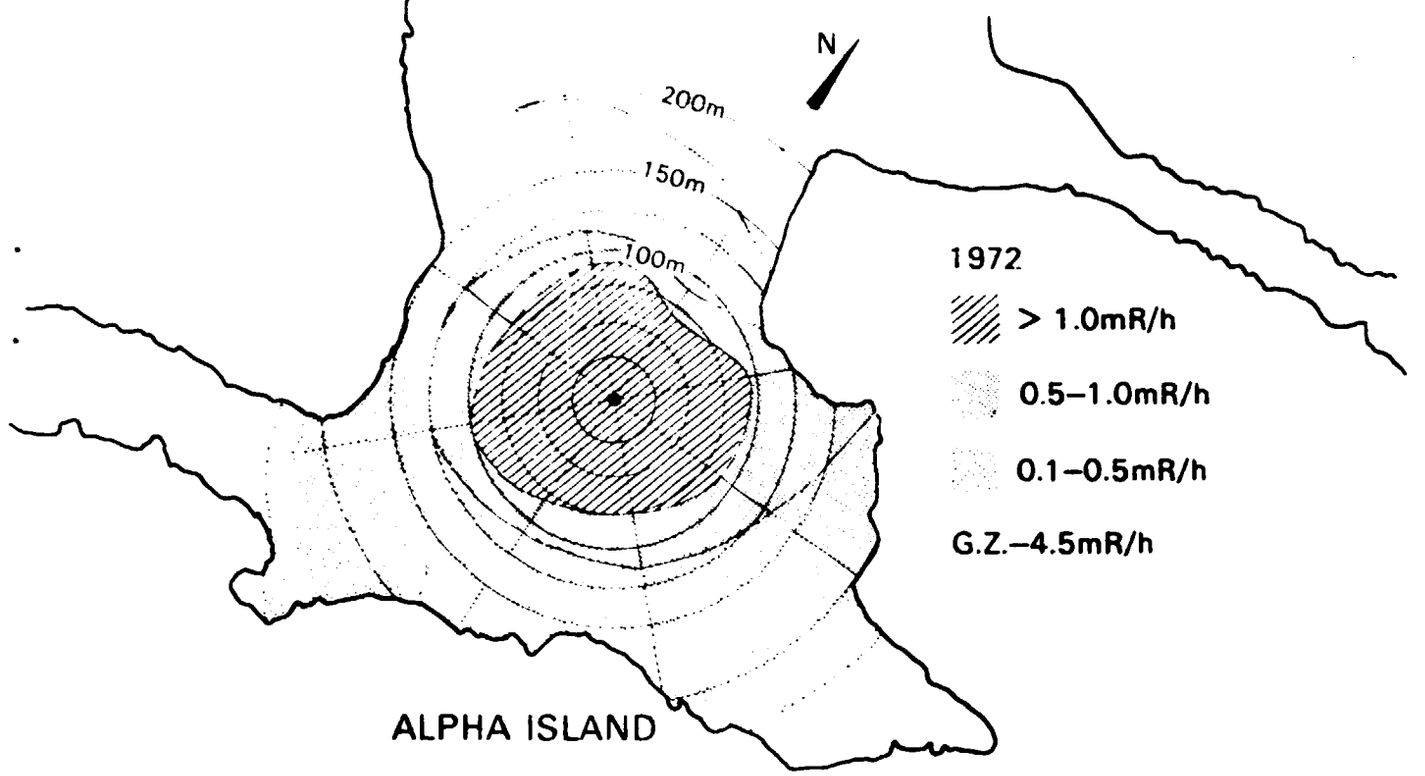

TRIMOUILLE ISLAND
N
GROUND
ZERO AND G.1.
GOAT HILL
17
16
18
15
19
20
14
21
22
396 X
403 X
200m
200m
26
27
34
25
28
33
24
29
32
23
30
37
31
38
35
36
X 408
397 X
392 X
391 X
X 390
FENCE
MAIN BEACH
• RADIATION MEASUREMENT
SOIL SAMPLE & SURVEY POINT No.
X 391 OYSTER SAMPLE

Figure 4.


N
200m
150m
100m
1972
> 1.0mR/h
0.5–1.0mR/h
0.1–0.5mR/h
G.Z.–4.5mR/h
ALPHA ISLAND

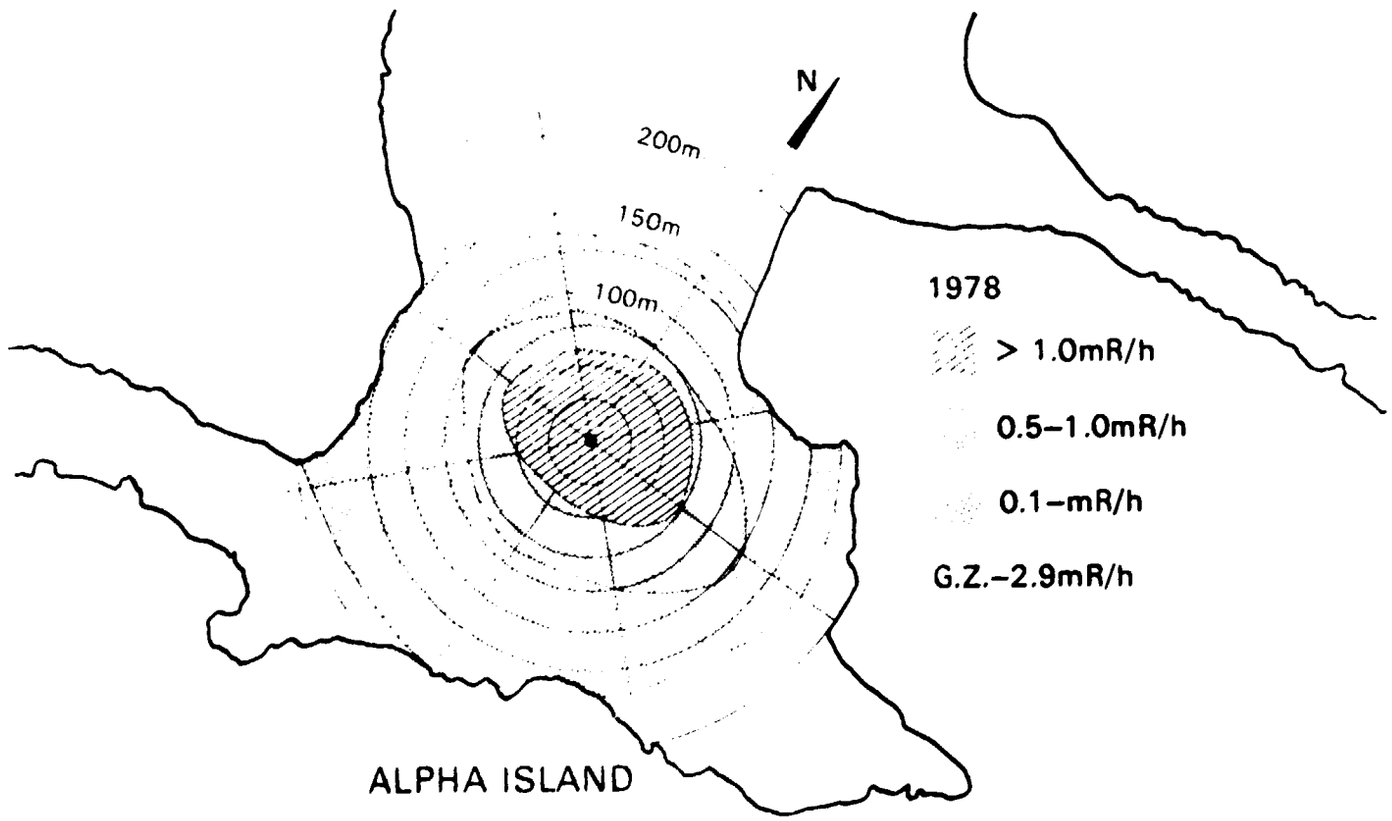
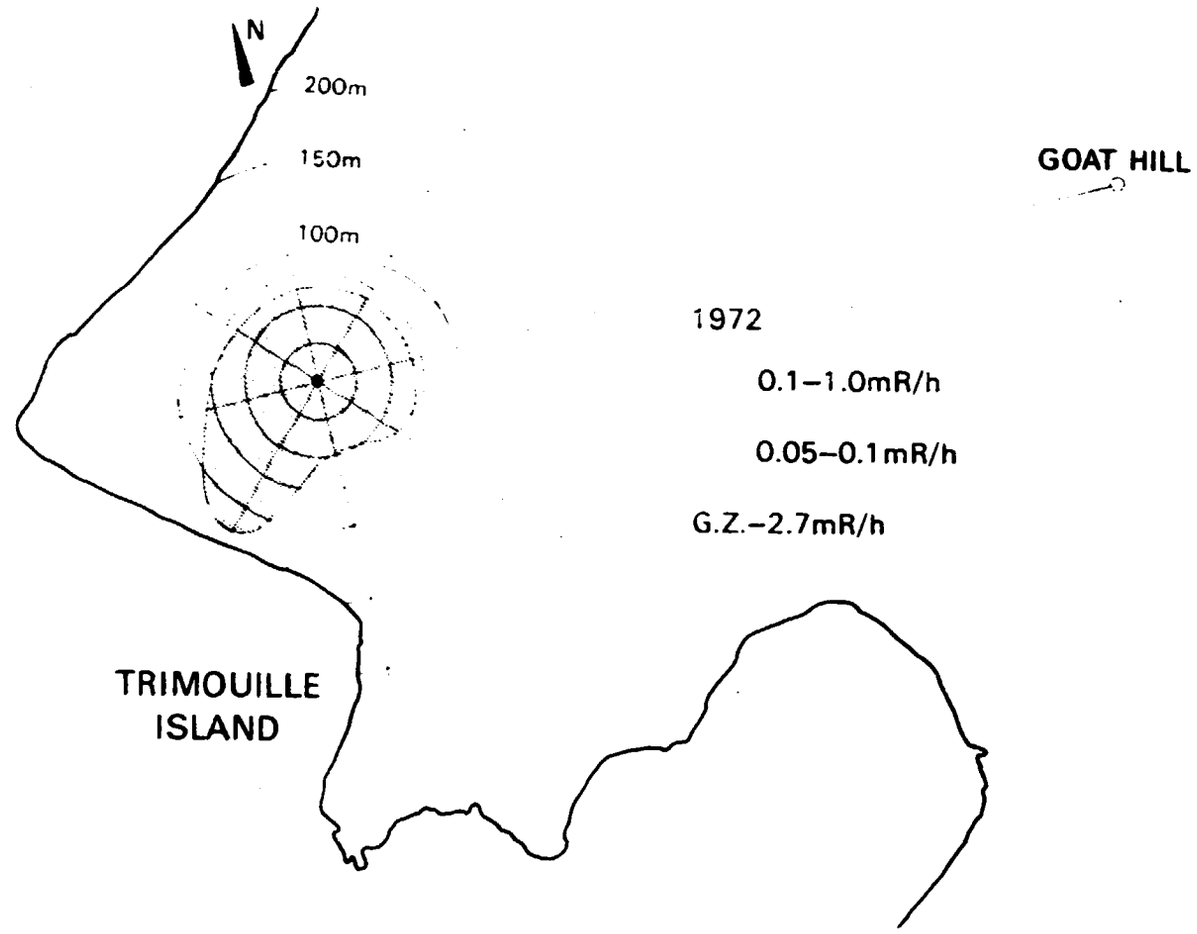

N
200m
150m
100m
1978
> 1.0mR/h
0.5–1.0mR/h
0.1–mR/h
G.Z.–2.9mR/h
ALPHA ISLAND

Figure 5


N
200m
150m
100m
GOAT HILL
1972
0.1–1.0mR/h
0.05–0.1mR/h
G.Z.–2.7mR/h
TRIMOUILLE
ISLAND

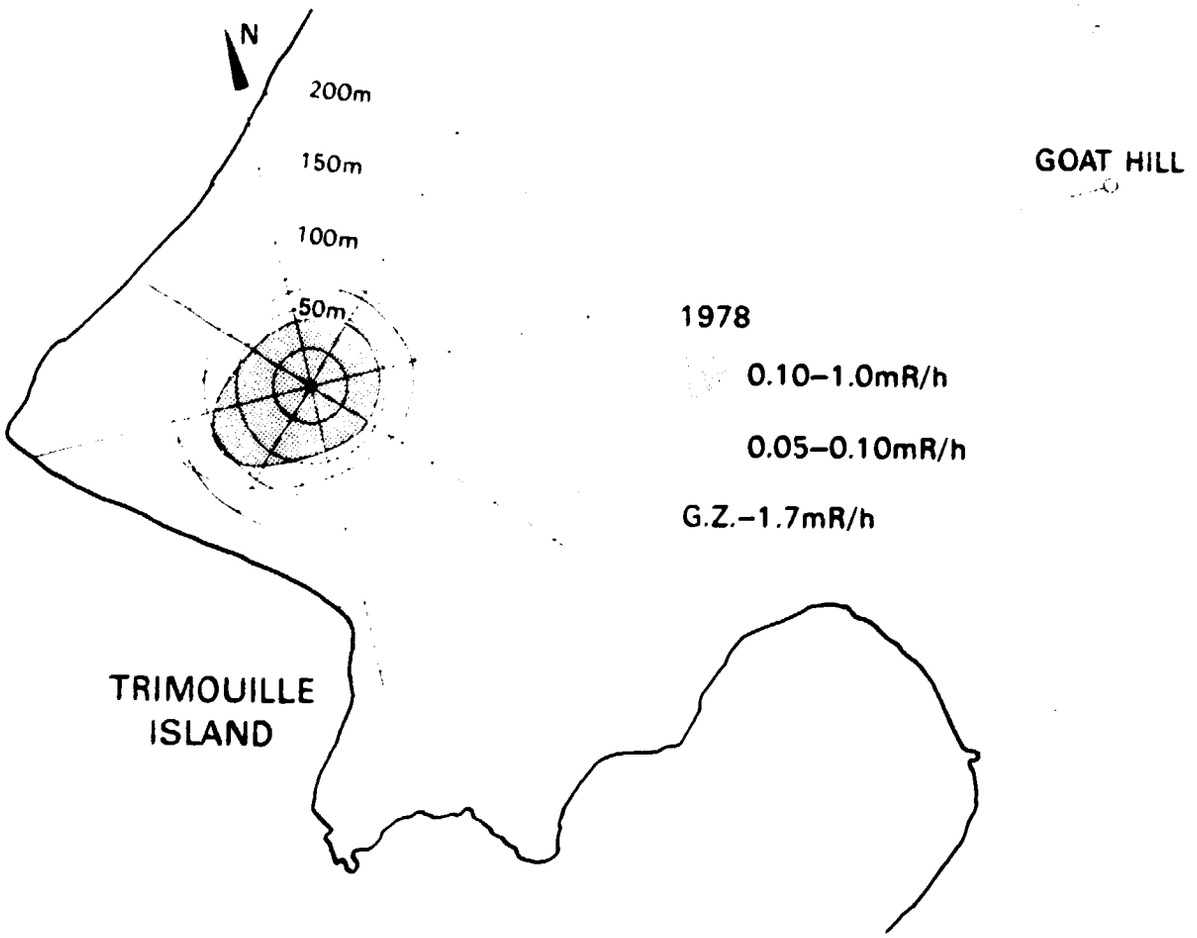

N
200m
150m
100m
50m
GOAT HILL
1978
0.10–1.0mR/h
0.05–0.10mR/h
G.Z.–1.7mR/h
TRIMOUILLE
ISLAND

FIGURE 6

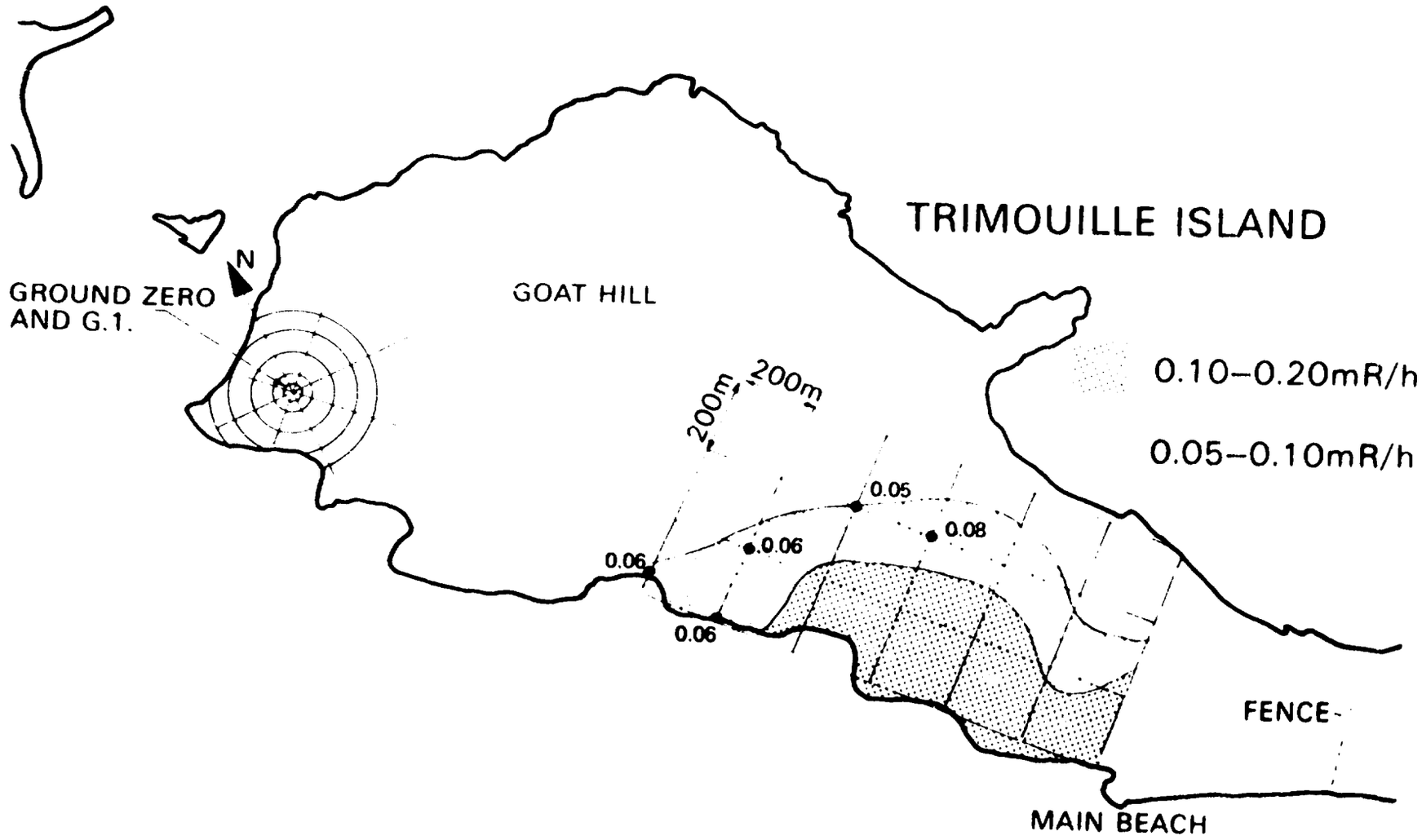

TRIMOUILLE ISLAND
N
GROUND ZERO
AND G.1.
GOAT HILL
200m
200m
0.10–0.20mR/h
0.05–0.10mR/h
0.05
0.08
0.06
0.06
0.06
FENCE
MAIN BEACH

Figure 7.

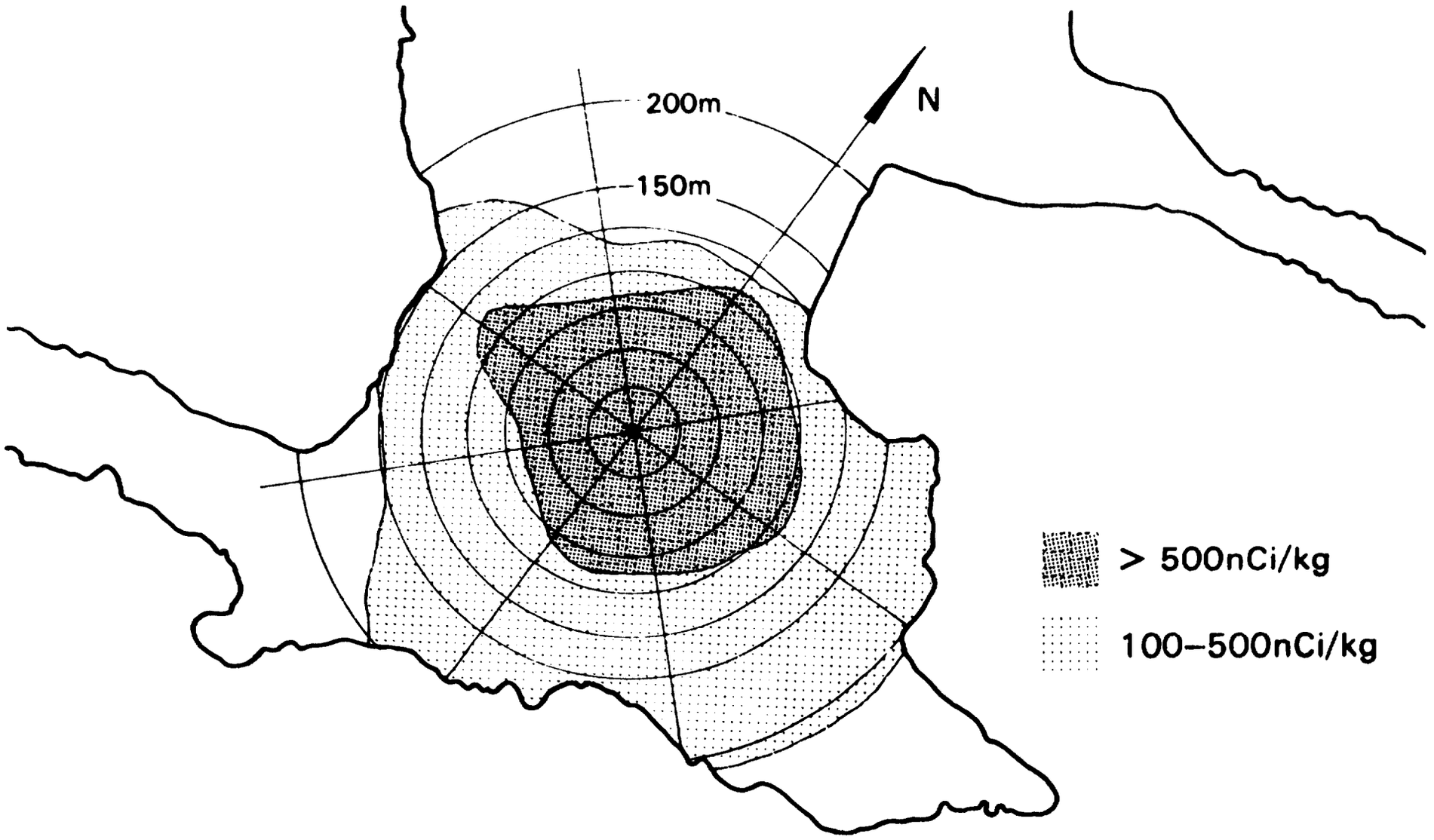


Figure 8. **Alpha Island**

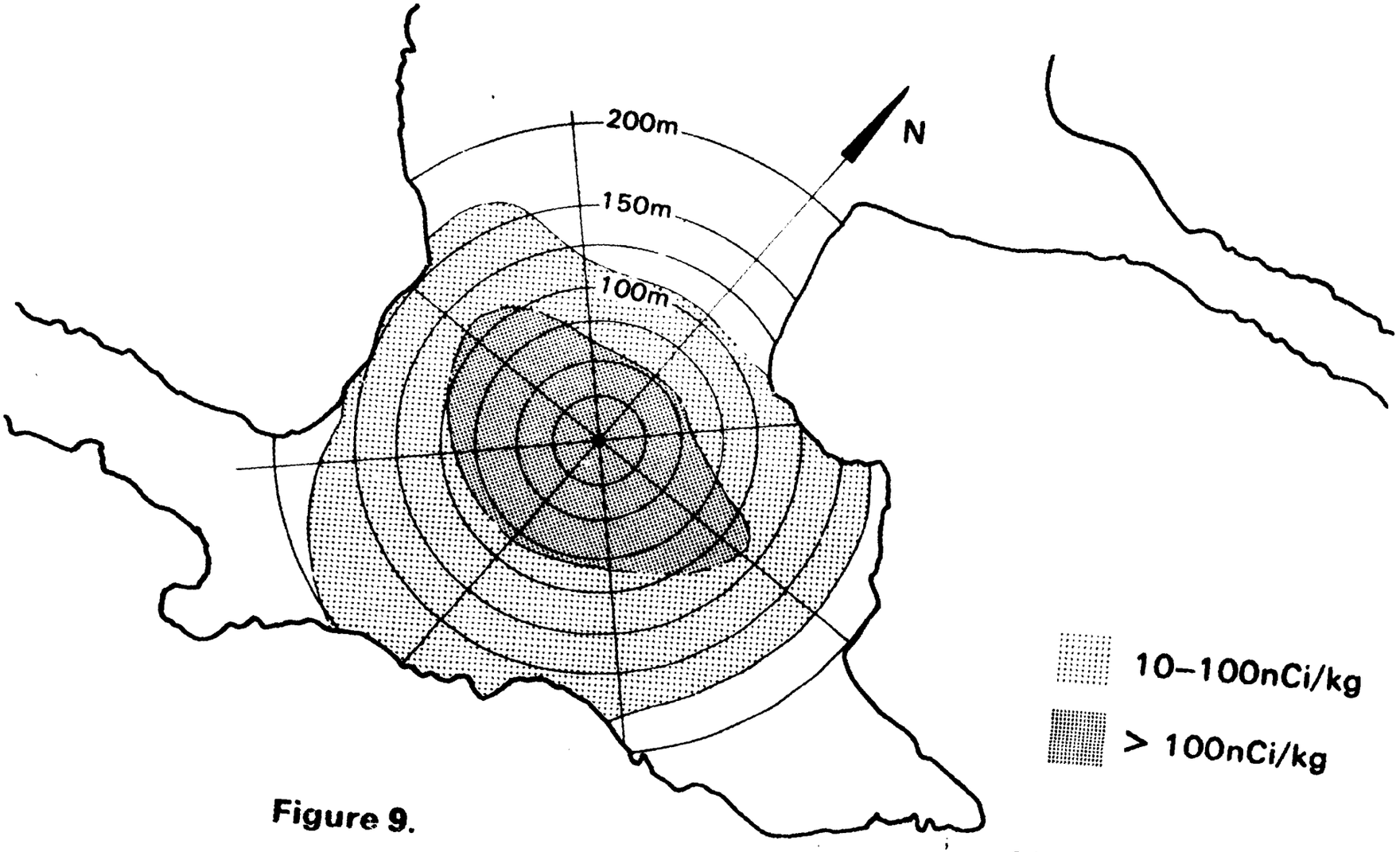


Figure 9.

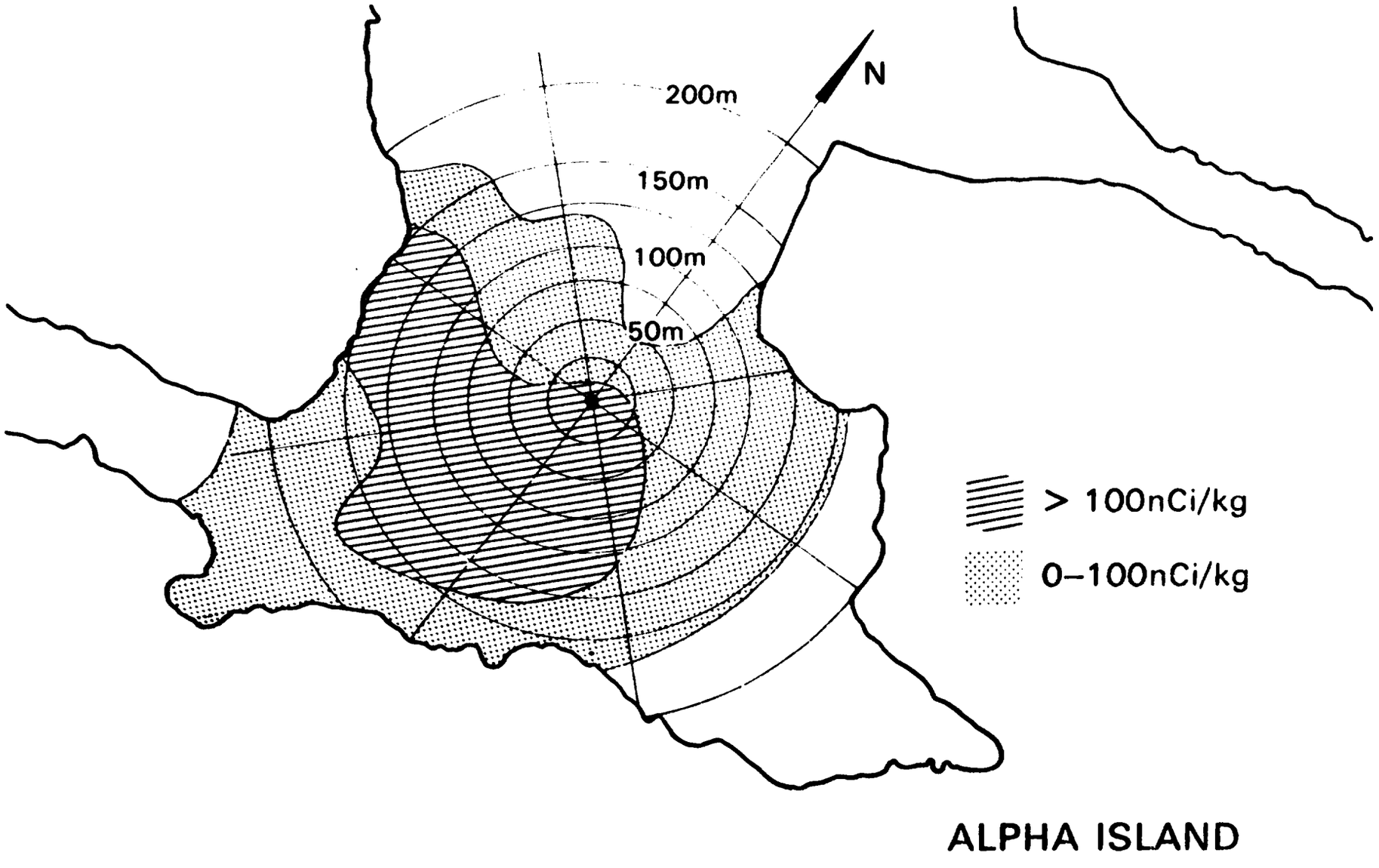


Figure 10.

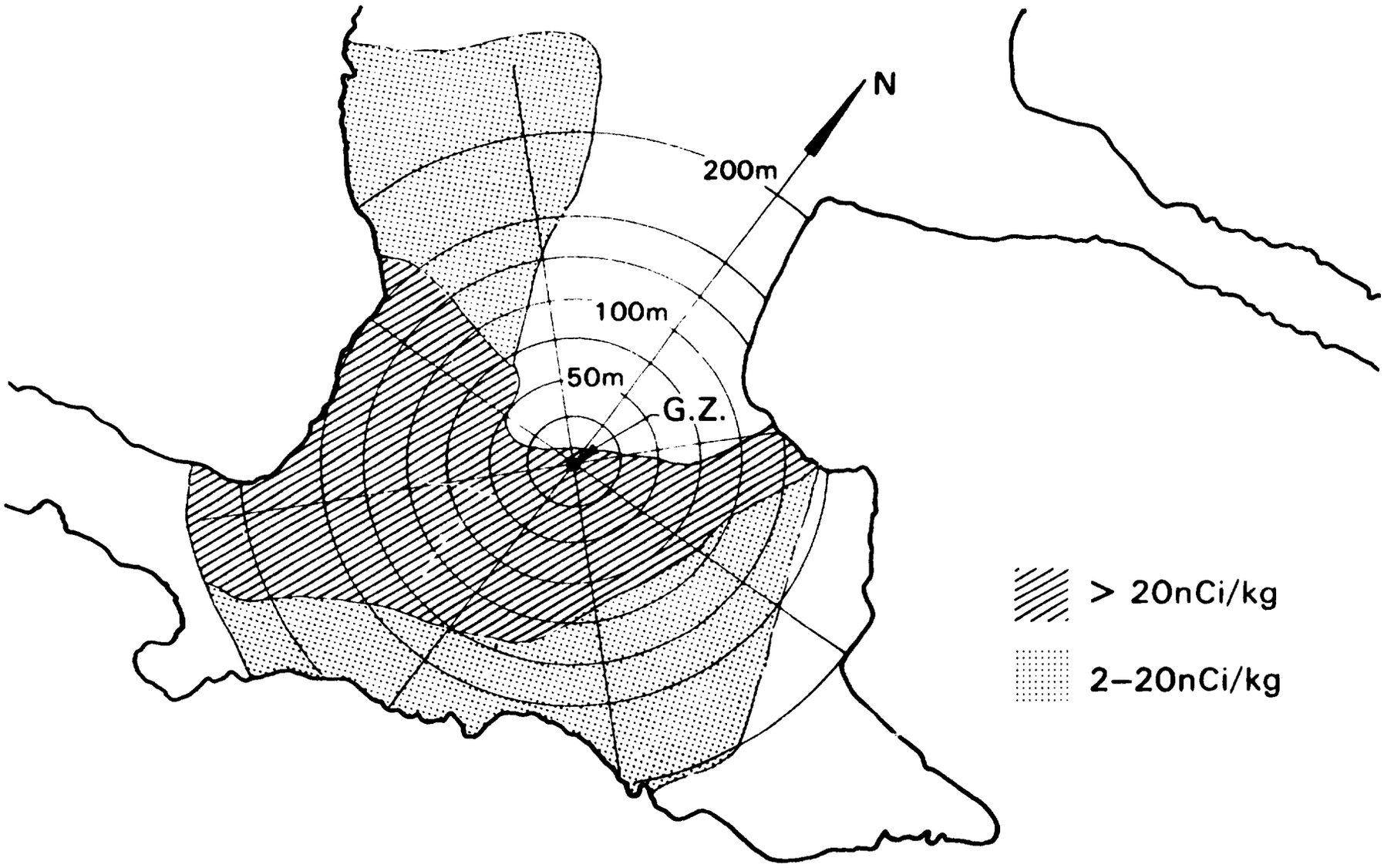


Figure 11.

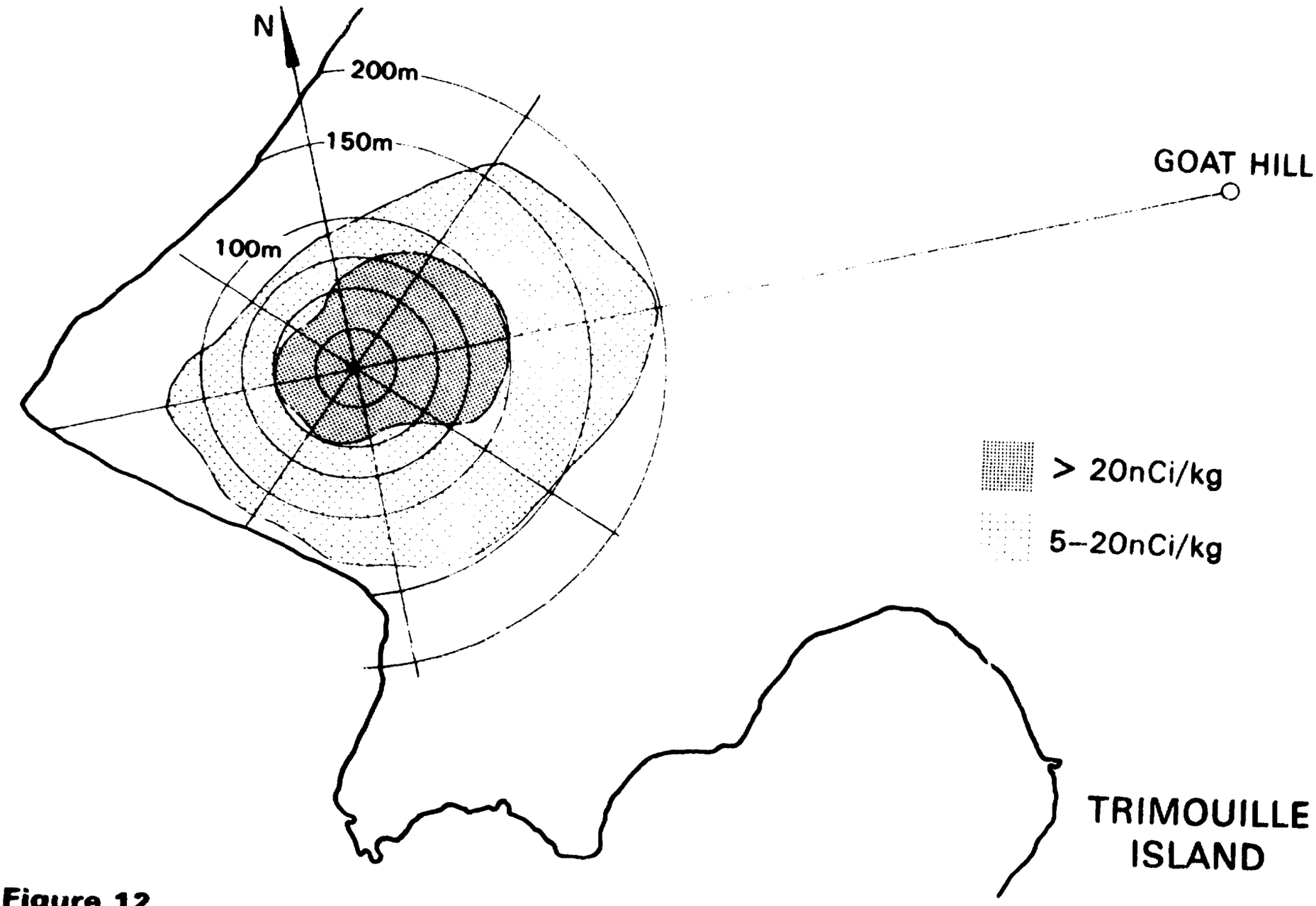

N
200m
150m
100m
GOAT HILL
> 20nCi/kg
5–20nCi/kg
TRIMOUILLE
ISLAND

Figure 12.

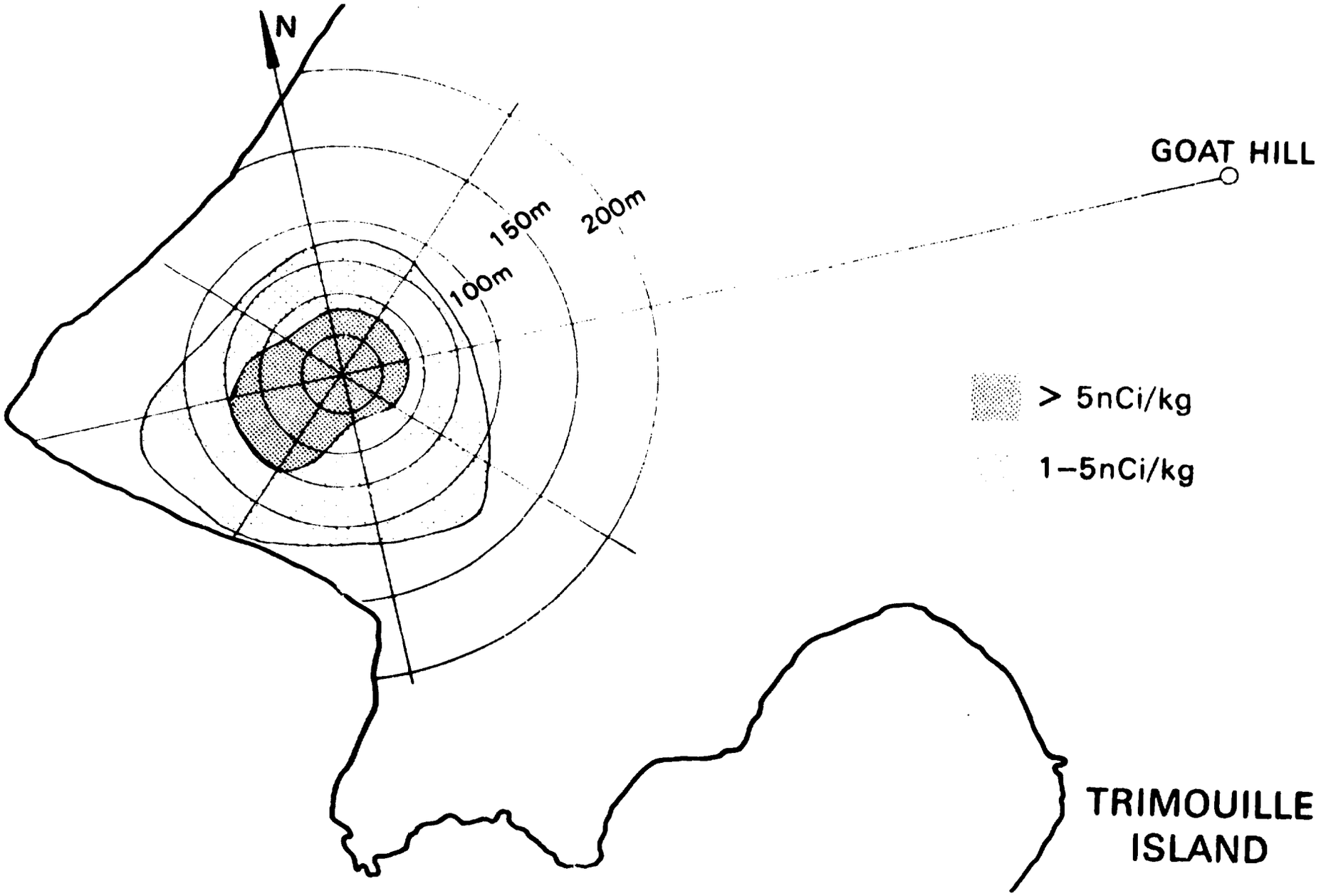

N
100m
150m
200m
GOAT HILL
> 5nCi/kg
1–5nCi/kg
TRIMOUILLE
ISLAND

Figure 13.

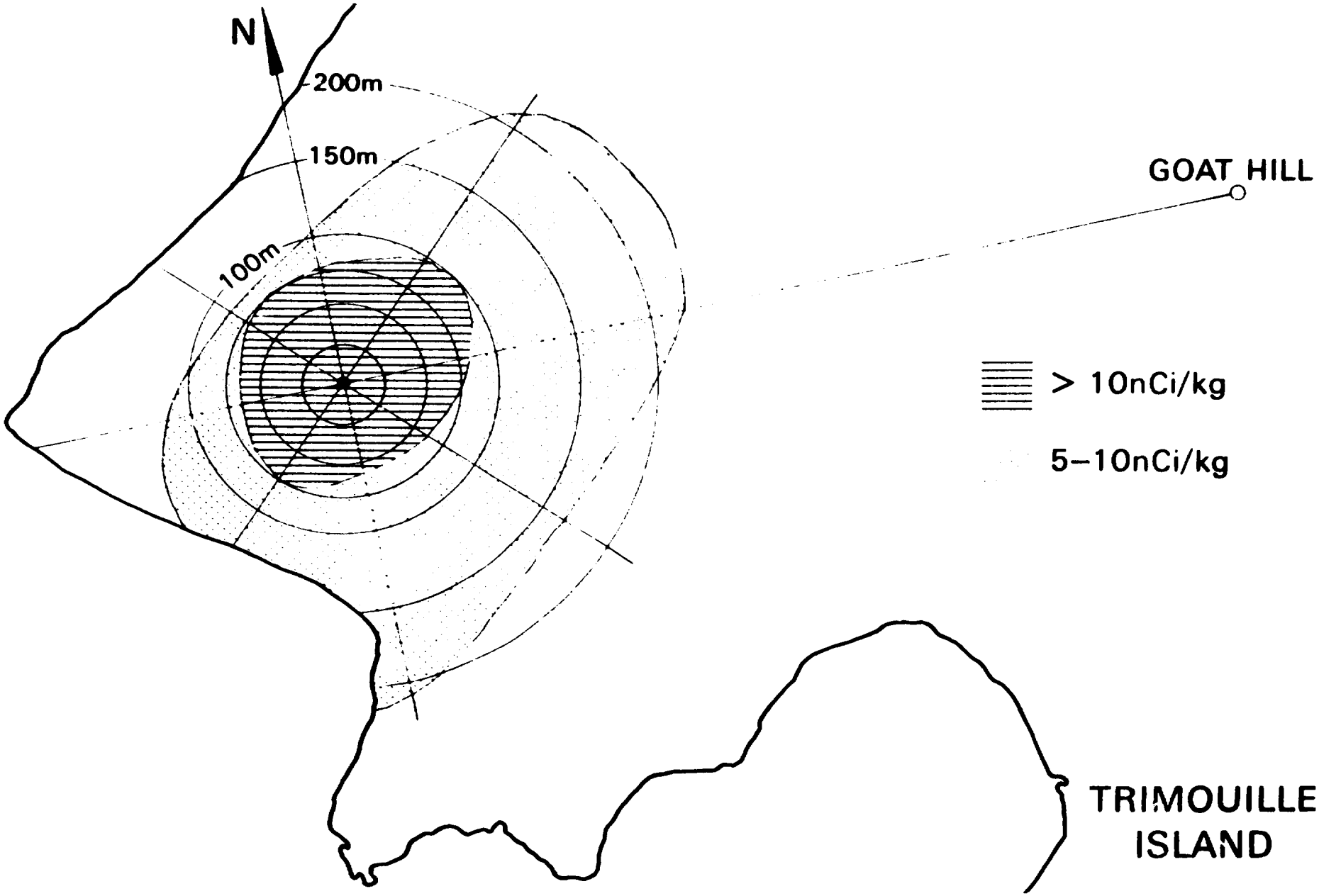

N
200m
150m
100m
GOAT HILL
> 10nCi/kg
5–10nCi/kg
TRIMOUILLE
ISLAND

Figure 14.

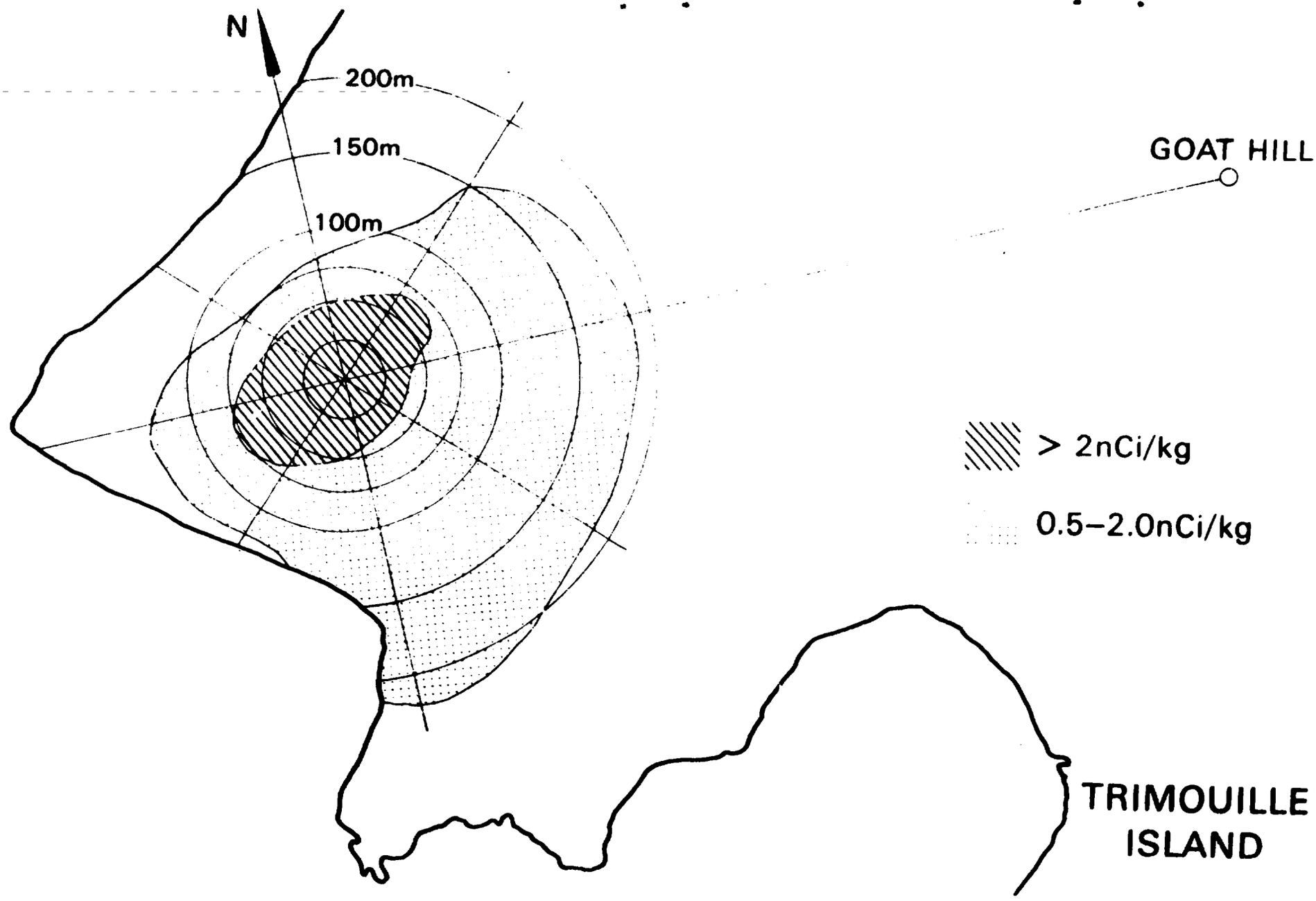

N
200m
150m
100m
GOAT HILL
> 2nCi/kg
0.5–2.0nCi/kg
TRIMOUILLE
ISLAND

Figure 15.

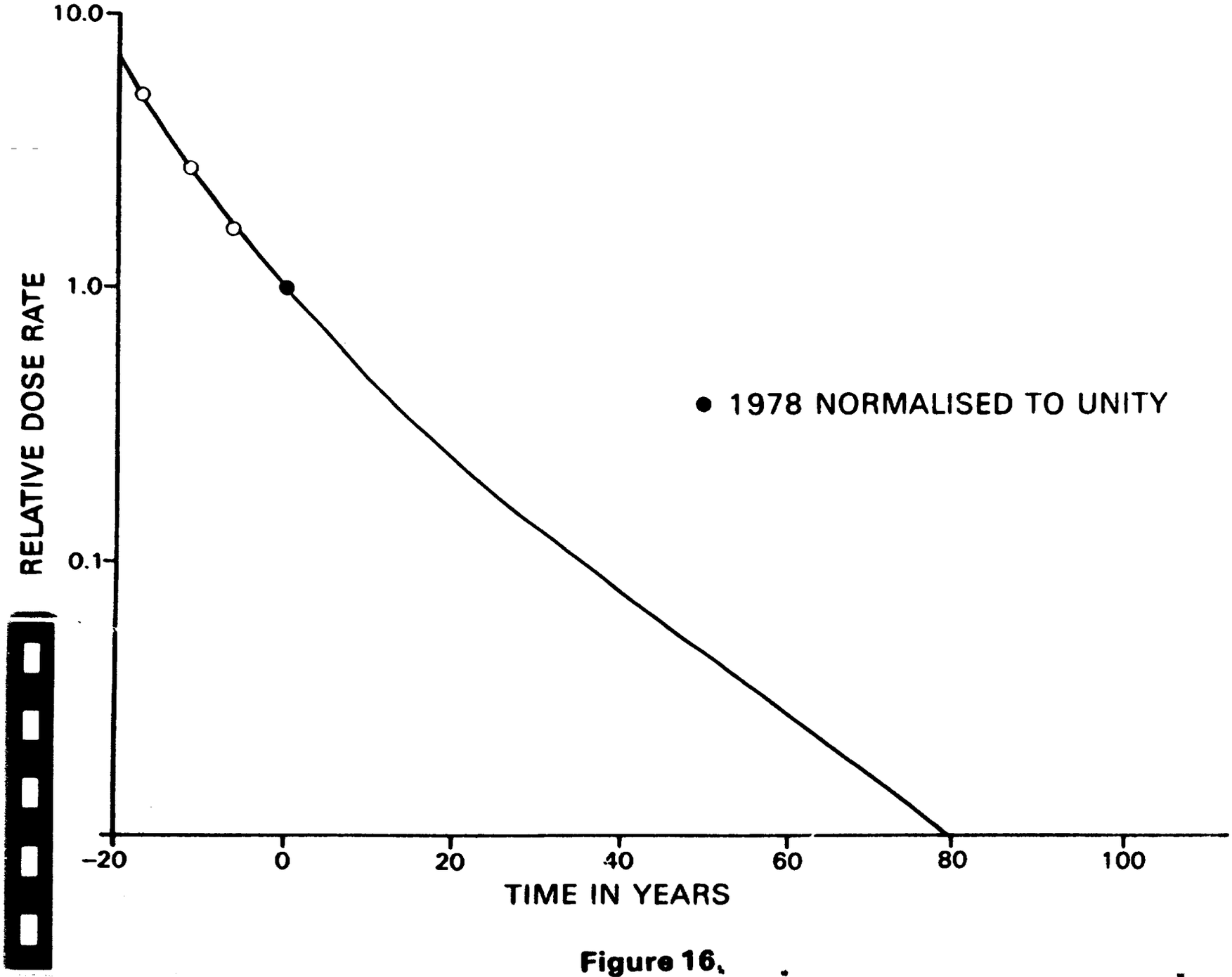

10.0
1.0
0.1
RELATIVE DOSE RATE
● 1978 NORMALISED TO UNITY
-20
0
20
40
60
80
100
TIME IN YEARS

Figure 16.