GROUNDWATER 13

Studies in Hydrogeology

HYDROGEOLOGY AND GROUNDWATER RESOURCES OF NAURU ISLAND, CENTRAL PACIFIC OCEAN

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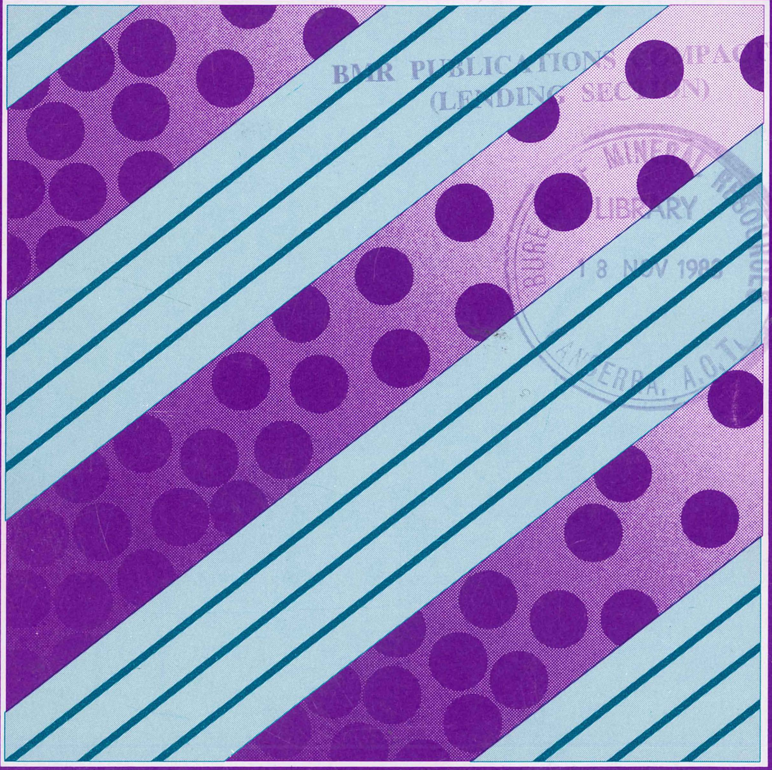

BUREAU OF MINERAL RESOURCES, GEOLOGY & GEOPHYSICS

DIVISION OF CONTINENTAL GEOLOGY

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HYDROGEOLOGY AND GROUNDWATER RESOURCES OF NAURU ISLAND, CENTRAL PACIFIC OCEAN

by

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SUMMARY

Nauru, in the central Pacific Ocean, is a raised atoll capping a volcanic seamount arising from an ocean floor depth of 4300 m. The land area is 22 km^2, and the island rises to 70 m above sea level. Drilling has proved dolomitised limestone of upper Miocene or younger age to a depth of 55 m below sea level. Gravity and magnetic surveys indicate that the limestone probably overlies volcanic bedrock at a depth of about 500 m. Reverse-circulation drilling and geoelectrical probes indicate that there is a discontinuous freshwater layer averaging 5 m thick beneath Nauru. This is underlain by a mixing zone of brackish water, 60-70 m thick. The exceptional thickness of the mixing zone is ascribed to high permeability of the karstified limestone. The forthcoming cessation of phosphate mining will mean a shortfall in water supply which will probably have to be met by the desalination of brackish water. Groundwater beneath the mined-out area, and the settled coastal terrace, is highly vulnerable to pollution, and waste disposal management needs to be considered in relation to groundwater protection.

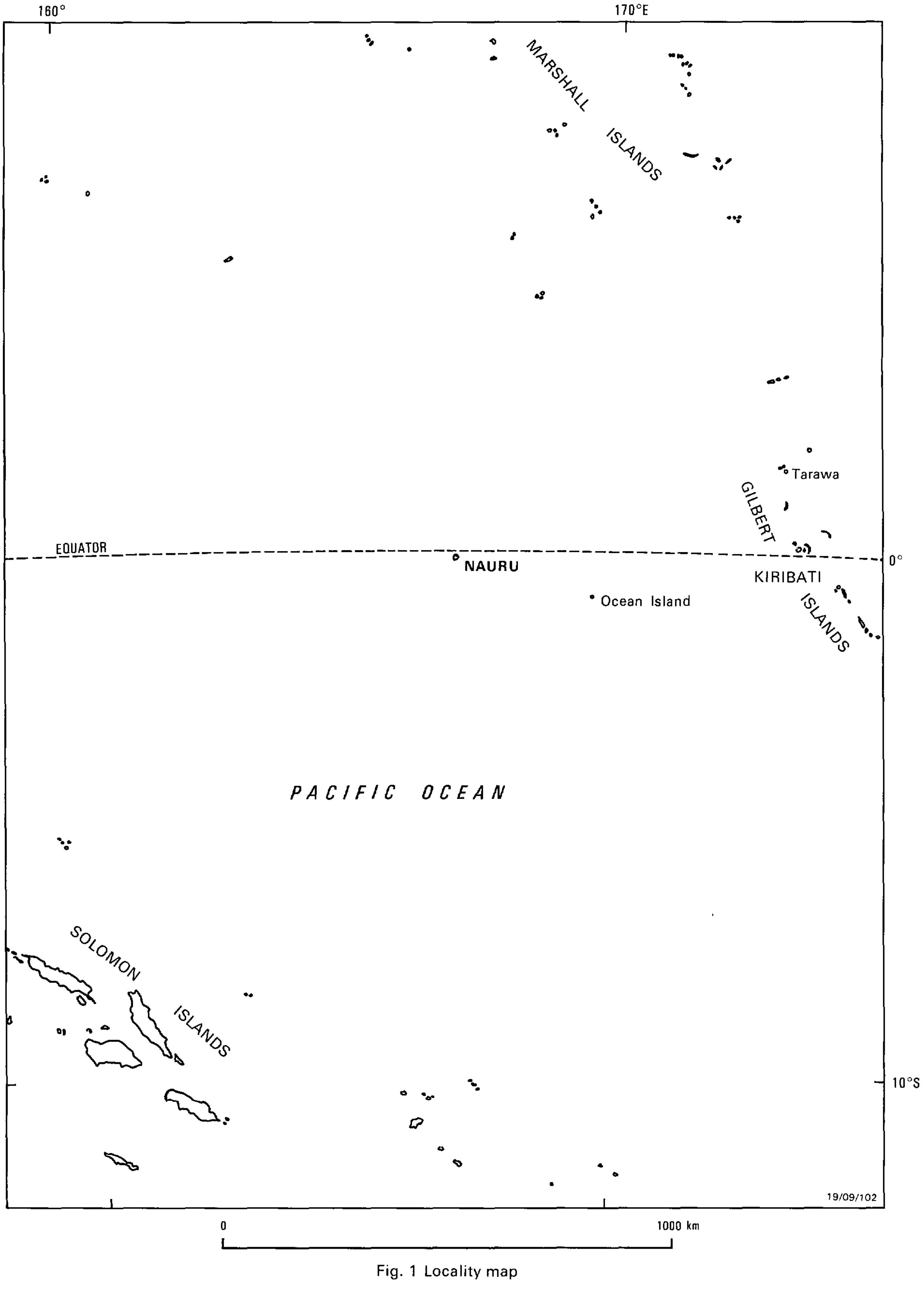

Fig. 1 Locality map

INTRODUCTION

Nauru, which supports a population of 8500, occupies a land area of 22 km^2 in the central Pacific Ocean at 0° 32'S, 166°56'E (Fig. 1) The island has been mined for its surficial phosphate deposits for about 80 years, and the current reserves indicate that the mine has approximately 9 years' life left. About 80 percent of the land area has had its vegetation and soil cover removed leaving an exposed limestone pinnacle surface, or karrenfeld. The pinnacles are residual features left after karstic solution of the limestone.

The present water supply is derived from rainwater tanks supplemented by dugwells and by water imported as ballast on the phosphate ships. Rehabilitation of the mined out land is under consideration and this is expected to increase the demand for water at a time when imported water will no longer be available. In this context an investigation of the hydrogeology and groundwater resources of Nauru was undertaken by a BMR team on behalf of the Commission of Inquiry into Rehabilitation of the Worked-out Phosphate Lands in Nauru. Field work was carried out from 6th to 19th October 1987, the BMR team comprising G. Jacobson (hydrogeologist) and P.J. Hill (geophysicist). The field investigation included inspections and sampling of springs and wells; gravity and magnetic surveys to determine the depth and shape of the island's basement; electrical resistivity surveys and drilling to determine the thickness of the freshwater layer; and measurements of tidal response in bores. The drilling program had a dual objective, being partly concerned with the evaluation of limestone and deep phosphate deposits; it was carried out by contractors using a reverse circulation rig and was supervised by Mr P.J. Barrett, consulting geologist to the Commission of Inquiry. Locations of drillholes are shown in Figure 2. Subsequently BMR arranged for the dating of some drill core samples, and for the chemical analyses of water samples.

GEOLOGY AND STRUCTURE OF NAURU

Nauru is a raised coral atoll which is underlain by a volcanic seamount that rises more than 4000 m from the floor of the Pacific Ocean (Fig. 3).

Bathymetry

The seafloor topography off Nauru is poorly known. Published bathymetric maps of the area are small scale or show generalized bathymetric contours.

The only near-shore bathymetric survey for which data are available was completed in 1980. This survey mapped water-depths out to the 540 m isobath along a 1.7 km stretch of coast at the ship moorings on the western side of the island. Beyond the fringing reef, the submarine slope of the island was shown to descend steeply at about 34°. No other bathymetric information appears to be available within the 3000 m isobath surrounding Nauru. Beyond the 3000 m isobath, the data sources comprise:

(i) Oceanic Soundings Sheet 261 (scale 1:1 000 000) compiled by the Hydrographic Office, R.A.N., Sydney (1977); and

(ii) research cruise data provided by the Defense Mapping Agency,

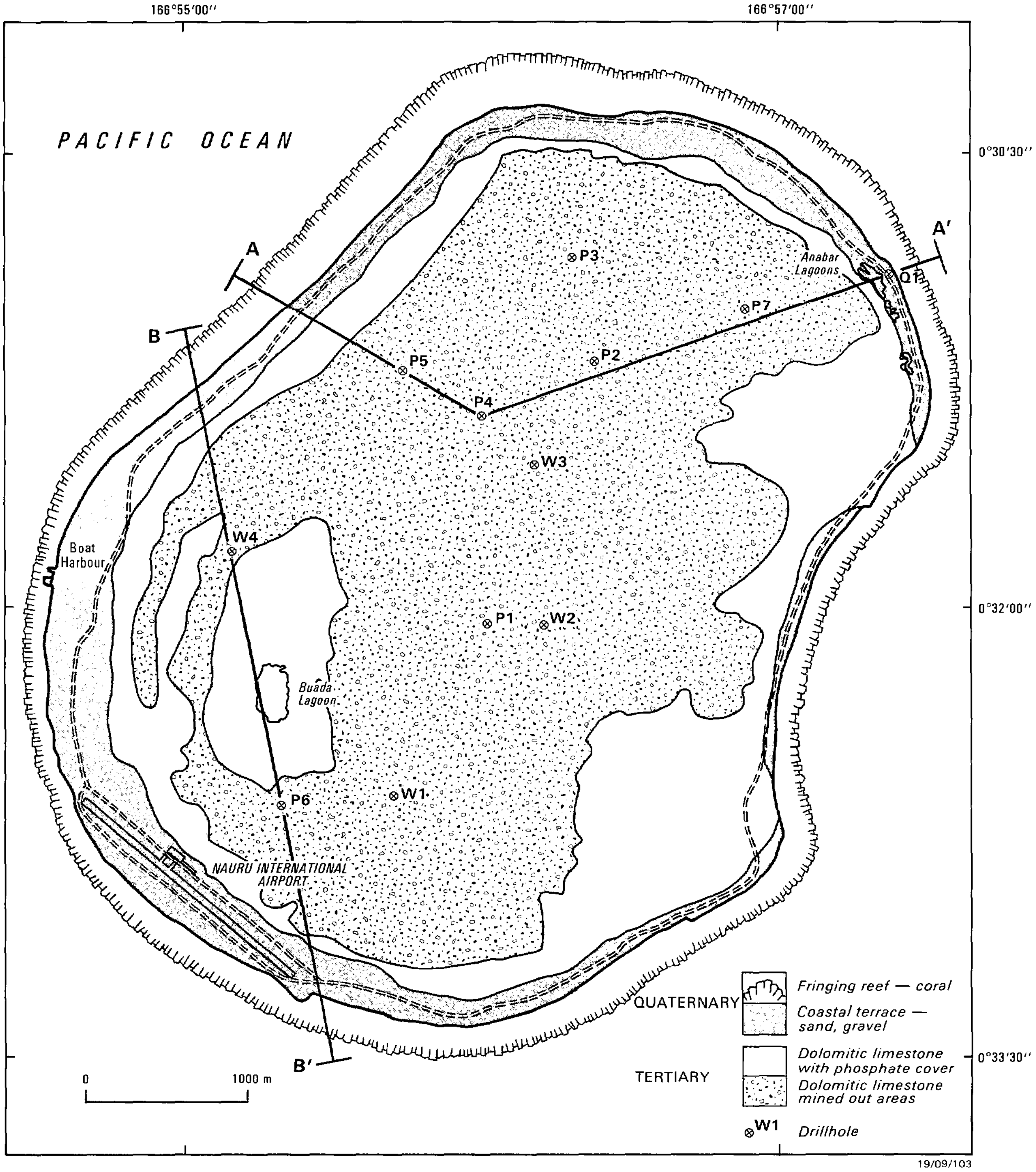

Fig. 2 Geology and drillhole locations

Aerospace Center, St. Louis, U.S.A. and the National Geophysical Data Center, National Oceanic and Atmospheric Administration, Boulder, Colorado, U.S.A. Relevant cruises included:

(a)	1971	R/V 'Dimitri Mendeleyev' (Cruise 6) - USSR Academy of Sciences, Institute of Earth Physics;
(b)	1972	R/V 'Vityaz' (Cruise 51) - USSR Academy of Sciences, Institute of Earth Physics; and
(c)	1977	R/V 'Vema' (Cruise 34) - Lamont Doherty Geological Observatory.

The bathymetric contour map (Fig 3) of Nauru was compiled from these data sources, and the distribution of these data over the map area is indicated. The submarine slopes descend steeply to water depths of about 3000 m then level off to the surrounding abyssal plain at a depth of about 4300 m.

Geology

The maximum elevation of the island is about 70 m. Even prior to mining, the original atoll topography had been modified by karstic erosion. An early map reproduced by Hutchinson (1950) shows an irregular island rim, 30-60 m above sea level surrounding four interior depresions, three of which had a base level of about 20 m. The fourth depression contains Buada Lagoon, in the southwest of the island, which is just above sea level.

A coastal terrace extends around the island: the terrace is up to 400 m wide (Fig. 2) and is a few metres above sea level. Between the inland plateau and the coastal terrace is a narrow chain of depressions including brackish lagoons at Anabar in the northeast of the island. Peripheral to the coastal terrace is a fringing reef which extends 200 m offshore with an outer slope dipping 34° into deep water.

Radiocarbon dates have been obtained from drillcore Q1 in the coastal terrace. The dates, for aragonitic coral, were 2730 ± 60 years for a sample at 1-2 m, and 2820 ± 60 years for a sample at 2-3 m (Table 1). The drillhole was sited on the storm ridge separating the Anabar lagoons from the sea, and the samples probably represent cemented storm deposits rather than coral reef in situ. The dates indicate that the coastal terrace is a youthful feature, and its construction is probably related to a high stage of Holocene sea level.

The phosphate capping of Nauru is, or was, several metres thick, and overlies an intensely dissected karrenfeld with karst limestone pinnacles up to 14 m high. Some isolated pinnacles are higher. The phosphate deposits also occupy the space between the pinnacles, and infill caves and joints in the limestone. A description of the phosphate deposits was given by Power (1910). The formation of the phosphate deposits from avian guano is believed to date back more than 300 000 years (Roe and Burnett, 1985).

Dolomitised limestone forms the bulk of the island and has been drilled to a maximum depth of 55 m below sea level. The limestone above this level is upper Miocene or younger in age (Appendix 1); Quaternary molluscs were identified near the island's surface by Ludbrook (1964). The limestone is intensely karstified, with phosphatic cave-fillings extending down to this

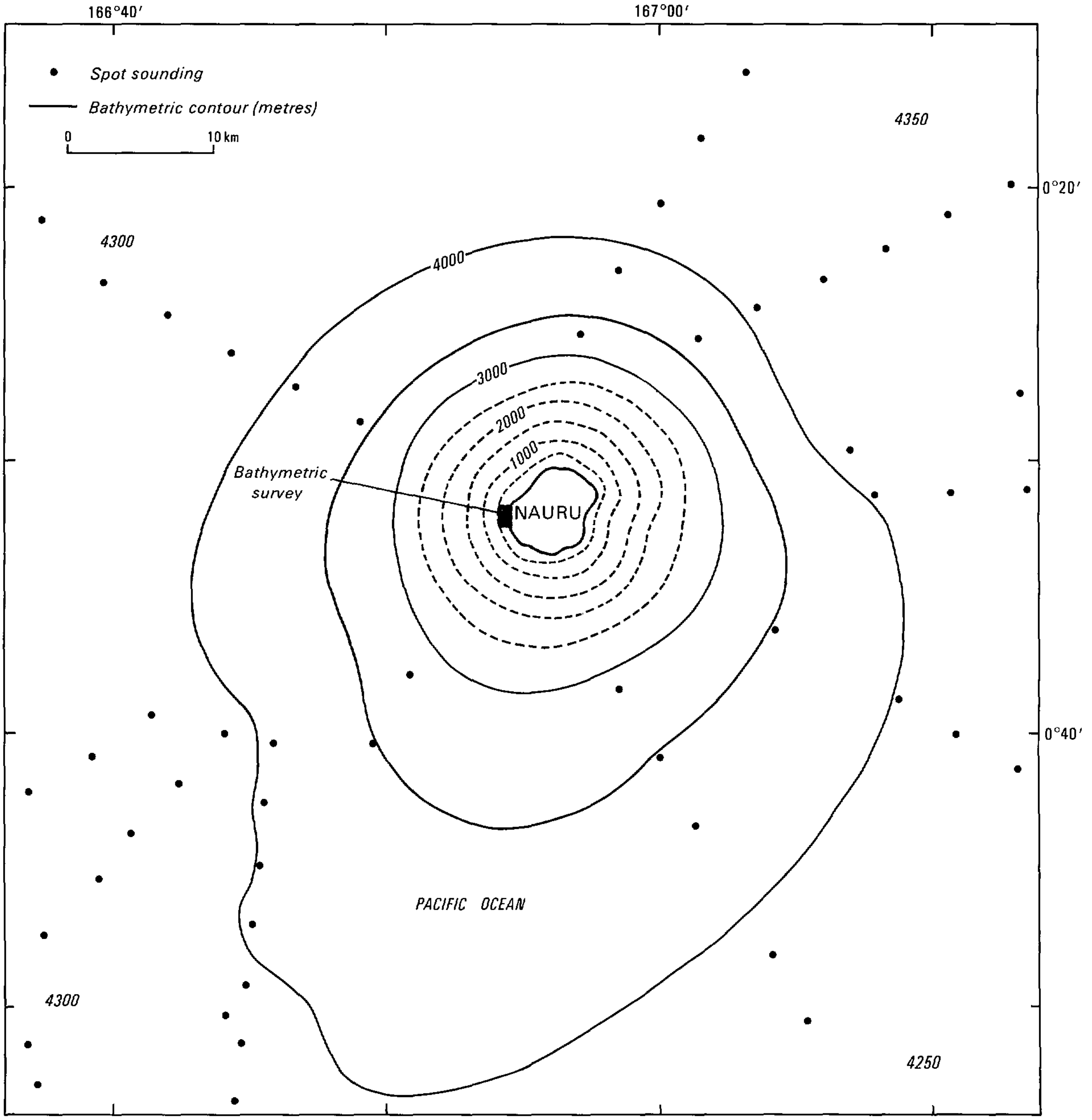

Fig. 3 Nauru bathymetry

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TABLE 1

RADIOCARBON DATES ON DRILLCORES

(by University of Waikato Radiocarbon Dating Laboratory)

Sample no	WK 1149	WK 1150
Drillhole	Q1	Q1
Depth (m)	1-2	2-3
Conventional age[1] (years B.P.)	2660 ± 60	2740 ± 60
True age [2] (years B.P.)	2730 ± 60	2823 ± 60
^{14}C depletion[3]	-281 ± 4.6	-288.9 ± 4.6
Delta ^{13}C	-0.1 $^{o}/oo$	0
Material	Coral 92% aragorite	Coral 95% aragonite

[1] 'Conventional age' implies use of Libby half-life (5568 years) with AD 1950 as reference year, and assumed constancy of atmospheric radiocarbon levels.

[2] 'True age' is based on new half-life of 5730 years.

[3] Carbon-14 depletion expressed as $^{o}/oo$ with respect to 0.95 oxalic acid.

level. Undoubtedly Nauru has been above sea level for much of its history. The last emergence that contributed to karstification was the glacial low, 15 000 years ago, when sea level was about 100 m lower than at present.

The arcuate eastern coastline probably represents the headward scarp of a submarine slump. Arcuate fractures subparallel to the coastline have been observed on air photos in the southwest and northwest of the island (Barrett, 1987), and there is also a series of generally NW-SE linear fractures across the island. Some of the latter have vertical displacement of up to several metres, visible in the exposed karrenfeld surface.

GEOPHYSICAL FRAMEWORK STUDY

Gravity and magnetic surveys have been undertaken by P.J. Hill to establish the depth and structure of the volcanics beneath the limestone capping.

Gravity survey

To minimize travel time and jolting of the instrument three gravity base stations were set up and tied gravimetrically. These were located at: (i) the entrance to Meneng Hotel; (ii) a benchmark at the NPC Office; and (iii) the entrance to the Survey Office in the Central Workshop area. For locating gravity stations and obtaining elevations the 1982 1:1000 topographic sheets were used. This set of 39 sheets provides 1 m contours and allows elevations to be scaled to 0.1 m.

The gravity data were corrected for drift and reduced to simple Bouguer anomaly by applying elevation and latitude corrections and adopting a density of 2.1 t/m^3 for above sea-level topography. A small number of stations located on or near steep slopes required terrain corrections.

A Sharpe gravity meter, S145, was used for this survey; this is not a geodetic instrument and because of its limited range could not be used to tie into the Australian network. Since it appears that no absolute gravity stations have been established on Nauru, the survey data are relative only.

The gravity map of Nauru (Fig. 4) shows a dome-shaped field with contours concentric about the centre of the island. The relative gravity field ranges from a high of about 22 mGals at the centre to 4 mGals at the SW coast. The pronounced gravity high over the centre of the island reflects the excess mass of the Nauru pedestal (density about 2.5 t/m^3) over that of the surrounding ocean (density 1.03 t/m^3). The central position of the gravity high and the almost circular, little-distorted nature of the contours indicate that the substructure of the island is radially symmetrical.

Gravity model

Three-dimensional gravity modelling of the submarine pedestal of Nauru was undertaken to obtain an estimate of mean density and to reduce the observed relative Bouguer anomalies to residual gravity values. Residual gravity is here defined as Bouguer anomaly minus the gravitational contribution of the island pedestal, and effectively represents gravity corrected for submarine terrain. The residual gravity field should highlight any anomalous density distributions within the edifice. The gravity modelling technique of Plouff (1976) was used for the analysis. By this method, the gravity field of geological bodies with complex shape can be calculated by representing

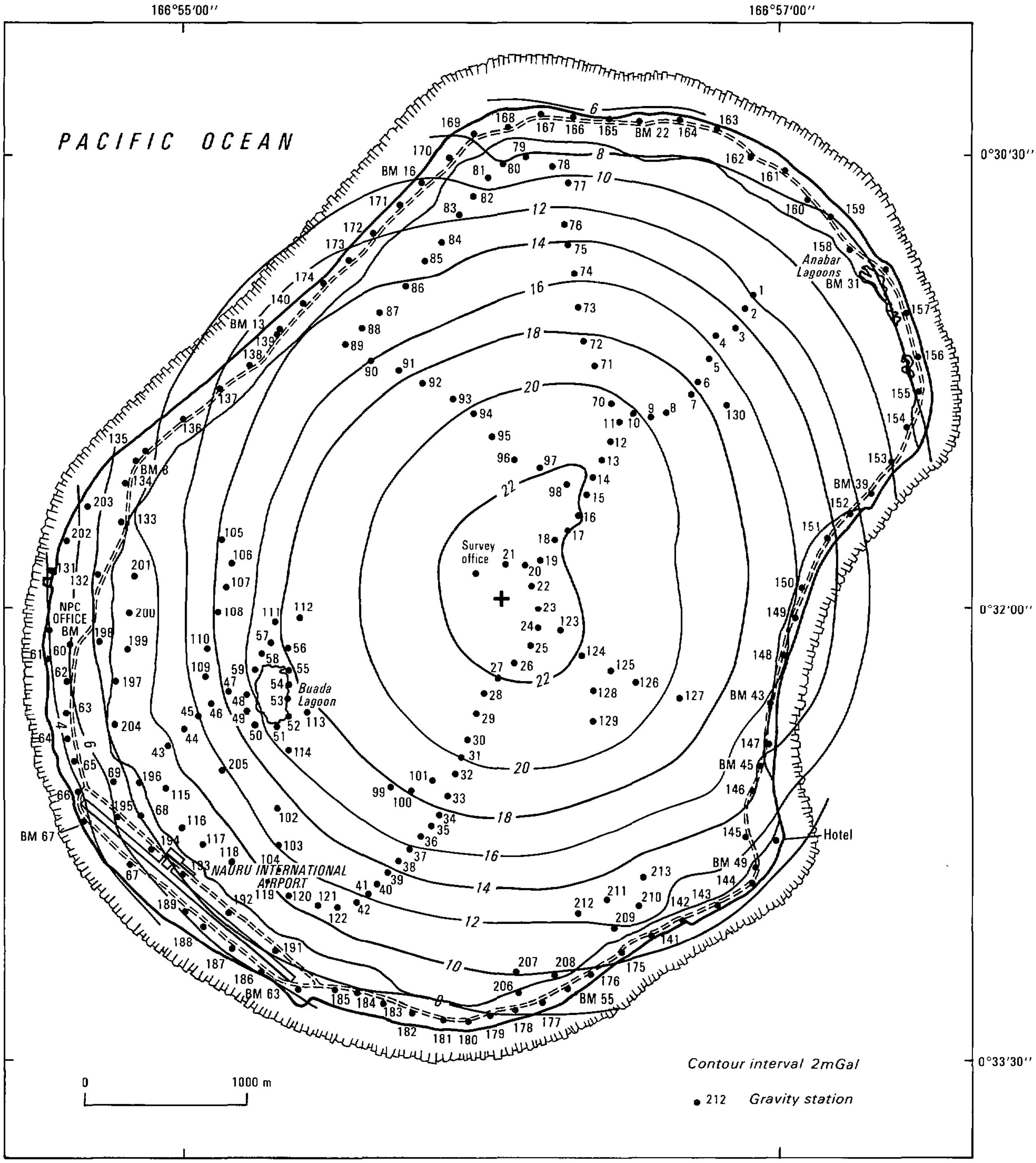

Fig. 4 Relative Bouguer gravity anomaly (Terrain corrected for asl topography)

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them as an equivalent set of polygonal prisms. Least squares inversion of the observed data allows best-fit density to be estimated.

For the modelling, the submarine pedestal of Nauru was approximated by a stack of 10 polygonal slabs, each with 9-19 vertical sides and horizontal upper and lower surfaces. The slabs represent horizontal layers of the seamount as defined by the bathymetric contours of Figure 3. Adopted depth extents of the slabs were: 0-200 m, 200-450 m, 450-1000 m, 1000-1500 m, 1500-2000 m, 2000-2500 m, 2500-3000 m, 3000-3500 m, 3500-4000 m and 4000-4300 m. The gravity model assumes that the loading of the crust by the Nauru edifice is compensated by a regional, rather than local isostatic mechanism. Input to the least-squares inversion analysis included gravity data from all 228 gravity stations.

The calculations give the density of the island pedestal as 2.51 t/m^3, assuming a sea water density of 1.03 t/m^3, with correlation coefficient of 0.94 and standard deviation 1.9 mGal. One of the results of the calculations is the derivation of a gravity datum which can be used to convert the relative Bouguer gravity to an approximation of absolute Bouguer gravity. The conversion is effected by adding 183 mGal to the gravity values in Figure 4. The calculated mean density of 2.51 t/m^3 is typical of Pacific seamounts and suggests a lithology largely composed of basalt flows beneath the carbonate platform.

Residual (observed minus calculated) gravity is depicted in Figure 5 as 0.5 mGal contours. The residual gravity field is fairly flat with a range of only -3.5 to +3.5 mGal. A broad high of about 2.4 mGal is located over the central part of the island and extends towards the eastern coast. Arcuate lows, about 0.8 km inland and sub-parallel to the coast, are present in the southwest and northern parts of the island. A band of high residual gravity extends along the eastern coastline. The calculation of residual gravity for stations along the coastal strip is sensitive to near-shore variations in bathymetry. Only the bathymetry off the southwest coast is well known, and the remainder of the coastal bathymetry has had to be interpolated. It is possible that some of the relatively high residual gravity values along the coastline may partly be due to the submarine slope being more gentle than assumed.

The central gravity high may be the expression of a volcanic plug or intrusive complex with density slightly higher than that of surrounding flows/tuffs. The diameter of the upper part of this structure is about 3 km. Assuming that the structure has steeply sloping sides and extends through the full height of the volcanic pedestal, the observed gravity anomaly represents a positive density contrast of less than 0.05 t/m^3. The residual gravity contours indicate no other prominent local or linear structural features that can be interpreted without further control such as exploratory deep drilling. The variations in residual gravity over Nauru probably reflect minor density changes within the interior of the volcanic edifice produced by the heterogeneous distribution of diverse lithologies. Ash tuff, hyaloclastite and vesicular basalts are generally less dense than basaltic intrusions and non-vesicular flows erupted at depth. Such low density materials are probably responsible for the arcuate gravity lows over the northern and southwest parts of the island.

Magnetic survey

The strategy adopted in the case of the magnetic surveying was to complete a series of relatively long detailed traverses, in combination with

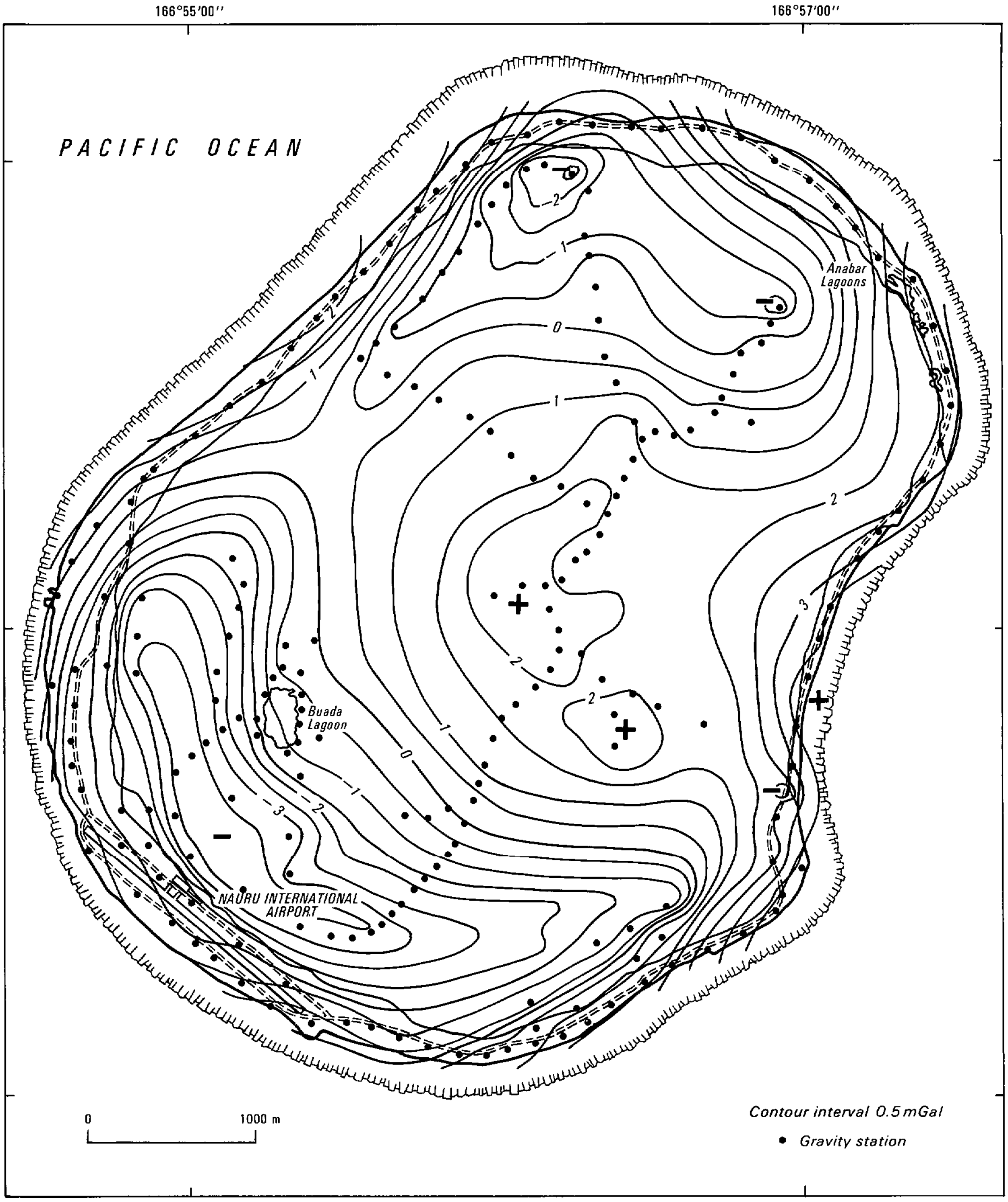

Fig. 5 Residual gravity

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isolated stations to fill data gaps over the island. It was envisaged that high resolution mapping of local anomalies along traverses would yield source depths, while the combination of traverses and isolated stations would provide the overall field of the volcanic substructure for mathematical modelling of its magnetic and geometric parameters.

Along traverses, readings were taken at 18 m intervals. The instrument used was an EG&G Geometrics G-856 Memory-Mag proton precession magnetometer with an aluminium staff to give a sensor height of 2.5 m. To correct for diurnal variation, a main base station was set up near Meneng Hotel and subsidiary base stations were occupied at points along the N-S mine road in the interior of the island. Station readings were corrected for diurnal variation relative to a datum taken as the mean value of readings at the Meneng base station (35870 nT). Much of Nauru is prone to man-made magnetic noise, owing to urban development along the coastal terrace and intensive mining activity in the interior. The problem is compounded in the interior by the fact that access is restricted to the mining roads because of the impenetrable pinnacle terrain. Abandoned mining equipment and other ferrous rubbish line these roads and are often difficult to detect visually because they have become overgrown by lush vegetation or have been incorporated as backfill in the road construction. Although the magnetic noise was a problem, the ultimate success of the survey was not affected. Steps taken to reduce the problem included: taking a number of readings at scattered points around the isolated stations to check for large gradients indicative of non-geologic magnetic sources; and surveying on the reef-flats at low tide. The outer reef-flats were an almost magnetic noise-free environment because of the absence of metallic litter.

The results of the survey are shown in Figure 6, which depicts the data distribution and magnetic contours at 50 nT intervals. The magnetic field has a range of 830 nT, going from a low of about 35140 nT over the NNE coastline to an E-W elongated high of 35970 nT over the southern sector of Nauru. The pattern suggests a reversely magnetised volcanic pedestal. Examination of the magnetic profiles along the detailed traverses indicates a smoothly varying, relatively long-wavelength field, ignoring the localised non-geological noise. This implies a fairly deep magnetic basement although the paucity of distinct high-amplitude anomalies makes estimates of depth difficult. However, from the observed gradients and subtle variation in the profiles, the source depth is estimated to be about 400-500 m.

Magnetic model

Magnetic modelling of the volcanic substructure of Nauru was done in a manner analogous to that of the gravity modelling, i.e. by approximating body shape by a set of polygonal prisms and estimating magnetisation parameters by least-squares inversion (Plouff, 1976). Uniform magnetisation of the magnetic body being modelled is assumed in the analysis. The input data for the modelling comprised 115 magnetic data points interpolated at 2 km intervals onto 9 lines distributed over Nauru. The lines were selected so that representative data coverage of Nauru was achieved, and so as to coincide with actual field traverses.

For the initial stage of modelling the magnetic field over Nauru, a uniformly magnetised island pedestal with a non-magnetic top section to represent the carbonate capping, was assumed. The same polygonal representation of the island's submarine topography as in the gravity modelling was used, except that some of the upper polygonal slabs were

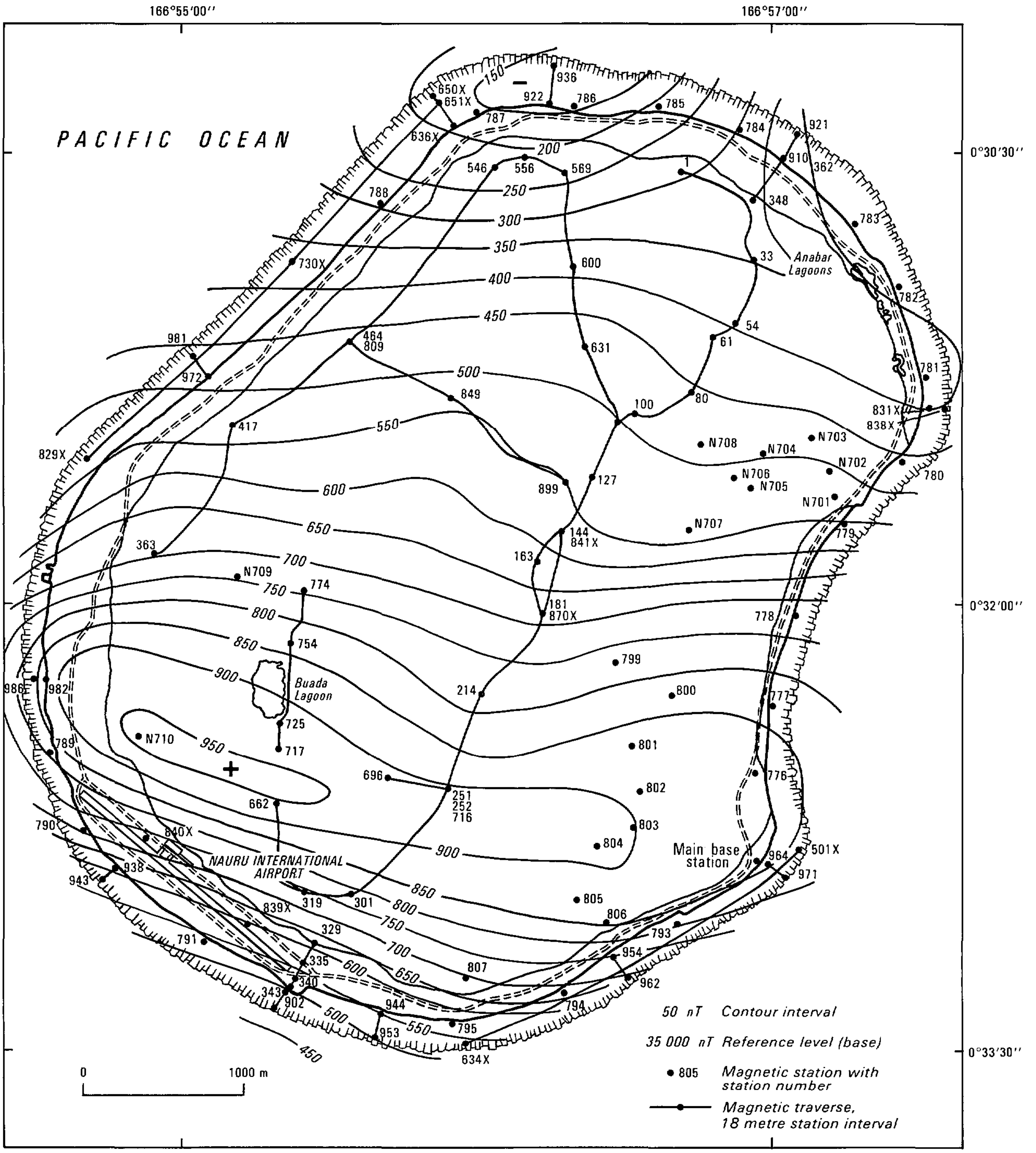


Fig. 6 Total magnetic intensity corrected field results

omitted to simulate a non-magnetic capping. This model produced an unsatisfactory fit to the observed field, indicating that the volcanic edifice of Nauru is not uniformly magnetised, and that the anomalous field is probably due to a magnetic core within a mainly non-magnetic or weakly magnetised volcanic pedestal.

By trial-and-error variations in geometry of the body representing a magnetised volcanic core, two simple but geologically plausible models were derived which produced an excellent fit to the observed data. The geometry of Models 1 and 2, together with their calculated magnetic fields are presented in Figures 7 and 8. Magnetisation parameters for these magnetic models are given in Table 1.

Model 1 represents a vertically-sided core laterally confined within the coastline of Nauru except for a minor excursion beneath the eastern side of the island. The top surface is horizontal but lies at two levels, 400 m deep beneath southern Nauru, and 600 m deep beneath northern Nauru. Model 2 is similar to Model 1, though less angular in overall shape. The sides of Model 2 slope at about 35° in contrast to the vertical sides of Model 1. The shallowest level of the upper surface of Model 2 is also located beneath southern Nauru at a depth of 400 m.

The magnetic core represented by Model 1 may consist of an intrusive complex while Model 2 suggests an intrusive complex or lava dome. The relatively flat upper surface of the core may have been produced by planation of the original volcano to sea-level. The surface shows a general dip to the north, possibly caused by tilting of the whole edifice in this direction or by a system of E-W striking normal faults with downthrow to the north.

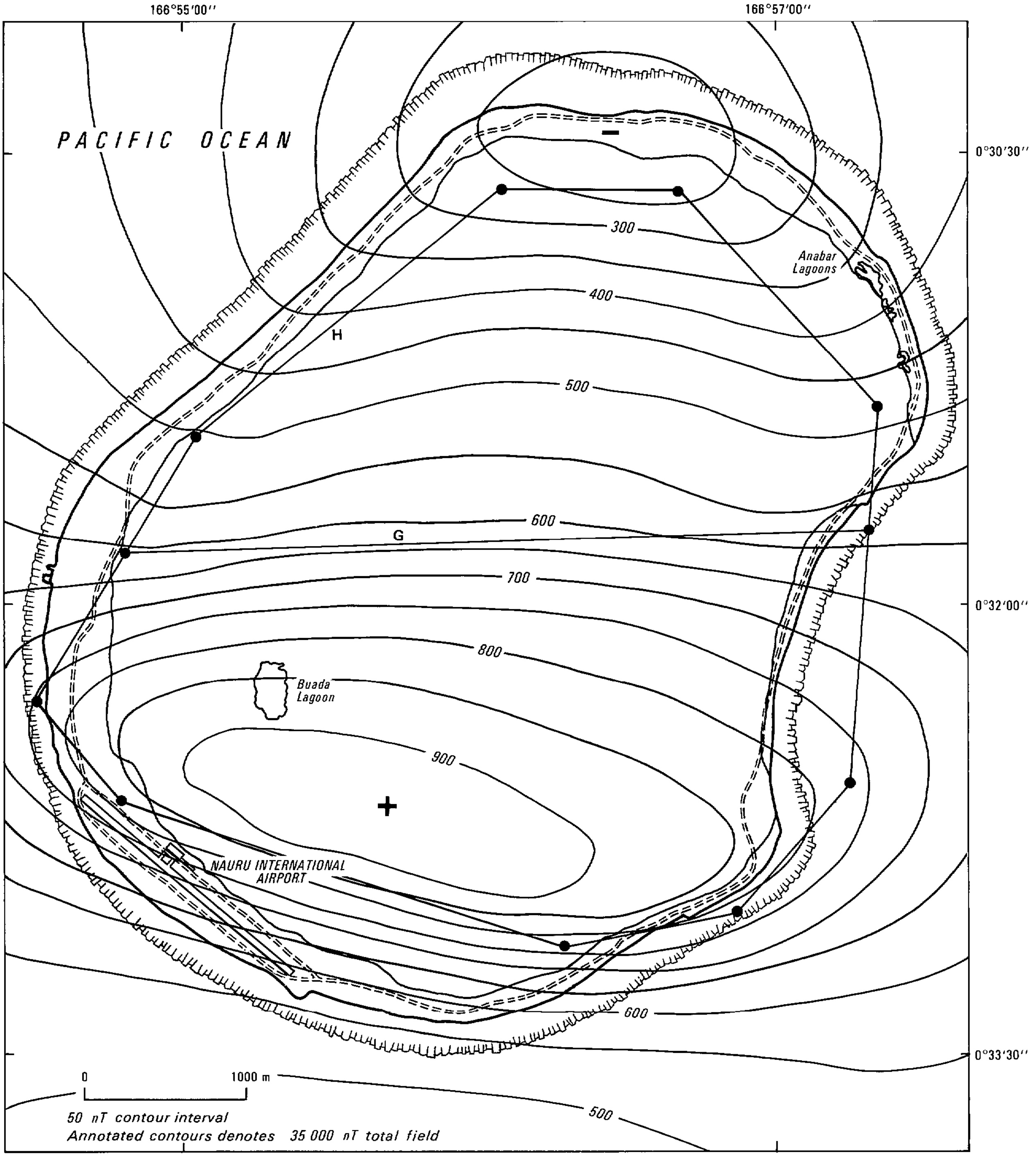
There is no significant correlation between model geometry and residual gravity (Fig. 5), implying that there is little or no density contrast between the magnetic core and adjacent volcanics.

According to the International Geomagnetic Reference Field (Peddie, 1982) total magnetic intensity at the Meneng Hotel base-station for the time of the survey is estimated as 36171 nT. The reference field over the rest of the island is expected to be within about 20 nT of this figure. The magnetic datums derived by modelling (Table 2) should correspond approximately to the reference field, but are in fact about 700 nT lower. The reason for this is not clear. It may be that the reference field is not a good representation of the magnetic field in the Nauru region because of inadequate local magnetic station control. Alternatively, Nauru may be located within a trough of the seafloor magnetic lineation pattern (Larson, 1976), or the base of the island pedestal may possess a significant normal-polarity magnetisation.

Paleomagnetism and age of Nauru

The magnetic lineation pattern in the Nauru Basin (Larson, 1976) implies that Nauru was constructed on oceanic crust formed at about the time of magnetic anomaly M15 i.e. 132 m.y. ago (Early Cretaceous). This represents the maximum possible age for Nauru.

Assuming that the geomagnetic field is essentially that of an axial geocentric dipole when averaged over a period of several thousand years, latitude and orientation of a seamount at the time of its construction can be determined from its magnetisation direction. The seamount must have



Intensity of magnetisation 1.47 A m^{-1} Declination 186° Inclination 24.4° Regional magnetic correction of 495 nT added

Magnetic core is represented by polygonal bodies with depth extents (km) G 0.4 – 0.6 H 0.6 – 4.3

Fig. 7 Theoretical magnetic anomaly field for magnetic core — Model 1

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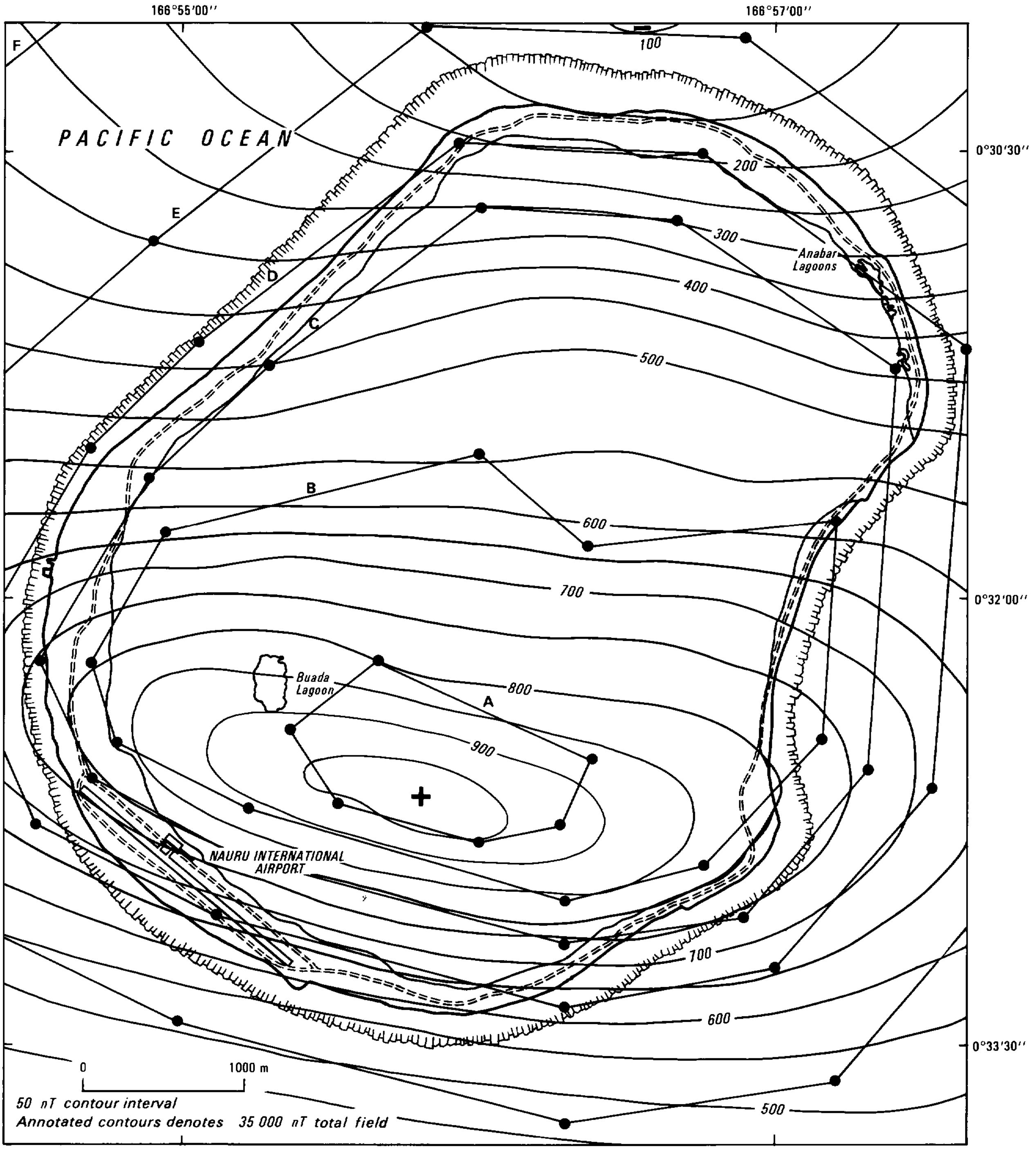

Intensity of magnetization 1.93 A m^{-1} *Declination 188°* *Inclination 14.0°* *Regional magnetic corretion of 348 nT added*

Magnetic core is represented by polygonal bodies with depth extents (km) **A** *0.4 – 0.5* **B** *0.5 – 0.7*

C *0.7 – 1.0* **D** *1.0 – 1.5* **E** *1.5 – 3.0* **F** *3.0 – 4.3*

Fig. 8 Theoretical magnetic anomaly field for magnetic core — Model 2

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TABLE 2

MAGNETISATION PARAMETERS FOR NAURU MAGNETIC MODELS

	Model 1	Model 2
Inclination (+ down)	24.4°	14.0°
Declination (+ east)	186°	188°
Intensity (A/m)	1.47	1.93
Standard deviation, 115 data points (nT)	40	49
Multiple correlation coefficient	0.98	0.97
Magnetic datum (nT)	35495	35348
Paleomagnetic pole	76°N 321°E	80°N 297°E
Paleolatitude (based on inclination)	12.8°S	7.1°S

formed over a long enough time interval so that geomagnetic secular variations are averaged out, and the magnetic anomaly must be primarily due to thermoremanent magnetisation acquired by the volcanic rocks as they cooled through the Curie temperature.

The two models for the magnetic core yield slightly different magnetisation vectors, but an estimate of the age of Nauru can still be obtained. Calculated paleomagnetic poles, and palaeolatitudes for Model 1 and Model 2 are shown in Table 2. The paleomagnetic poles for Nauru plot just west of the apparent polar wander curve for the Pacific plate (Suarez & Molnar, 1980).

The degree of misfit implies a possible rotation of the Nauru area by about 8^{o} in a clockwise direction relative to the rest of the Pacific plate. The paleolatitude data indicate that since its evolution, Nauru has drifted northward on the Pacific plate by 12.3^{o} according to Model 1 or 6.6^{o} according to Model 2. From absolute Cainozoic angular velocities of the Pacific plate given by Gordon & Jurdy (1986), the northward movement of the Pacific plate in the region of Nauru's current position is estimated as 25 mm/yr from 0 to 43 m.y. ago and 72 mm/yr from 43 to 64 m. y. ago. It follows, therefore, that the age of Nauru is 47 m.y. according to Model 1 and 29 m.y. according to Model 2. Combination of the two results puts the probable time of Nauru's evolution in the period mid-Eocene to Oligocene. The bend in the Hawaiian-Emperor chain marks a major change in the motion of the Pacific plate at 43 m.y. (Dalrymple et al., 1980), and plate re-organisation associated with this event may have triggered the volcanism which created Nauru.

HYDROGEOLOGY

A groundwater investigation on Nauru was previously carried out by the British Phosphate Commission (1965). The investigation included a rotary drilling programme but results were inconclusive (AGC, 1972). In the present investigation, we have undertaken reverse-circulation drilling and Schlumberger-geoelectrical soundings to estimate the thickness of the freshwater layer beneath Nauru.

Field Investigation

With the reverse circulation drilling rig, fragmented drillcore was obtained, and water samples were obtained at intervals for electrical conductivity measurement. Some difficulty was experienced in delineating groundwater from drilling water which was used in the section of the drillhole above the aquifer. A total of 12 holes were drilled to depths ranging from 26 to 83 m (Table 3). Three of the holes were completed as open-hole piezometers with 40 mm diameter plastic casing to enable the measurement of standing water level. Caving ground prevented the installation of casing in the other drillholes. Geological logs of the drillholes and electrical conductivity measurements of groundwater samples are given in Figures 9, 10 and 11.

Locations of the geoelectrical soundings are shown in Figure 12 and a list is given in Table 4. A total of 10 soundings were made in three hydrogeological environments:

(i) in the interior of Nauru, at elevations 12-27 m (DP's 1, 2, 6 & 8);

TABLE 3

LIST OF INVESTIGATION BORES, NAURU, OCTOBER 1987

Bore	R.L. (m)	Total depth (m)	S.W.L. (m below ground)	Estimated freshwater layer thickness (m)	E.C. Bottom of hole. (microS/cm)
P1	34.53	30	-	-	-
P2	26.56	70	-	7	19500
P3	12.74	54	11.23	3	33400
P4	30.89	43	-	7	6000
P5	27.27	50	-	0.5	22100
P6	27.18	70	-	7	43500
P7	28.98	83	-	4.5	39500
Q1	4.80	26	-	3.5	27000
W1	25.32	32	-	6.5	1000
W2	35.43	65	-	3.5	22000
W3	39.34	65	37.85	6.5	30300
W4	26.14	55	24.56	3.5	27000

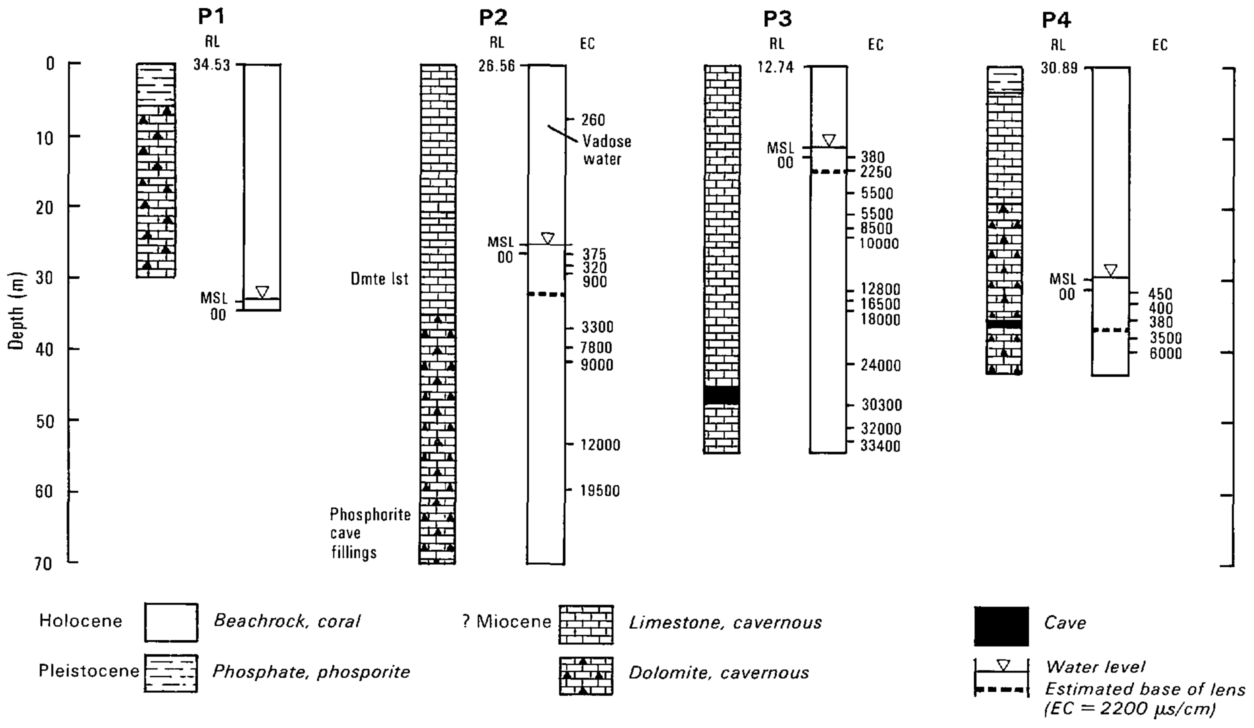

Fig. 9 Logs of drillholes

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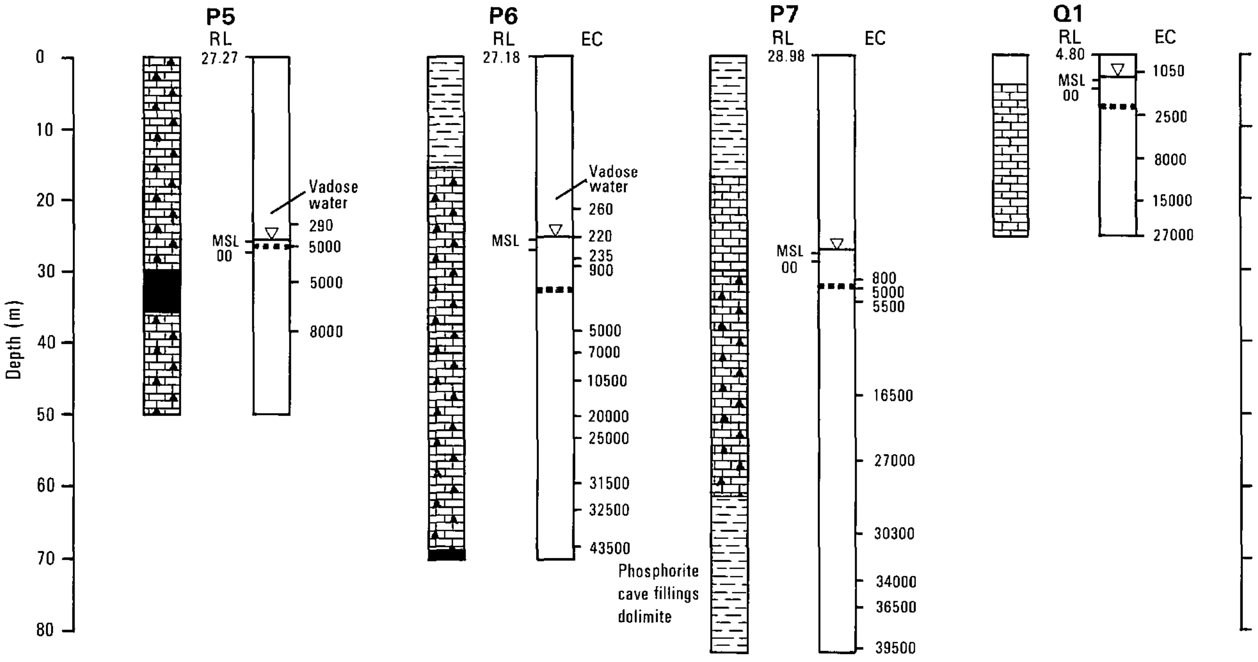

Fig. 10 Logs of drillholes

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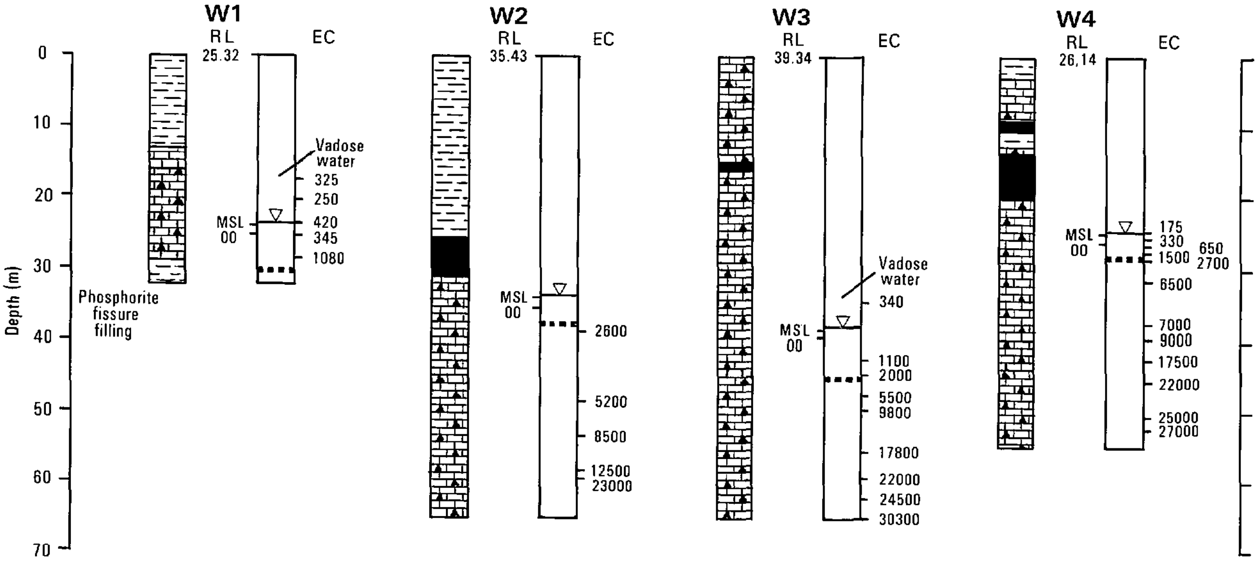

Fig. 11 Logs of drillholes

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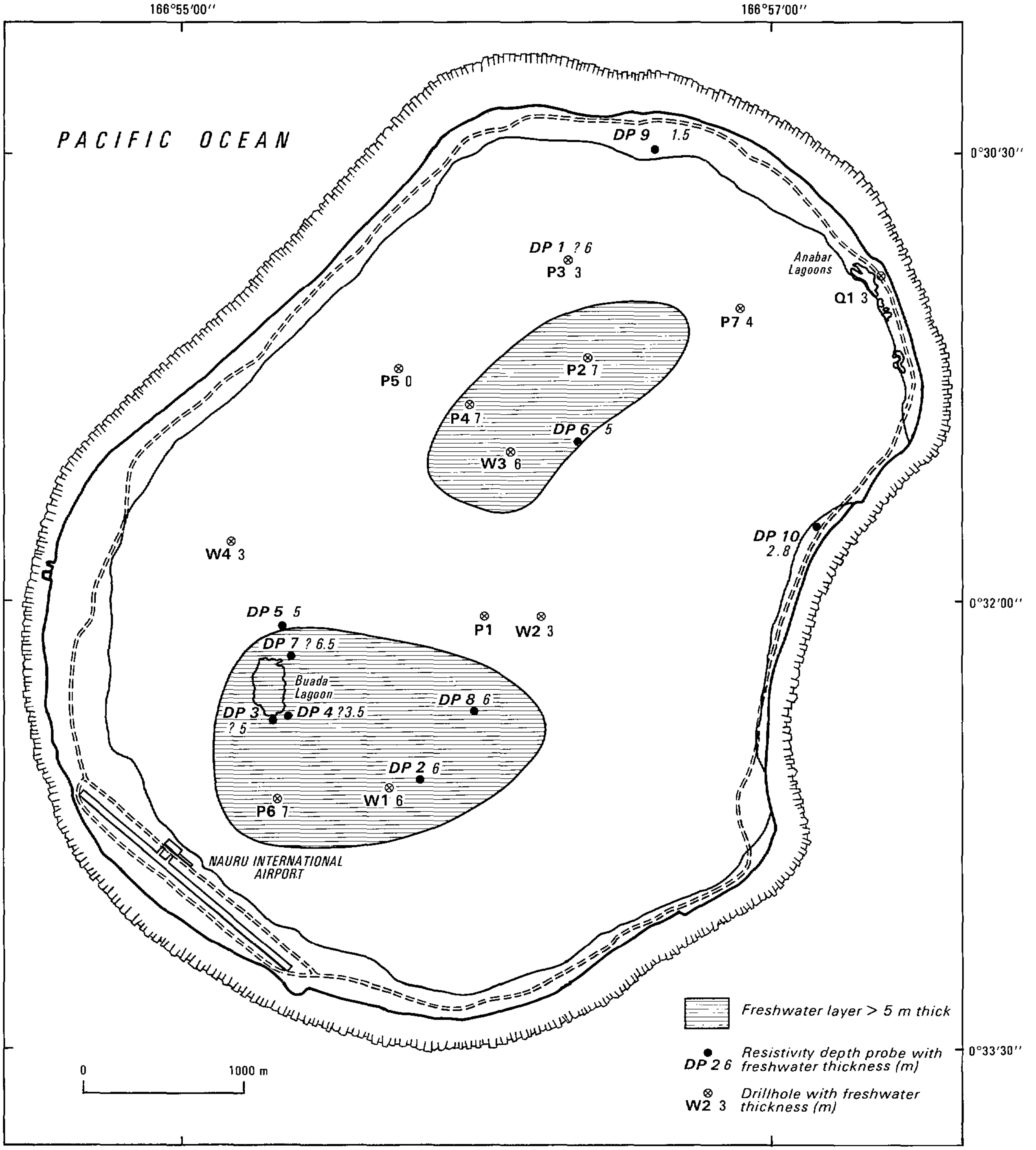

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Fig. 12 Thickness of freshwater layer

TABLE 4

LIST OF GEOELECTRICAL SOUNDING LOCATIONS

	Location	R.L.(m)*	AB/2(m)
DP1	Flat-bottomed depression, northern Nauru	12.8	150
DP2	Topside Sports Oval, mid-southern Nauru	26.4	180
DP3	Buada Lagoon	3.3	100
DP4	Buada Lagoon	4.0	100
DP5	North of Buada Lagoon	3.4	100
DP6	Stockpile area, central Nauru	28.0	400
DP7	Buada Lagoon	3.0	80
DP8	Radio transmitter, central Nauru	26.3	900
DP9	Anetan coastal strip, northern Nauru	3.9	100
DP10	Coastal strip, east Nauru	4.9	90

* Mean sea level = R.L. 1.34 m.

(ii) adjacent to Buada Lagoon, elevations 2-3 m (DP's 3, 4, 5 & 7); and

(iii) on the coastal terrace, elevations 3-4 m (DP's 9 & 10).

The instrument used was an ABEM Terrameter SAS 300B with Booster SAS 2000. Field curves of apparent resistivity and their interpretation are presented in Appendix 2. Drilling results have shown that the water-table invariably lies just above mean sea-level. For this reason the resistivity models have been constrained to comply with this observation, i.e. the depth of resistivity reduction associated with the top of the aquifer has been set close to mean sea level (R.L. 1.0 m). An example of the layered resistivity model compared with a drill log, is given in Figure 13.

Routine interpretation of subsurface resistivity structure is practical only for horizontal layering because of the complex mathematical analysis and modified field techniques required for more complicated configurations. Therefore in selecting electrical sounding sites on Nauru, the requirement for at least approximate horizontal resistivity stratification was an important consideration. Site selection was accordingly made on the basis of available geological information, particularly surface indications. With the shallow to medium-depth soundings there appear to be no problems. However, two deeper soundings, DP6 (AB/2 = 400 m) and DP8 (AB/2 = 900 m) were completed in the interior of Nauru where long electrical arrays are possible only along linear sections of the mine roads and in these cases some departure from horizontal stratification is evident from distortion of the field curves. Theoretically, if horizontal stratification applies, the apparent resistivity curves cannot rise at angles greater than 45° The distortion of the field curves is caused by the channelling of electrical current through the relatively low-resistivity soil and phosphate forming the road foundation. In contrast, the pinnacled, worked-out areas adjacent to the roads are significantly more resistive.

Because of the distortion, the field curves for DP6 and DP8 cannot be interpreted accurately, although they do provide an approximate model for the resistivity layering. The interpretations shown for DP6 and DP8 indicate the probably resistivity structure, based partly on inference and partly on the field curves. The freshwater layer thickness, in particular, cannot be determined precisely. An important feature of the DP6 and DP8 field curves is that the curves descend rapidly at large electrode spacings, without any apparent up-turning. This confirms that any dense volcanic core must be deeper than about 200 m. Hydrogeological interpretations of the resistivity models for DP 1-10 are given in Table 5.

Freshwater layer and mixing zone

Drilling and geoelectric soundings show that Nauru is underlain by a discontinuous layer of freshwater up to 7 m thick, overlying a mixing zone of brackish water up to 60 m thick, which in turn overlies sea water. Salinity increases gradationally downwards as shown in cross-sections (Figs 14 and 15).

The water-table, the upper boundary of the freshwater layer, is at an average elevation of R.L. 1.50, or 0.30 m above mean sea level, throughout Nauru, with the exception of the Buada Lagoon catchment which appears to be a different hydrological system. According to topographical survey data Buada Lagoon is at an elevation of R.L. 2.40; it is perched above the regional water-table, on impermeable phosphatic alluvium (Fig. 15).

TABLE 5

RESISTIVITY DEPTH PROBE INTERPRETATIONS

		RESISTIVITY MODEL		HYDROGEOLOGICAL INTERPRETATION	
Depth Probe	Layer	Resistivity (ohm-m)	Thickness (m)	Groundwater	Lithology
1	1	450	0.6	Nil	Soil/coral sand
	2	4000	0.8	Nil	Coral sand/gravel
	3	450	6.5	Nil	Phosphatic coral sand/gravel
	4	1700	3.5	Nil	Dolomite/limestone
	5	150	6	Fresh-brackish	"
	6	80	15	Brackish	"
	7	40		Saline	"
2	1	270	3.2	Nil	Topsoil
	2	1100	7	Nil	Coral sand/gravel
	3	10000	15	Nil	Dolomite/limestone
	4	1000	6	Fresh	"
	5	200	20	Brackish	"
	6	6		Saline	"
3	1	500	1.4	Nil	Topsoil
	2	80	1.0	Nil	Silt
	3	50	5.5	Fresh-brackish	Phosphate/limestone
	4	11		Brackish-saline	Limestone
4	1	800	1.9	Nil	Topsoil
	2	60	1.1	Nil	Silt-clay
	3	30	3.5	Brackish	Phosphate/limestone
	4	14	2	Brackish-saline	"
	5	7		Saline	Limestone
5	1	700	1.0	Nil	Topsoil
	2	180	1.4	Nil	Soil/silt
	3	70	5	Fresh	Phosphate/limestone
	4	11		Saline	Limestone
6	1	400	0.7	Nil	Soil
	2	90	3.0	Nil	Phosphate
	3	5000	23	Nil	Dolomite/limestone
	4	500	5	Fresh	"
	5	6		Saline	"
7	1	600	1.0	Nil	Topsoil
	2	200	1.0	Nil	Soil-silt
	3	65	6.5	Fresh-brackish	Phosphate/limestone
	4	10		Saline	Limestone
8	1	500	0.7	Nil	Topsoil
	2	60	3.0	Nil	Phosphate
	3	4500	21	Nil	Dolomite/limestone
	4	500	6	Fresh	"
	5	6		Saline	"
9	1	370	2.9	Nil	Topsoil/coral sand
	2	200	1.5	Fresh-brackish	Coral/limestone
	3	35		Saline	Limestone/dolomite
10	1	1300	2.0	Nil	Soil/coral sand
	2	3000	1.9	Nil	Coral sand/gravel
	3	500	2.8	Fresh	Limestone/dolomite
	4	100	3	Brackish	"
	5	35		Saline	"

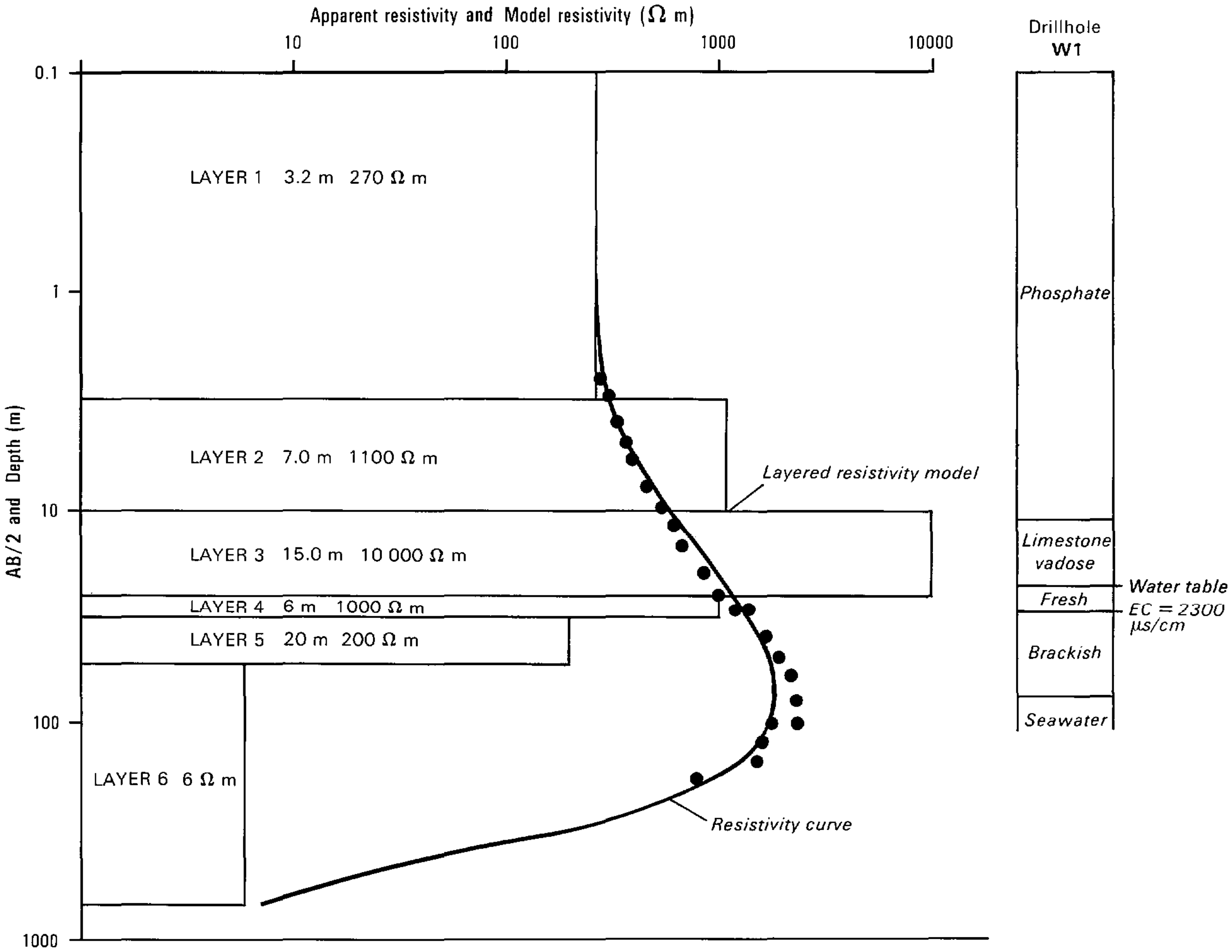

Fig. 13 Resistivity layered model (DP2) compared with drill log (WI)

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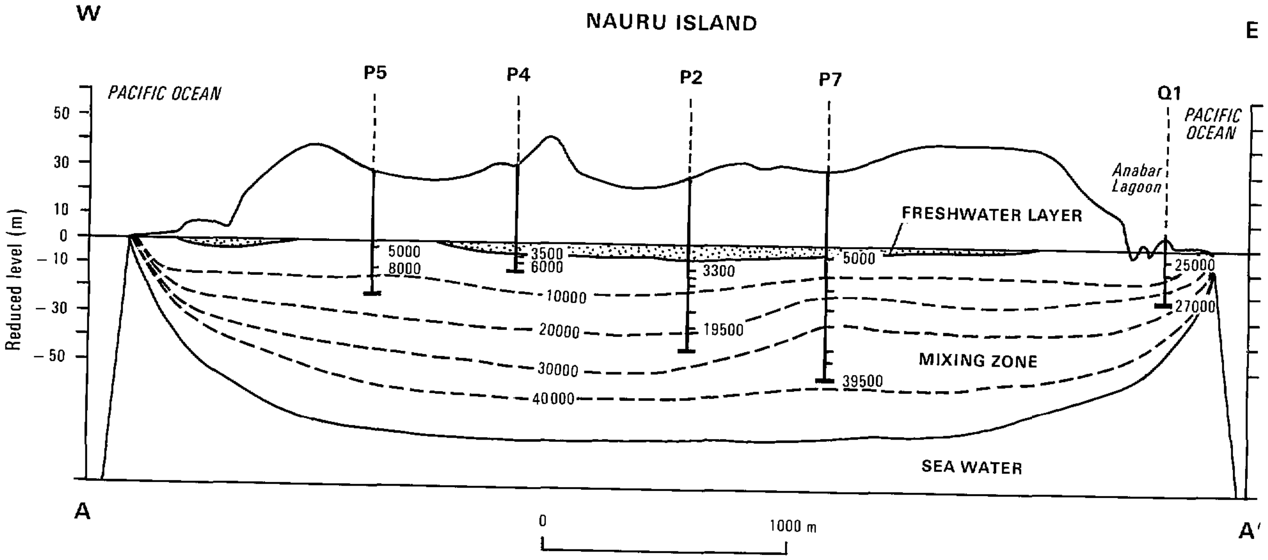

Fig. 14 Cross section showing groundwater salinity (Electrical conductivity in µs/cm)

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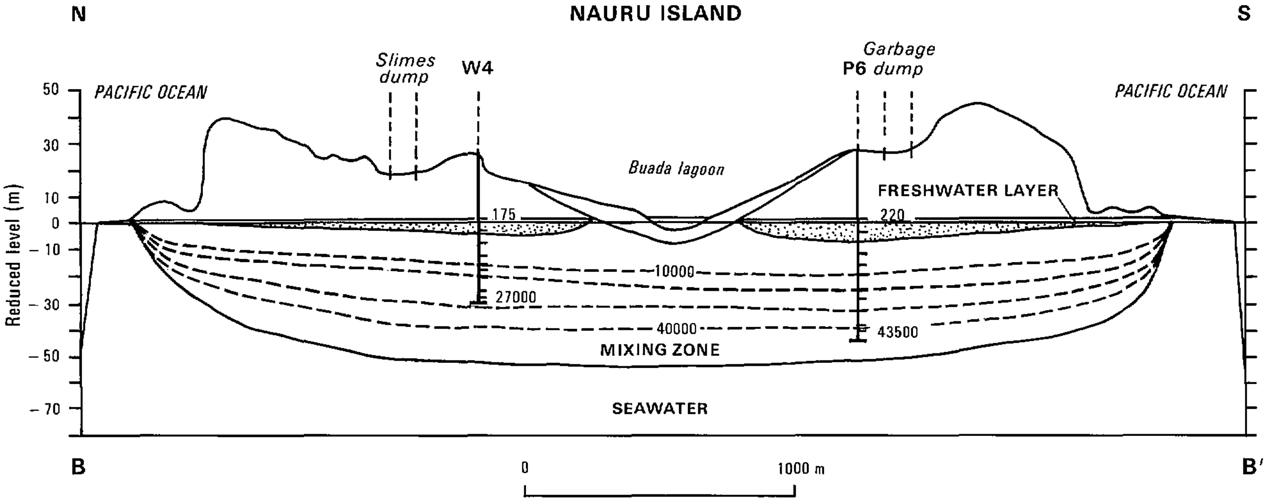

Fig. 15 Cross section showing groundwater salinity (Electrical conductivity in µs/cm)

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The average thickness of the freshwater layer is 4.7 m based on intersections in 11 drillholes (Figs. 9, 10, and 11). Its lower boundary is defined at a salinity level of 1500 mg/L total dissolved solids, which is equivalent to electrical conductivity of 2200 microSiemens/cm and is the upper limit for drinking water.

The unusually thick mixing zone of brackish water is due to high permeability in the limestone; open karst fissures allow intrusion of seawater beneath the island and diffusion to form a zone of brackish water. Quantitative estimates of hydraulic conductivity have not been undertaken on Nauru, but by analogy with similar raised limestone islands and plateaux elsewhere it is probably about 3000 - 3500 m/d. Estimates have been made for Barbados, 3400 m/d (Goodwin, 1980); Florida, 3000 m/d (Kohout, 1960); and Northern Guam, up to 3500 m/d (Goodrich and Mink, 1983).

Groundwater recharge

The annual rainfall for Nauru is shown in Figure 16. Records are available for 60 years, but there are significant gaps with no information. The available records indicate a mean annual rainfall of 1994 mm, with a high degree of variability; the maximum recorded was 4590 mm in 1930 and the minimum 280 mm in 1950.

High annual rainfalls commonly occur in the years corresponding to, or immediately following major El Nino-Southern Oscillation Events (Philander, 1983) such as those of 1957, 1964, 1972 and 1982 (Fig. 16). The occurrence of this phenomenon every few years is probably responsible for the bimodal frequency distribution of Nauru annual rainfall (Fig. 17).

Ten of the 60 years for which records are available, had less than 1000 mm of rain. Drought periods with less than 100 mm in 3 months occurred in 34 of the 60 years. The most severe historical droughts occurred in 1916-17, when 95 mm of rain was recorded in 8 months; 1938, when 97 mm was recorded in 8 months; and 1950, when 83 mm was recorded in 6 months.

The seasonality of the rainfall is shown in Table 6. The mean monthly rainfall ranges from 118 mm in May to 279 mm in January, with the months from December to March each averaging more than 200 mm. (Fig. 18).

Potential evapotranspiration was calculated on the basis of Fleming's (1987) formula, derived for Tarawa atoll which has a similar climate to Nauru and is 700 km away. Figure 19 shows the empirical relationship between monthly rainfall, and potential evapotranspiration for Tarawa, from which

$$E = 115 + \frac{(300 - P)^2}{1286}$$

where P is the monthly rainfall, which is less than 300 mm, and E is the monthly potential evapotranspiration. On this basis, using monthly data, the potential evapotranspiration estimated for Nauru ranges from 115 mm in January to 141 mm in May (Table 6) and the mean annual total is 1547 mm.

Actual evapotranspiration is less than potential evapotranspiration. To estimate actual evapotranspiration requires information on soil moisture and vegetation characteristics which is not available for Nauru.

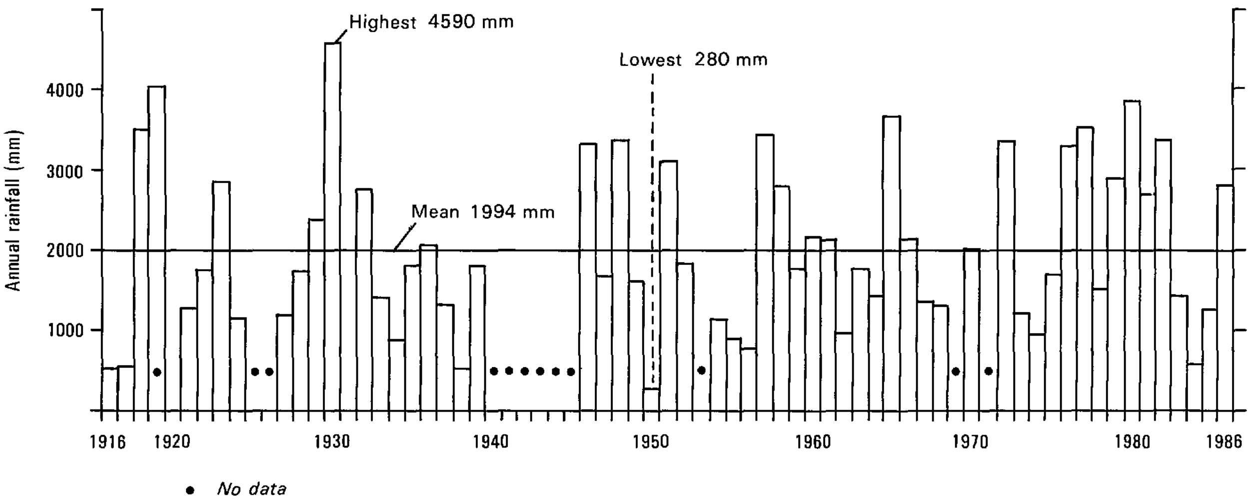

Fig. 16 Nauru annual rainfall 1916 –1986

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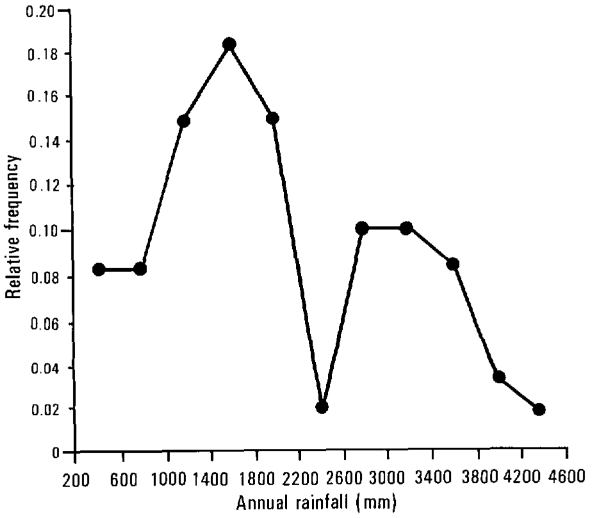

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Fig. 17 Nauru annual rainfall frequency distribution

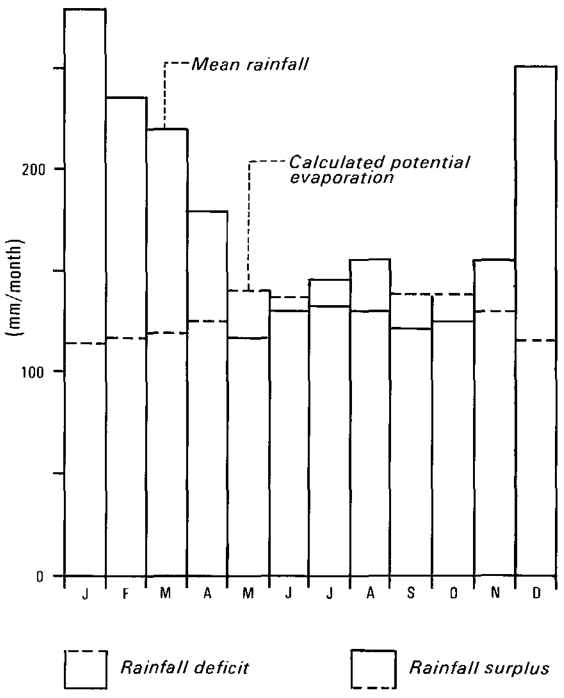

Fig. 18 Nauru mean monthly rainfall and potential evaporation 1916–86 19/09/117

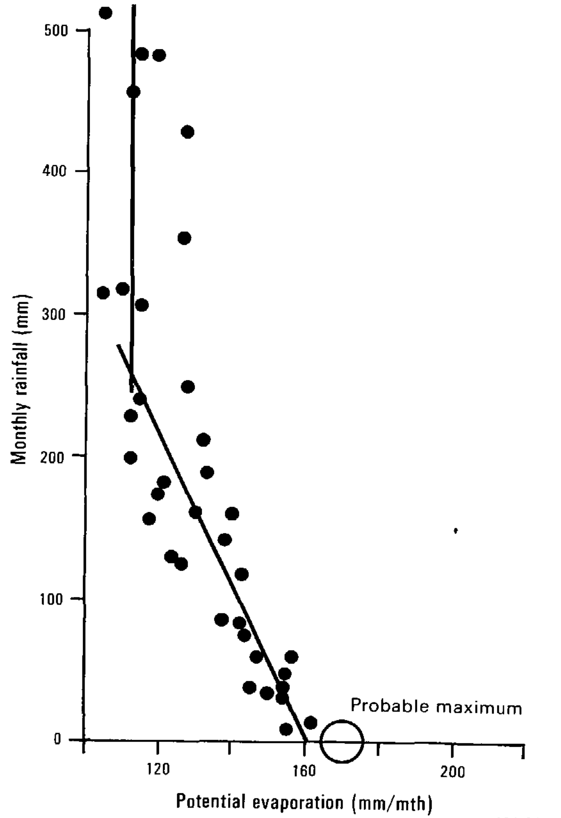

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Fig. 19 Relationship between monthly rainfall and potential evapotranspiration derived for Tarawa (after Fleming, 1987)

TABLE 6
MONTHLY RAINFALL AND POTENTIAL EVAPORATION (in mm)

	Mean rainfall	Potential* evaporation
January	279	115
February	236	118
March	220	120
April	179	126
May	118	141
June	130	137
July	146	133
August	156	131
September	123	139
October	126	139
November	155	131
December	252	117

*Estimated from Fleming's (1987) formula

Disregarding some groundwater discharge to, and surface water evaporation from lagoons, the water balance for Nauru can be considered as:

Rainfall = Actual evapotranspiration + Groundwater recharge

A detailed estimate of actual evapotranspiration for another central Pacific atoll, Kiritimati, showed that recharge is 29% of rainfall for a freshwater lens where the land is not vegetated (Falkland, 1984). This atoll is appreciably drier than Nauru . On Tarawa, the closest atoll to Nauru where information is available, and with comparable annual rainfall, recharge was estimated at 34% of rainfall (Daniell, 1983). This coefficient was adopted for an atoll with 80% coconut tree cover and 20% grass. On Nauru, with its extensive bare karrenfeld surface, recharge is probably about 40% of rainfall. Adopting this latter value for the recharge/rainfall ratio, we derive an annual water balance for Nauru:

Rainfall (1994 mm) = Actual evapotranspiration (1196 mm)
+ groundwater recharge (796 mm).

Recharge is assumed to be uniform throughout the island although it is probably greater inland beneath the mined-out area.

Groundwater flow and discharge

The amount of recharge indicates that a substantial amount of groundwater flows through the Nauru groundwater system. Water-table measurements in present and previous investigation drillholes indicate that the groundwater head throughout most of the interior of Nauru is about R.L. 1.50 which is about 0.30 m above mean sea level. There are some difficulties in establishing this, as tidal oscillations of groundwater-level are significant, and mean sea level is also not static. Figure 20 shows the relationship of adopted mean sea level on Nauru to the island datum.

Averaged elevations of the water-table are shown in Figure 21. Groundwater flow is probably radially outwards to the sea, and is generated by the 0.30 m head differential between the inland water-table and mean sea level. Buada Lagoon is perched (R.L 2.40) above the general water-table (R.L. 1.50) which extends throughout the island. Measurements of Buada Lagoon water levels in October 1987 indicated that the lagoon is not tidal but its level is affected by rainfall and evaporation.

Groundwater discharges around the circumference of the island, to the chain of lagoons at Anabar in the northeast, and elsewhere, to springs in the reef (Fig. 21). Several caves at the inland edge of the coastal terrace, provide a window on the water-table close to the discharge end of the flow system. The largest of these is Maqua Pool in the southwest of Nauru.

Tidal fluctuations

Tidal information for Nauru is available for 13 years: Table 7 shows monthly mean sea level, in terms of the tidal gauge. The mean monthly sea level is 1.169 m above tide gauge zero. This compares with the adopted mean sea level for survey purposes on Nauru, of 1.186 m above tide gauge zero (Fig 20), equivalent to R.L. 1.352.

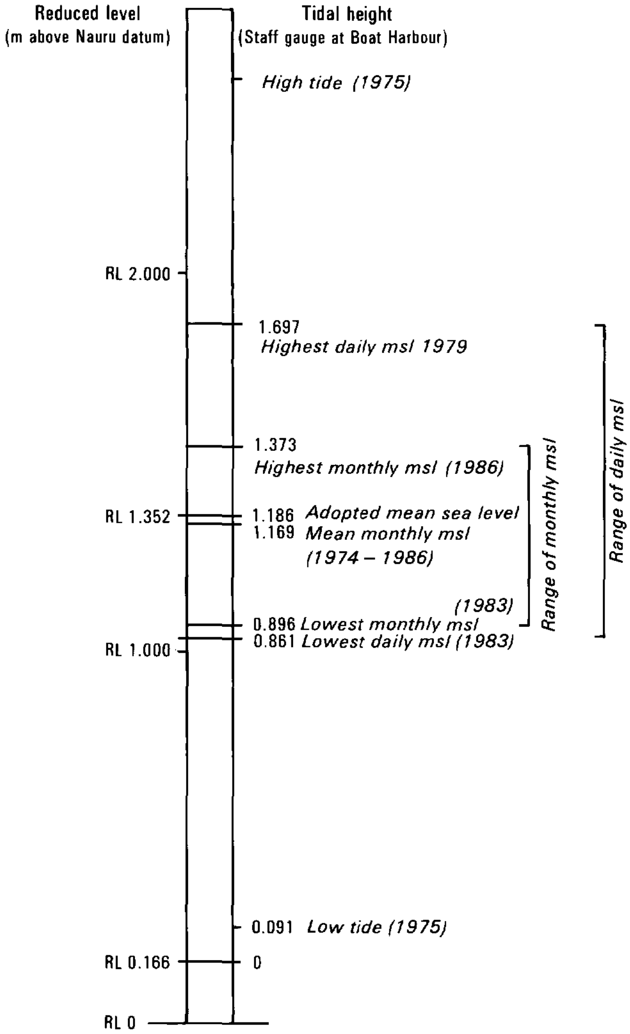

Fig. 20 Mean sea level at Nauru (after S. Nowak, NPC and K. Wyrtski UH) 19/09/123

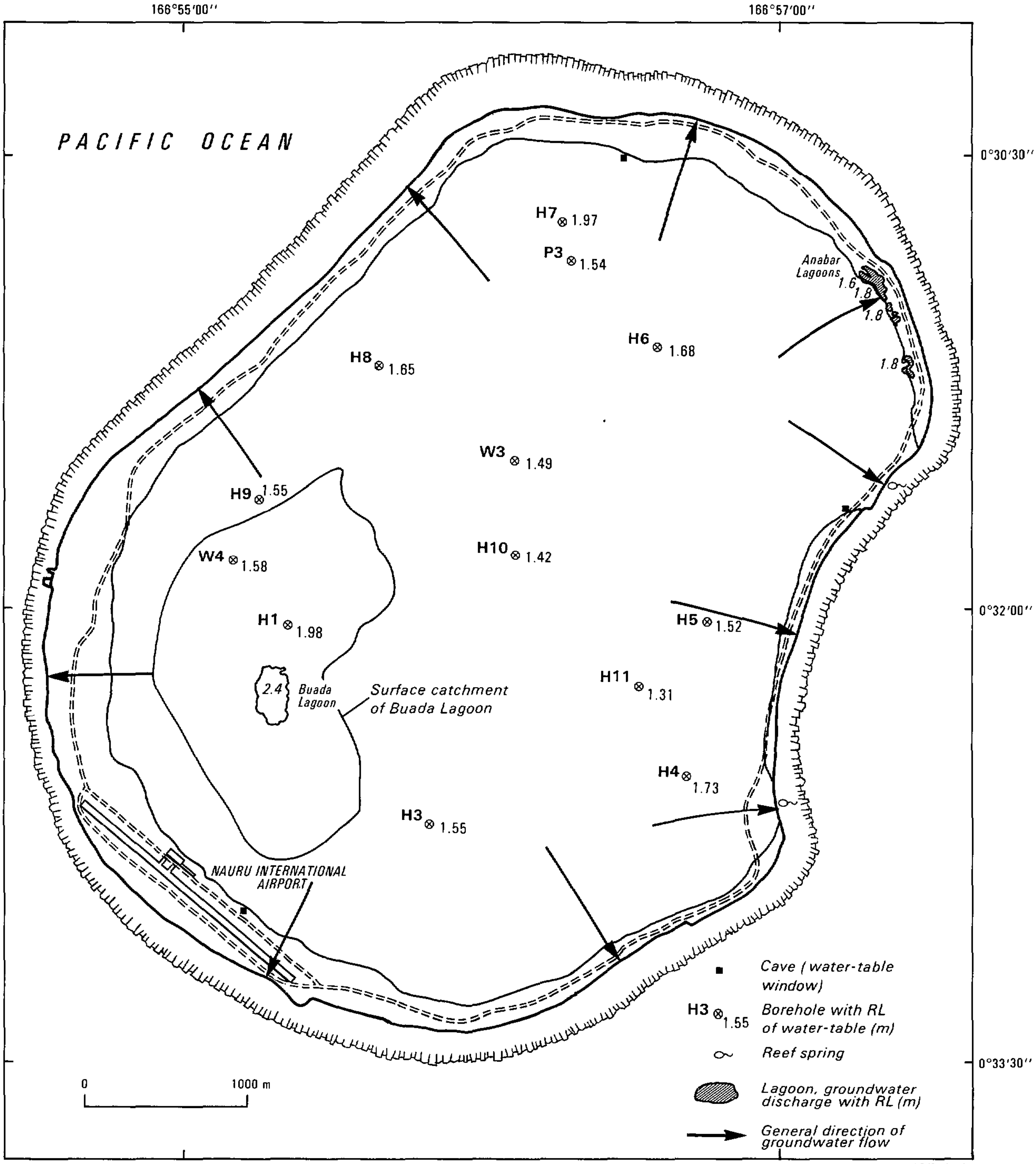

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Fig. 21 Nauru groundwater flow system

TABLE 7
MONTHLY MEAN SEA LEVEL AT NAURU
(in mm above tidal gauge zero)

	J	F	M	A	M	J	J	A	S	O	N	D
1974	-	-	-	-	1137	1127	1103	1102	1102	1128	1184	-
1975	-	1182	1156	1162	1111	1108	1105	1116	1113	1130	1195	1174
1976	1225	1242	1218	1274	1219	1164	1200	1178	1198	1166	1272	1249
1977	-	-	1146	1142	1100	1140	1199	1196	1230	1200	1309	1262
1978	-	1243	-	-	1065	1085	1110	1143	1184	1221	1239	1302
1979	1225	-	1165	1116	1126	1130	1177	1204	1130	1227	1239	-
1980	-	-	1260	1170	1184	1146	1203	1207	1266	1222	1270	1264
1981	1255	1283	1273	1160	1098	1051	1121	1143	1146	1168	1162	1282
1982	1227	1256	1299	1264	1207	1190	1315	1315	1234	1250	1219	1019
1983	940	908	896	928	939	996	1060	986	1000	1043	1058	1164
1984	1102	1030	1044	1031	1061	1078	1085	1096	1092	1159	1199	1214
1985	1325	1146	1190	1151	1132	1121	1200	1173	1170	1156	1194	1285
1986	1274	1248	1168	1200	1288	1188	1202	1274	1286	1205	1332	1373

*Information supplied by K. Wyrtski, University of Hawaii

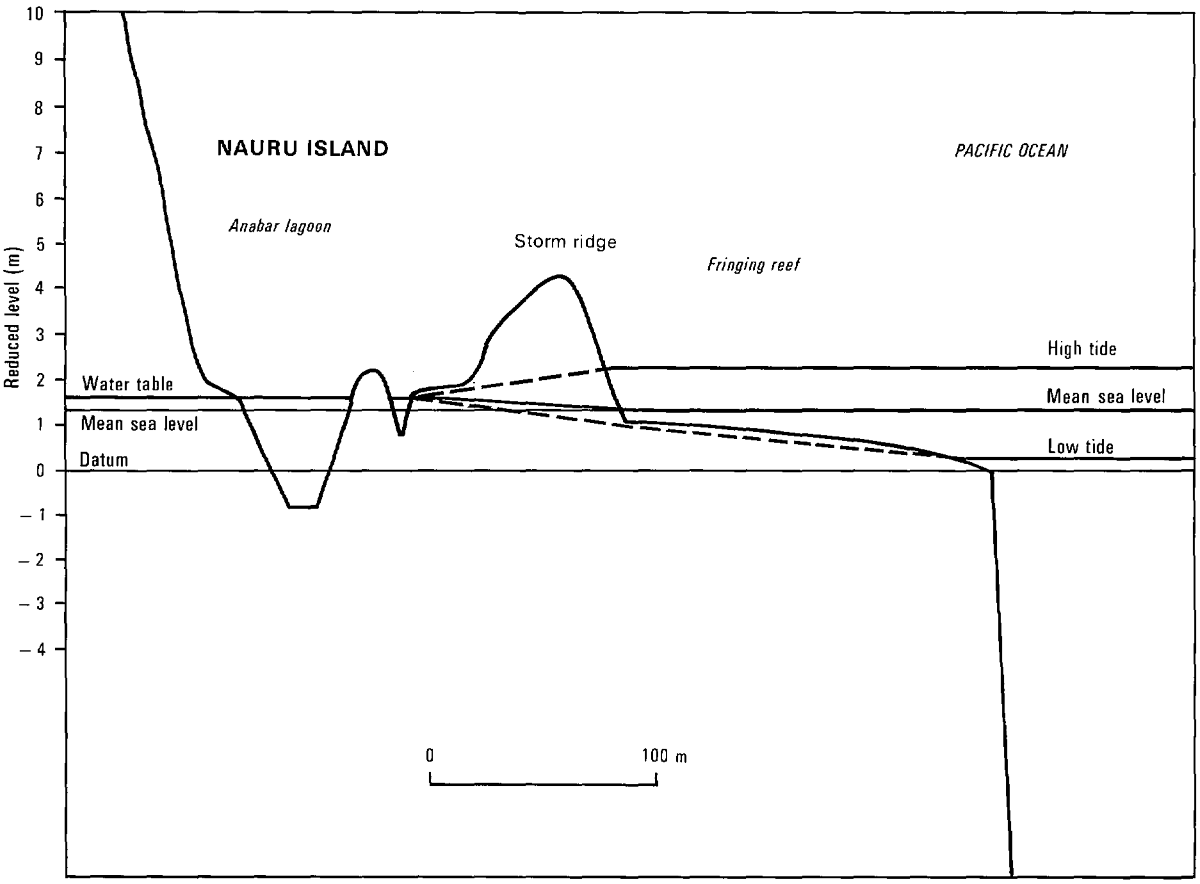

Fig. 22 Reversal of hydraulic gradient with tidal fluctuation

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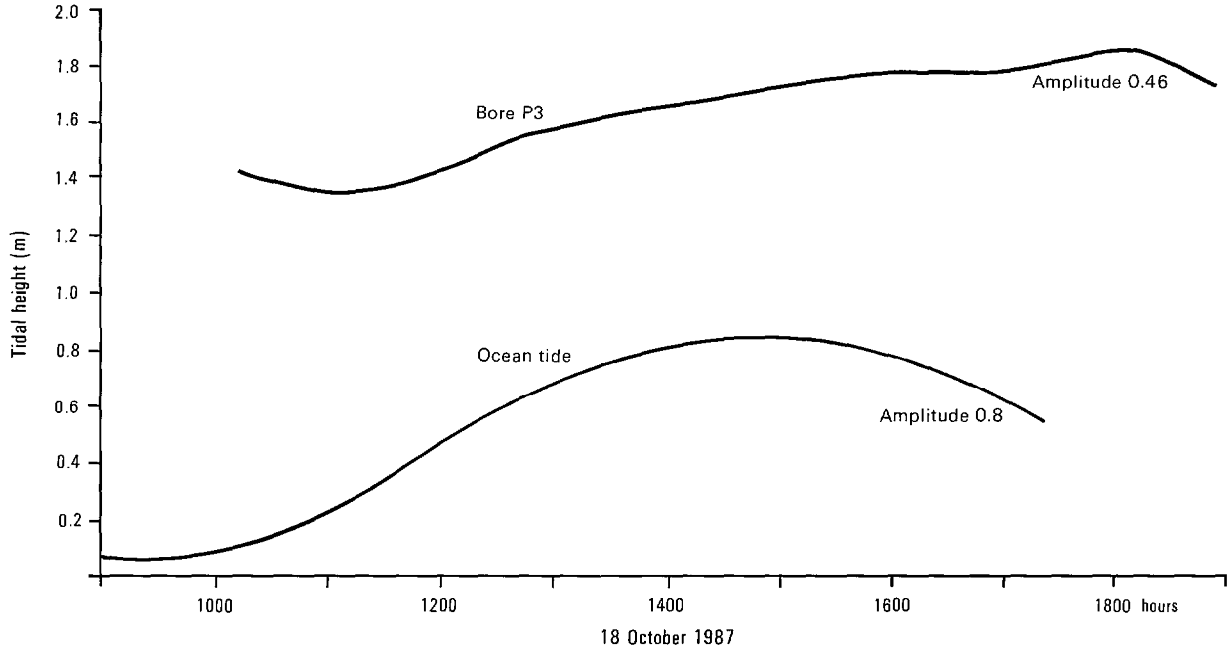

Fig. 23 Tidal fluctuations in observation bore P3, 800 m inland 18 October 1987

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The tidal range at Nauru is from R.L. 0.86 m, the lowest mean daily tide, to R.L. 1.70 m, the highest mean daily tide, over the 13 years records. The effect of daily and longer term fluctuations in ocean tide level is shown in Figure 22. There is a reversal of hydraulic gradient at the shore line with drainage outwards at low tide, and seawater flow inwards at high tide.

Tidal effects in observation bore P3, 800 m inland, were measured during the present investigation, and additional information on this phenomenon is available from an unpublished N.P.C. report (Gormley, 1987). Tidal effects on groundwater levels are substantial, being close to half the amplitude of the ocean tidal stage throughout the island (Fig. 23). The tidal movement of the water-table is commonly of the order of 0.5 m and the lag of the tidal peak in water bores is generally 1.5-3 hours.

Figure 24 shows the tidal efficiency, which is the ratio of tidal movement in groundwater to that in the ocean, plotted against distance from the sea; and the time lag plotted against distance from the sea.

HYDROCHEMISTRY

Chemical analyses of Nauru waters are given in Appendix 4.

The relationship between electrical conductivity and total dissolved solids for Nauru waters is shown in Figure 25. The total dissolved solids content in mg/L is 0.69 x the electrical conductivity in microS/cm, with a high degree of correlation.

Nauru rainwater contains about 10 mg/L total dissolved solids, and is slightly acid, and bicarbonate-rich. Buada Lagoon was fresh in October 1987, with about 200 mg/L total dissolved solids; it is believed to become brackish with evaporation in long dry periods. The Anabar Lagoons are brackish with about 5000 mg/L total dissolved solids. Accessible cave waters at Ijuh and Anatan are potable and used for small-scale water supplies. The largest cave supply, at Maqua Cave, is brackish, containing about 1750 mg/l total dissolved solids.

Samples from the freshwater layer taken during drilling (P6 and W1) are in the range 85-295 mg/L total dissolved solids. The freshwater is bicarbonate rich, and is moderately hard (55-108 mg/L). The pH is between 6.90 and 7.80 and temperature 25^{o} - 26^{o}.Low nitrate, fluoride and iron contents confirm its suitability for drinking water.

Samples from the brackish water zone (P4, H10, P5, P3, W3) are increasingly saline with depth, and the water is very hard with more than 400 mg/L total hardness. These waters are alkaline with pH between 7.4 and 8.9. With increasing salinity the groundwater approaches seawater composition and becomes a chloride water, with sodium the dominant cation. The nitrate content is low, less than 13 mg/L, with the exception of samples from drillhole H10, in the centre of the island, which might be polluted by septic tanks. Fluoride and iron levels are also low in the brackish groundwater samples.

Chemical analyses of 22 wells sampled in the coastal terrace (Fig. 26) are in the range 290-3245 mg/L total dissolved solids. Of these wells 17 were within the limit for drinking water of 1500 mg/L dissolved solids, and 5

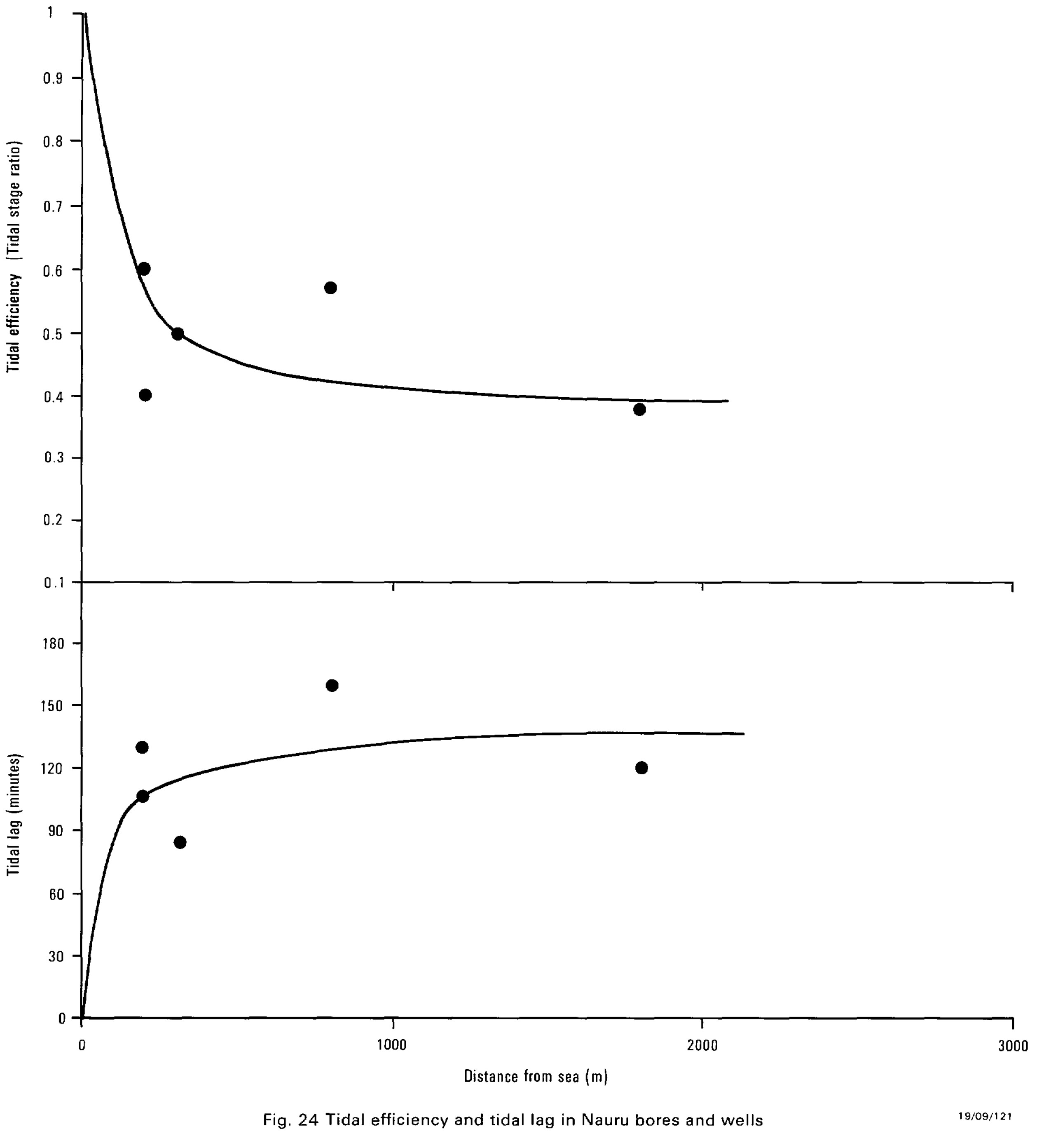

Fig. 24 Tidal efficiency and tidal lag in Nauru bores and wells

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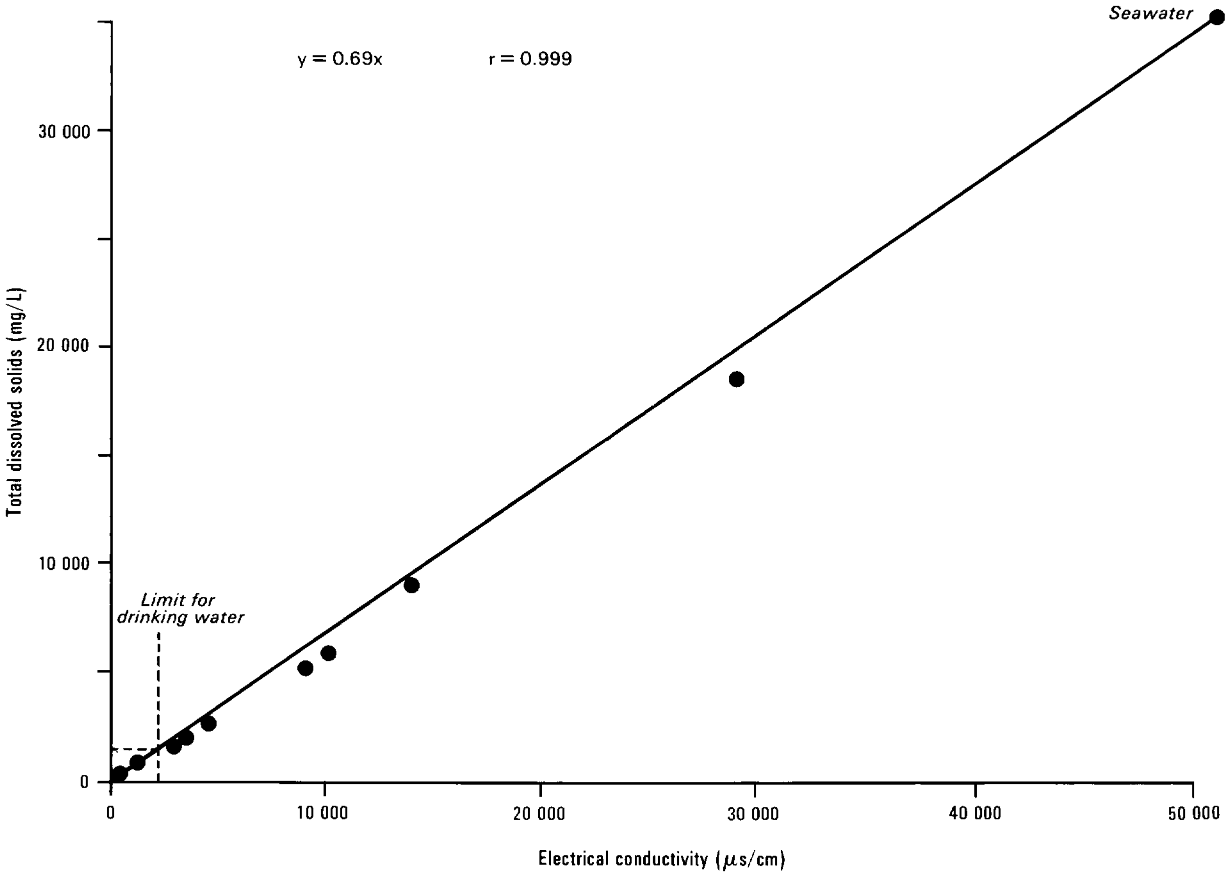

Fig. 25 Relationship of total dissolved solids to electrical conductivity

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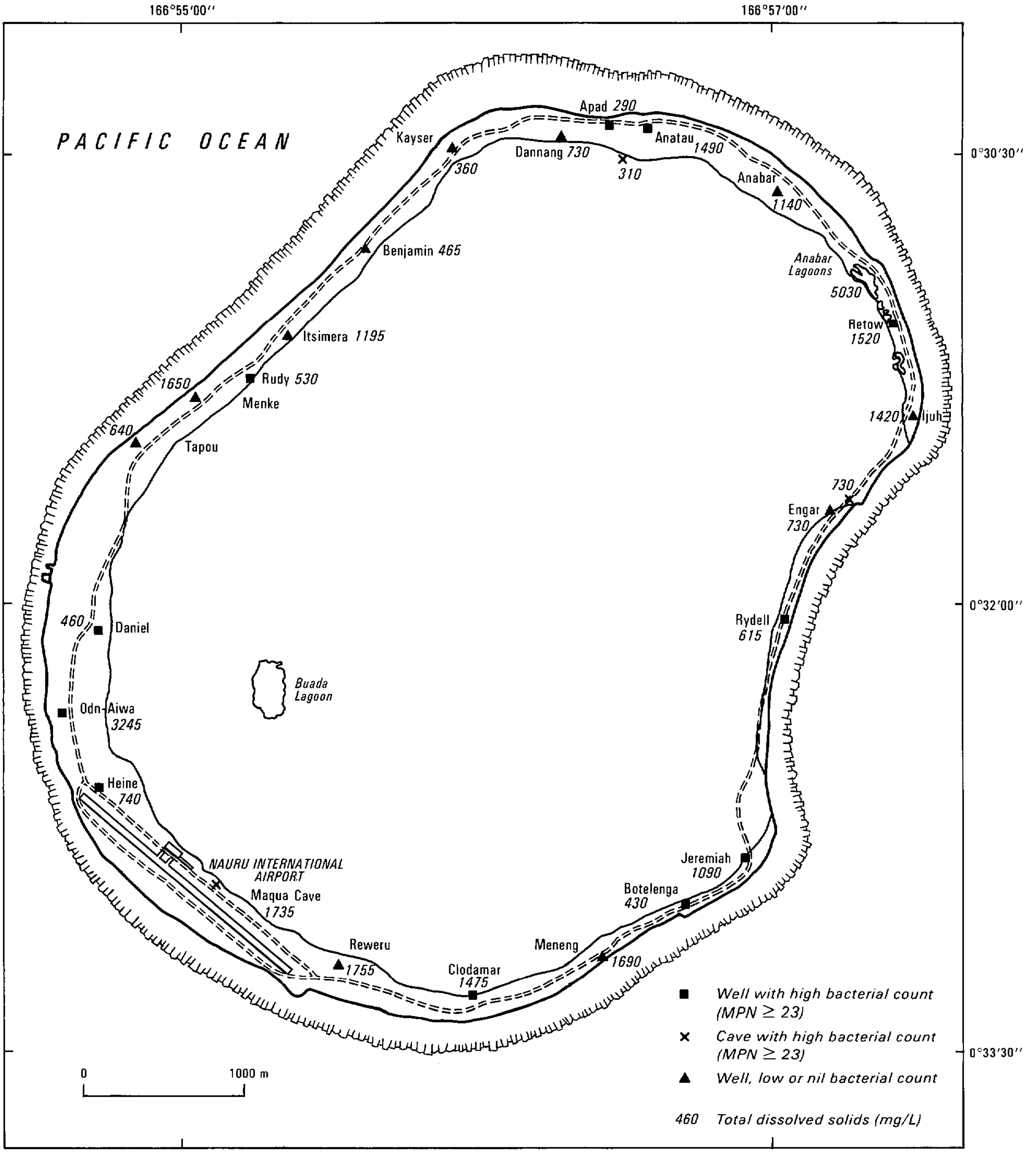

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Fig. 26 Nauru coastal plain groundwater quality contain more saline water. The variation in salinity is due to factors such as the depth of the well, and its pumping rate; it is likely that nearly everywhere in the coastal terrace a thin layer of freshwater overlies a mixing zone of brackish water. Composition ranges from bicarbonate dominant in the fresher waters to chloride dominant in the saltier waters (Fig. 27). Nearly all the coastal plain groundwaters are hard or very hard, with total hardness between 172 and 776 mg/L. Most of these waters are slightly acid: pH ranges from 6.70 to 7.16. The temperature of the coastal terrace groundwater is constant at 28°C. Nitrate levels are generally low, up to 35 mg/l and all are within recommended limits for drinking water. Fluoride and iron levels are low. However 14 wells were bacteriologically polluted, when sampled.

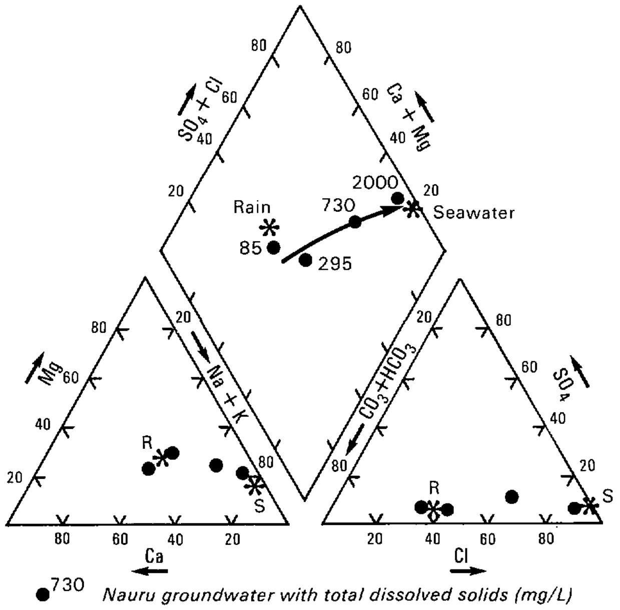

Fig. 27 Trilinear diagram showing ionic composition of Nauru groundwaters, in percent milliequivalents/litre

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WATER SUPPLY

The present water consumption is estimated as about 1300 m^3/day, derived from the following sources:

Rainwater catchments	700
Imported water (phosphate ships)	400
Groundwater (coastal terrace wells)	200 (?)
	1300

These estimates are based on calculations at 140 L/capita/day including industrial use but excluding sewage (Hadwen, 1986). Predictions of future water demands are difficult, but the imported water will not be available when phosphate mining ceases in the next decade. Thus, at present consumption rates, there would be a shortfall of 400 m^3/day. If more water is required for irrigation of land rehabilitation projects then the shortfall would be greater than 400 m^3/day. Additional sources that should be considered are groundwater from the inland plateau, and desalination.

Rainwater

Rainwater is particularly important in the island context as it is the best quality water available for domestic use and some industrial purposes. On Nauru it presently forms more than half the water supply. Rainwater supply systems are likely to fail in severe droughts, and further study is needed on Nauru to assess total catchment area and storage capacity installation in relation to water demand and probability of failure. Construction of additional storage capacity is desirable but this may be costly compared with groundwater extraction or desalination.

Rainwater catchments could be extended by construction of special purpose catchments and storage tanks in the interior of the island, for reticulation to the coastal terrace.

Imported water

To continue importing water by ship when mining ceases would be feasible, but may be costly in comparison with groundwater extraction or desalination.

Groundwater (coastal terrace)

The coastal terrace groundwater is abstracted from several hundred wells; it is regarded as a second class water source, being used for sewage and other secondary domestic purposes and as a backup domestic supply in drought years. The high salinity in some wells is due either to their being constructed too deep, or to overpumping. Some improvement to the present extraction of coastal plain groundwater could be made by the introduction of skimming well/infiltration gallery technology.

Treatment would be necessary for the coastal terrace groundwater to be widely used for drinking water, owing to the variations in salinity and the incidence of bacteriological pollution. The coastal terrace groundwater would be suitable as brackish water feedstock for desalination.

Groundwater (inland plateau)

A large amount of groundwater is available beneath the inland plateau of Nauru. The thinness of the freshwater layer (4-5 m) precludes the use of pumping bores because of the likelihood of upconing saltwater and disrupting the freshwater layer. Bores could however be used to pump brackish water as feedstock for desalination.

The possibility of excavating shafts and infiltration galleries (tunnels) to skim the freshwater layer, requires further assessment. This technology is used in some islands to abstract water beneath thick limestone cover and has previously been proposed for Nauru (Gormley, 1987). In Barbados, horizontal galleries are developed at the bottom of shafts 40 m deep; however the minimum thickness of the freshwater layer is 13 m so that there is a buffer against upconing of saltwater (Goodwin, 1980). Freshwater lenses 8-10 m thick have been safely skimmed in some atolls, but the thin lens and open fissures, on Nauru make the prognosis doubtful.

Desalination

Desalination of groundwater may be the best long term option for Nauru's water supply, and costs could be more favourable than importing water or rainwater systems. The electrodialysis, reverse osmosis and Sirotherm technologies are appropriate for brackish water feedstock (Fig. 28) which would be available on the coastal terrace or inland plateau.

Reverse osmosis systems have been used successfully in many places, with either brackish water or seawater as feedstock. However this technology has relatively high energy requirements. Reverse osmosis systems need a constant salinity of feedstock water, which may not be attainable with brackish water on Nauru, so that a seawater-based system may be economic. Desalination technology is advancing rapidly, and serious consideration of this option for Nauru would require an updated technical and economic evaluation.

WATER QUALITY CONSIDERATIONS

Future groundwater development on Nauru requires consideration of the possibility of saltwater intrusion, and of pollution from sewage and other wastes and natural radioactive elements.

Saltwater intrusion

The main threat to future groundwater development would be saltwater intrusion through overpumping, and for this reason careful management of groundwater extraction will be necessary. At the present time, some saltwater intrusion is evident in the deeper and more heavily pumped coastal wells. There is also some possible contamination from overflowing saltwater storage tanks.

Sewage Pollution

In order to assess the effects of pollution from sewage and animal wastes, 23 wells and 3 cave water supplies on the coastal terrace were sampled. These samples were taken at 1 km intervals around the island. Results are given in Appendix 4.

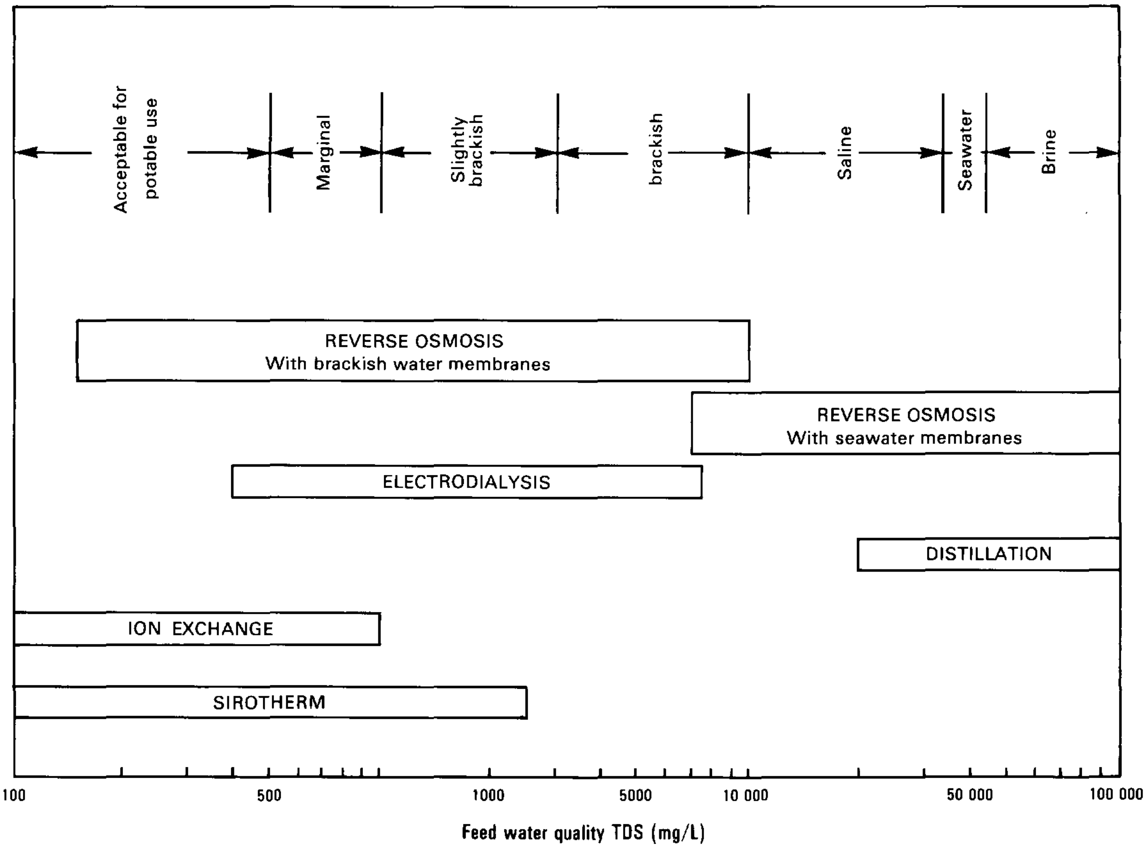

Fig. 28 Application of desalination technology to feed waters of varying quality (after Guttridge, Haskins and Davey, 1983)

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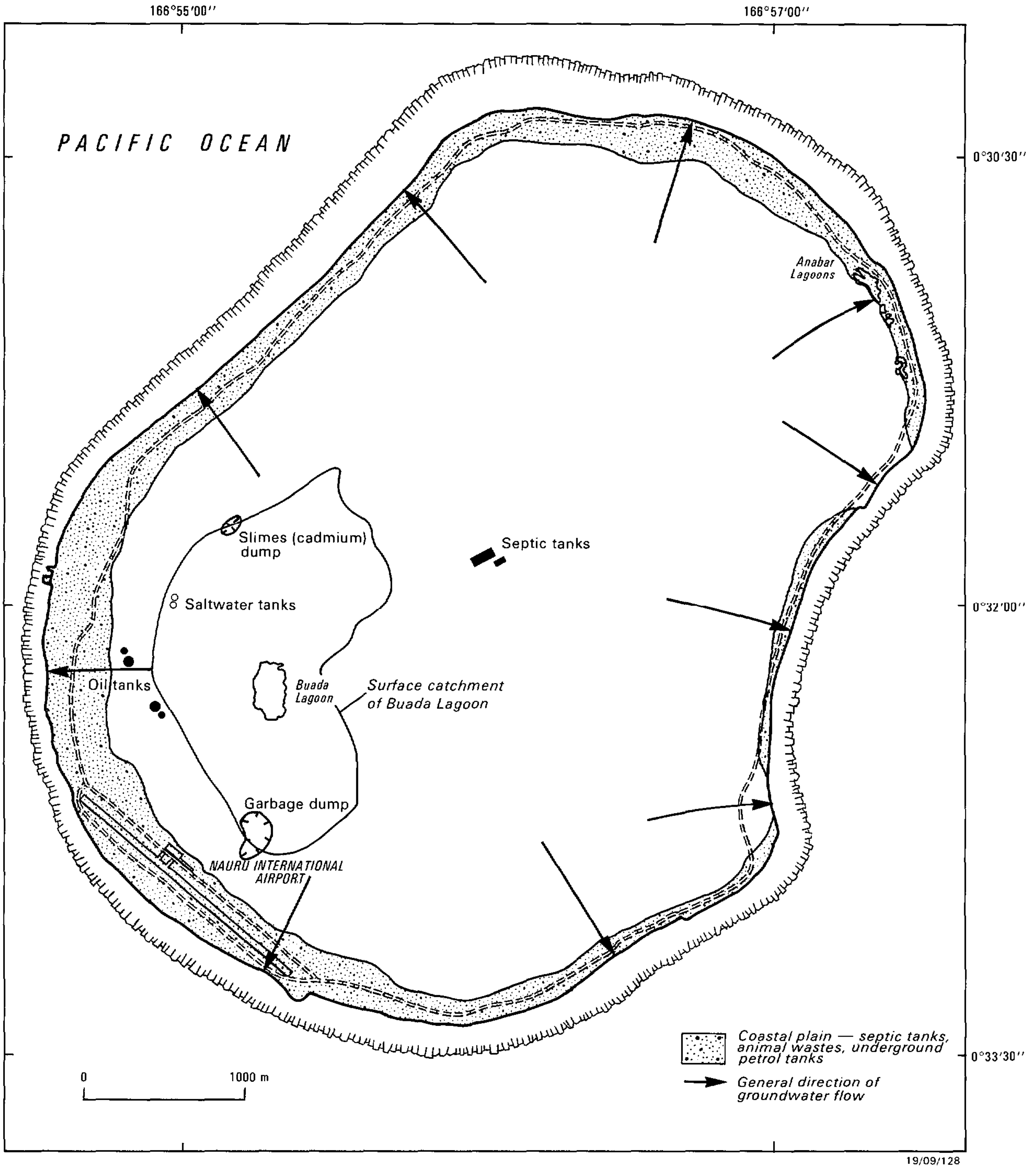


Fig. 29 Nauru groundwater pollution hazard

Of the 26 groundwater sources sampled, 12 had bacterial counts below the MPN index (Most Probable Number of E coli) of 23, indicating the suitability of the water for human consumption, untreated. The 14 samples with bacterial counts greater than the MPN index of 23 indicate that these water supplies would require chlorination. One of these samples had a count of 1100, and this water supply would require double chlorination. The wells with high bacterial counts are located at intervals around the coastal plain and the contamination is probably of local origin, i.e. sewage and animal wastes.

Thus, it is likely that approximately half the wells in the coastal plain aquifer are bacteriologically polluted by sewage and animal wastes. Nitrate levels in the groundwater remain low at the present time.

Waste Disposal

Pollution of the main freshwater layer is possible from waste deposited in mined out karst limestone areas; known waste dumps include slimes containing zinc and cadmium, and also domestic garbage (Fig. 29).

Natural soils on Nauru contain from 6 to 173 p.p.m. cadmium with a mean content of 70 p.p.m. at 16 sampling points. In the calcination process on Nauru, raw phosphate is roasted at 1050^{o} to remove cadmium and organic carbon. Sludge from the calcination plant contains about 200 p.p.m. cadmium and about 2000 p.p.m. zinc. The sludge has been dumped in mined out areas where leaching to the water-table could readily occur. Municipal garbage is also dumped in mined out areas.

Groundwater samples collected during the present investigation showed low levels of zinc and less than 0.01 mg/L cadmium. The upper limits in drinking water are generally taken as 5 mg/L zinc and 0.01 mg/L cadmium; the upper limit of cadmium in irrigation water is also 0.01 mg/L (Hem, 1985).

Although groundwater is not polluted from this source at present, a waste disposal policy must be considered in conjunction with proposals for future water supply development.

Radioactive elements

Some phosphatic soils are known to contain radioactive elements deleterious to health. For this reason we carried out a gamma-ray spectrometer survey of Nauru soils and mapped the distribution of radiometric properties. An "Exploranium" 4-channel DISA-400A instrument was used for the survey. This measures radioactive intensity over the following spectrum ranges:-

(i) energy above 0.4 meV (total count).
(ii) the K-40 1.46 meV peak, window width 200 keV.
(iii) the Bi-214 1.767 meV peak, window width 200 keV.
(iv) the Tl-208 2.62 meV peak, window width 400 keV.

The instrument was calibrated to yield potassium (K), uranium (U) and thorium (Th) concentrations as given by the following formulae, after readings were corrected for background count, and assuming radioactive equilibrium:

$K(\%) = 0.2962\ Kc - 0.3311 Uc - 0.0224\ Thc$

$U(ppm) = 0.0254\ Kc + 3.543\ Uc - 1.802\ Thc$

$Th(ppm) = -0.0273\ Kc - 0.3709\ Uc + 8.003\ Thc$

where Kc, Uc and Thc are measured window count rates in counts/second. Measurements were made at 58 stations evenly distributed over the island. To obtain representative measurements, two or more readings were taken over different parts of the soil surface at each location. The survey results are presented in Figures 30, 31, 32, and 33 showing gamma-ray total count, calculated K(%), U(ppm) and Th(ppm) concentrations respectively.

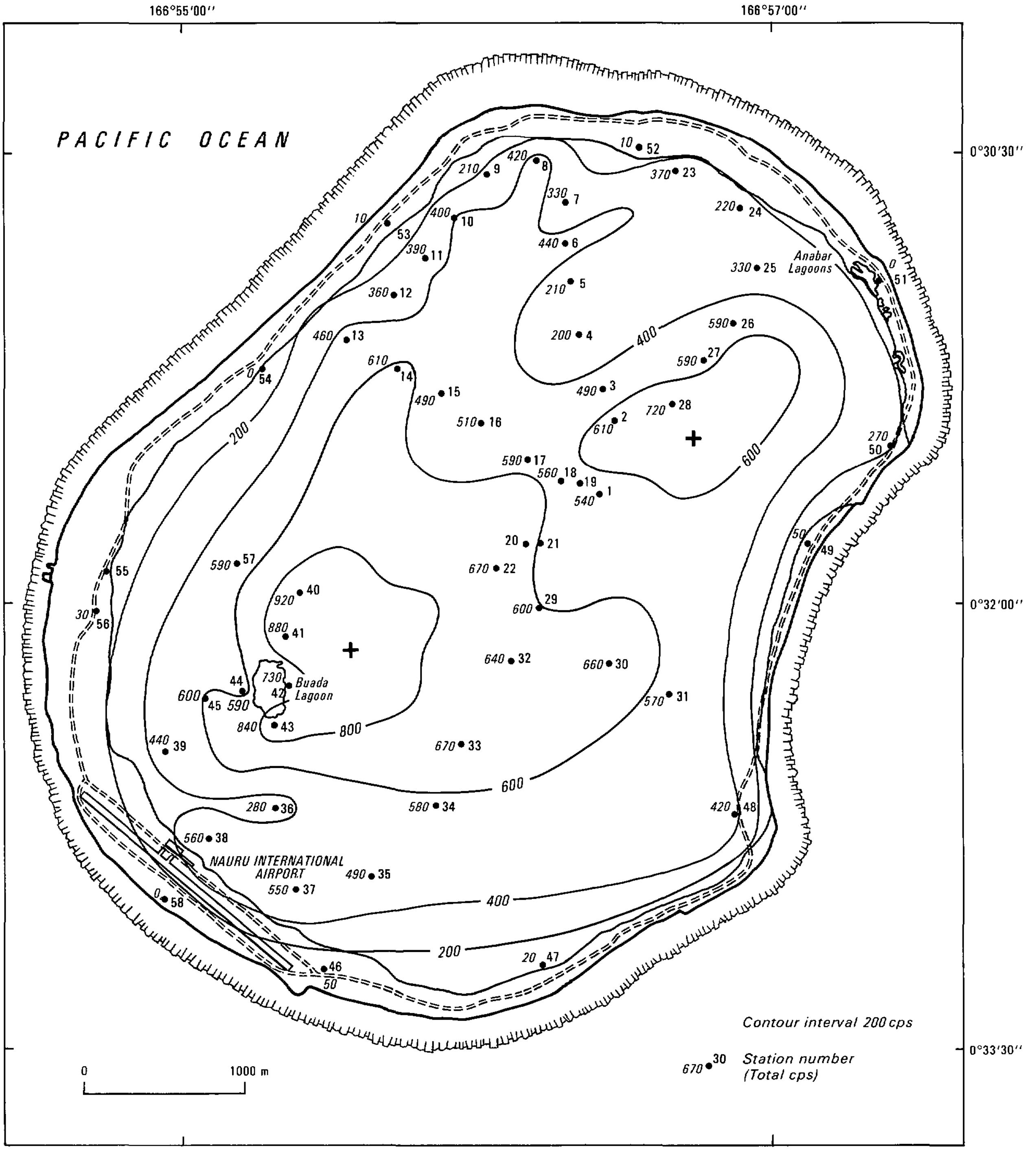
Measurements were also made on the new phosphate stockpile (station 19), on top of the black soil stockpile (station 20) and at a freshly exposed part of the base of the black soil stockpile (station 21). Results for these locations were as follows:

	Total Count	K%	U(ppm)	Th(ppm)
Stn 19	570	3.14	37	40
Stn 20	660	3.67	49	46
Stn 21	710	4.12	55	49

These materials are not in-situ and so these data were not used in producing the contour maps. Data from station 55 (total count 210, K 1.23%, U 17 ppm and Th 10 ppm) were also not incorporated, as station 55 was located on the golf course, on which the soil may have been imported. Measurements made on limestone/dolomite blocks in the mined areas show a reduction of radioactivity on all 4 channels to only about 10-40% of values obtained from the surrounding phosphatic soils. Much of the radioactivity in the soils is related to their phosphate content, as well as their organic carbon content, as indicated by the high values for the black soil stockpile.

The total count contours (Fig. 30) show a very low level of radioactivity along the coastal strip, increasing rapidly across the coastal escarpment and forming a broad high over the island's interior. The area of highest radioactivity is located to the NE of Buada Lagoon (920 cps max), while a subsidiary high occurs in the central NE of the island (720 cps max). The patterns for K, U and Th concentrations (Fig. 31, 32, 33) differ in detail, but show similar distribution. Maximum recorded concentrations are: K 4.8%, U 84 ppm, and Th 67 ppm. As a comparison, the average abundances of these elements in the earth's crust are K 2.1%, U 2.7 ppm and Th 9.6 ppm.

The concentration of uranium in the soil is relatively high, about 31 times that in average crust. The uranium is likely to be 'fixed' in the soil profile by absorbing action of the phosphate and organic carbon, and it is unlikely that sufficient leaches down to the aquifer to cause a groundwater pollution problem.



19/09/129

Fig. 30 Gamma ray total count

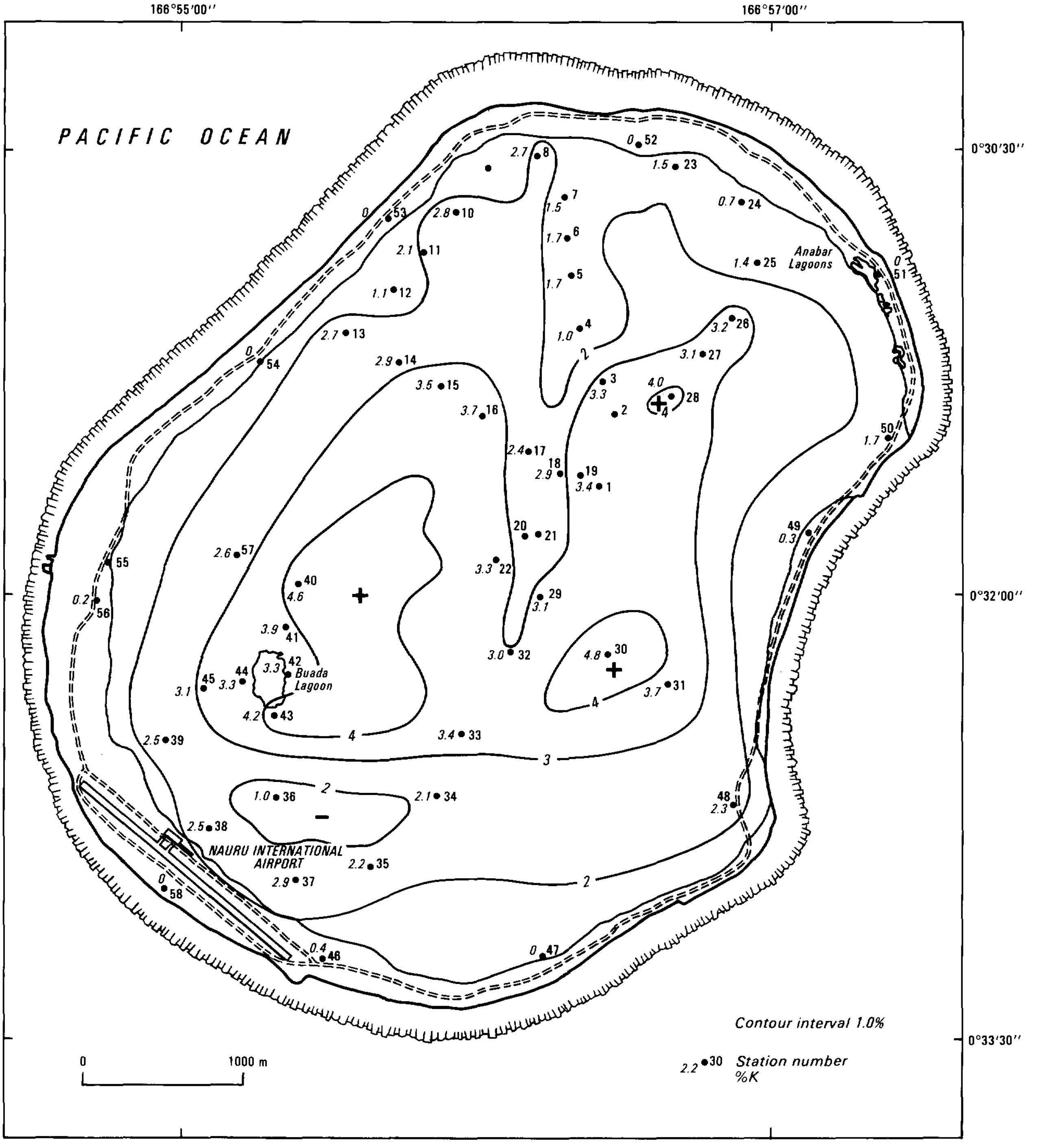
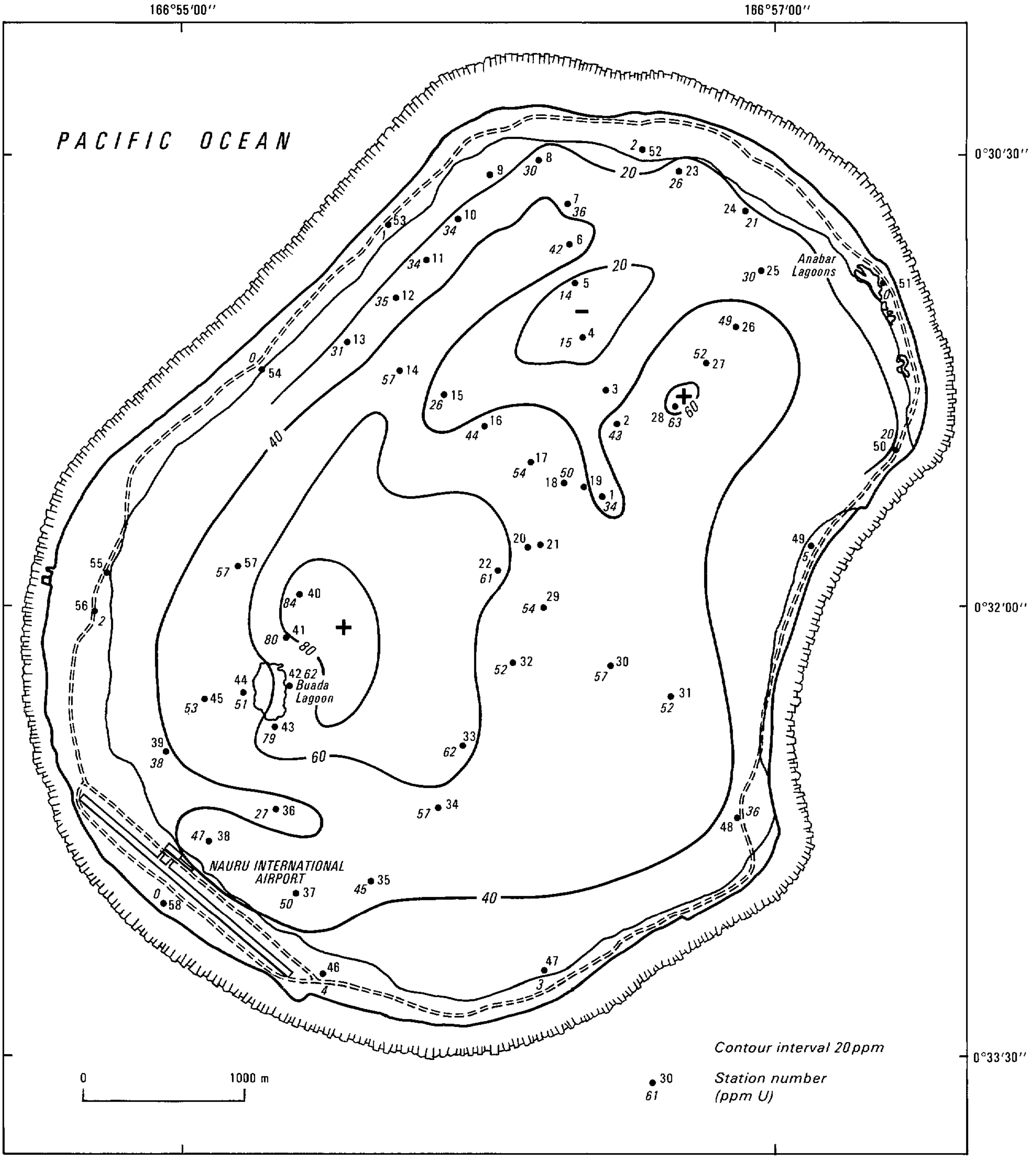
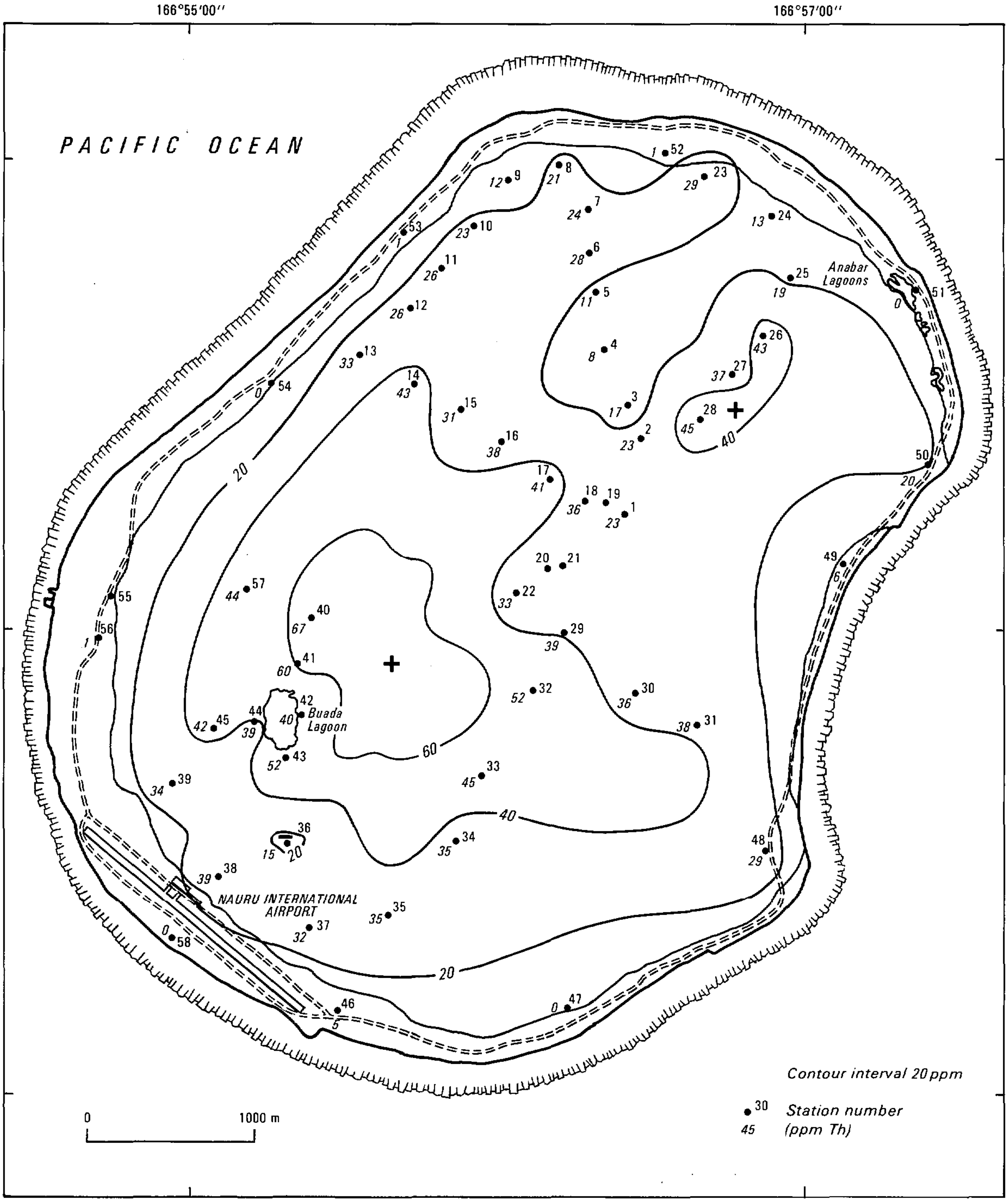


Fig. 31 Potassium (K) concentration in soil (%)



19/09/132

Fig.32 Uranium (U) concentration in soil (ppm)



19/09/131

Fig 33 Thorium (Th) concentration in soil (ppm)

CONCLUSIONS

1. Drilling and geoelectrical soundings indicate that the freshwater layer on Nauru is discontinuous and averages 4-5 m in thickness with a maximum of 7 m. The brackish water zone beneath the freshwater layer is unusually thick (60 m) owing to high-permeability limestone allowing ingress of seawater beneath the island. Salinity increases progressively downwards in the brackish water zone.

2. The substructure of Nauru is radially symmetrical with the volcanic core at a depth of 500 m beneath the limestone, which is of late Tertiary to Quaternary age.

3. The conjunctive use of rainwater catchments and coastal terrace groundwater wells will form the basis of Nauru's water supply for the foreseeable future, and some improvements to these systems are desirable.

4. Additional groundwater development will be necessary to make up the shortfall in supply when importation of water ceases. The freshwater layer beneath the island is too thin to sustain heavy pumping from bores without upconing of saltwater. Desalination of brackish groundwater, which is available in large quantities, is the most likely option for future development.

5. The coastal plain aquifer is polluted in part from sewage and animal wastes, as evidenced by bacterial counts in a number of wells. The level of radioactivity in Nauru soils is low enough not to pose a threat to groundwater development. Waste disposal in mined out areas is a potential hazard, and a waste disposal policy should be developed to protect future groundwater resources from pollution.

ACKNOWLEDGEMENTS

Field work was facilitated by the Nauru Phosphate Corporation, and we thank David Newick (General Manager), Don Lauder (Chemist) and Stan Nowak (Surveyor) for their assistance in this regard. Drilling was undertaken by Jetstream Exploration Testing of Brisbane, and supervised by Peter Barrett, under contract to the Commission of Inquiry.

Tidal information was supplied by Prof. K. Wyrtki of the University of Hawaii, and rainfall information was supplied by the Australian Bureau of Meteorology and the the Nauru Phosphate Corporation. Chemical analyses of water samples were done by AMDEL, Adelaide and carbon dating of coral samples was done by the University of Waikato, New Zealand.

We thank Tony Falkland of the A.C.T. Administration, and Fred Ghassemi of the Australian National University for comments on an earlier draft of this report.

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Follows from p. 57

APPENDIX 1

MICROPALAEONTOLOGICAL REPORT ON SAMPLES FROM NAURU

by

G.C.H. CHAPRONIERE

Follows from p. 59

MICROPALAEONTOLOGICAL REPORT ON SAMPLES FROM NAURU

George C.H. Chaproniere

A number of samples from surface and cores from Nauru Island were submitted for micropalaeontologic examination. Of these, 9 were thin-sectioned; one was from the surface, and the remainder were from the lowest core samples so that only the oldest samples were examined. The studied samples are stored in the BMR palaeontological collections under numbers 8764004 to 87640012.

The accompanying table sets out the results and gives the field number as well as the BMR registered number. All samples showed some recrystallisation features; four (87640004, 87640006, 87640009, 87640012) were too recrystallised to permit identification of foraminiferids present. The remaining samples contained either _Marginopora vertebrallis_ or _Sorites marginalis_ or both; coral, coralline algae and echinoids were the other main bioclastic components present, with _Halimeda_ (in 87640007) and undifferentiated molluscs in some samples.

All but one of the samples where recrystallisation was weakly developed are bioclastic packstones; one sample (8764007) is a bioclastic grainstone with all grains being rimmed with calcite spar.

The presence of _Marginopora_ and _Sorites_ indicates an age of no older than Middle Miocene, but as these range to the present, the age could be much younger. The absence of miliolines such as _Flosculinella_ suggests post-Middle Miocene. I suspect that all samples are either Pliocene or Pleistocene, but there is no palaeontologic evidence to confirm this.

The lack of rotalines and dominance of miliolines suggests that the samples were deposited in metahaline conditions, that is in a situation with a restricted circulation. The sediment types (packstones and grainstones) indicate deposition in a lagoonal situation, where some scouring by currents took place.

In conclusion, the sediments are probably very young and were deposited in a lagoonal setting with a restricted circulation. They are typical "back reef" sediments.

12 April 1988

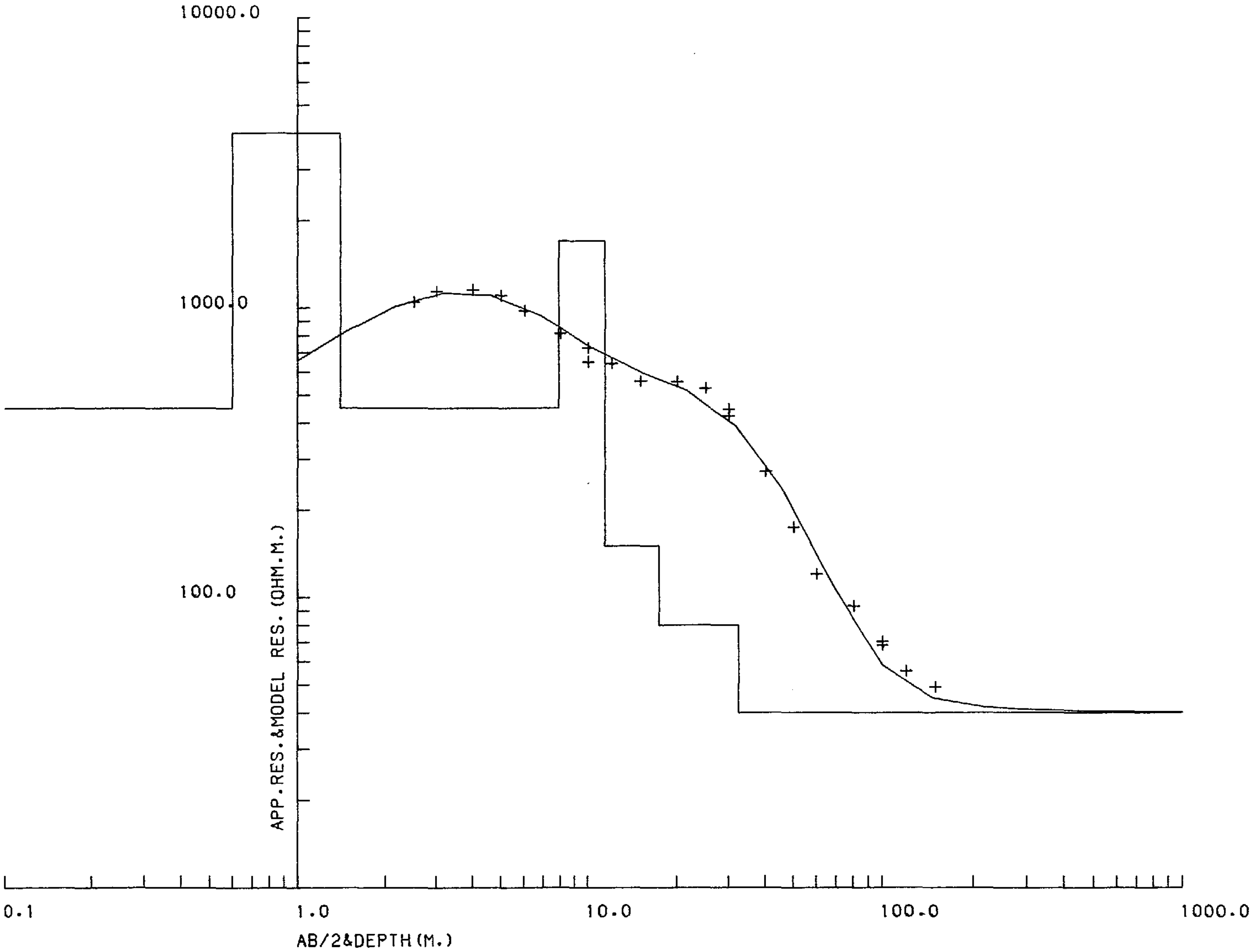
FIELD NO.	BMR REG. NO.	ZONE/SUBZONE	E.I. LETTER STATE	EPOCH
P2	87640001	Not determinable	Not determinable	
P2/32-33	87640005			Miocene, middle - Holocene
P2/42-43	87640006	Not determinable	Not determinable	
P2/51-52	87640007			Miocene, middle - Holocene
P2/61-62	87640008			Miocene, middle-Holocene
W3/33.5	87640009	Not determinable	Not determinable	
W3/44.5	87640010			Miocene, middle - Holocene
W3/52.5	87640011			Miocene, middle - Holocene
W3/63.5	87640012	Not determinable	Not determinable	

APPENDIX 2

RESISTIVITY FIELD CURVES

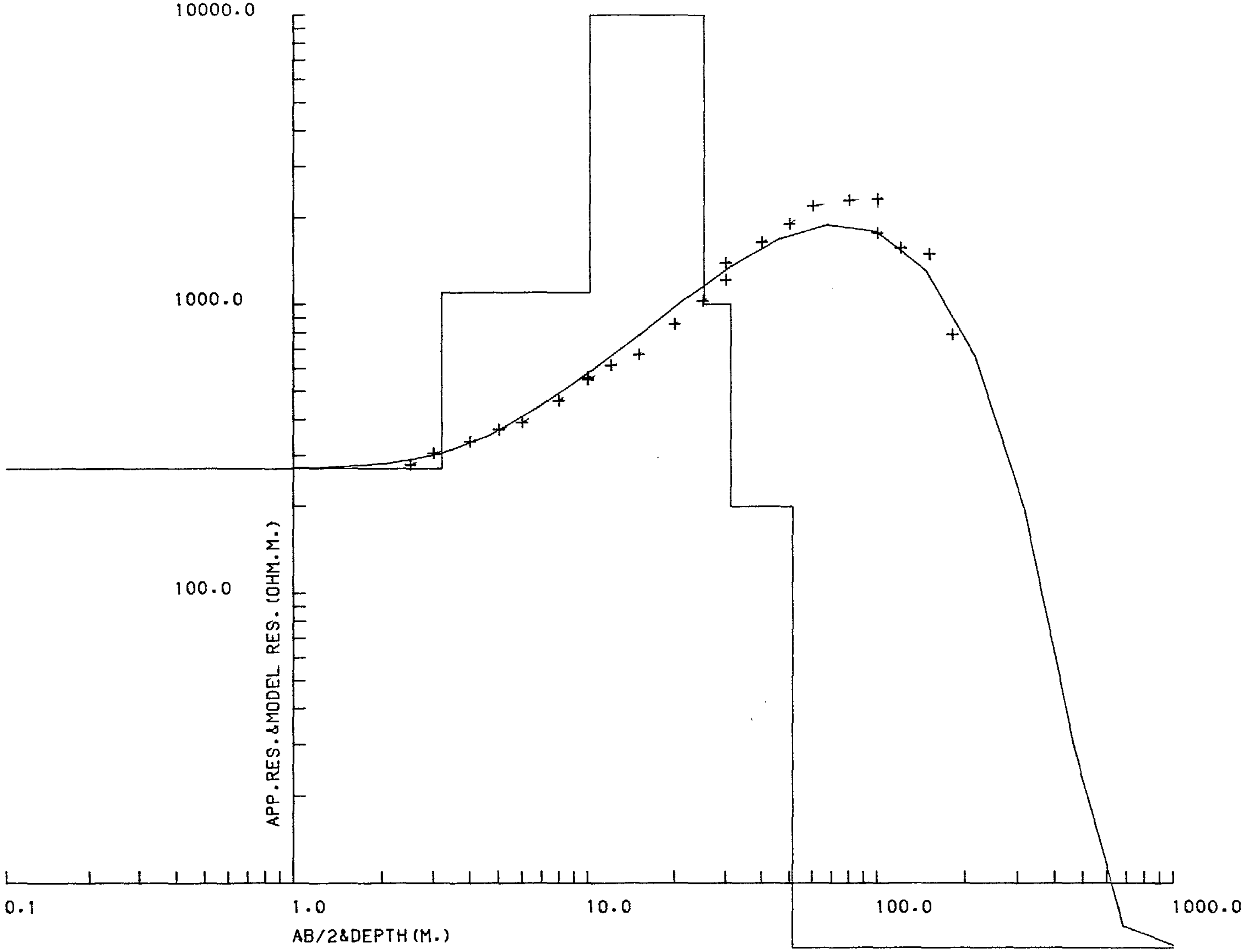
Follows from p. 63

NAURU 1. OCT 1987



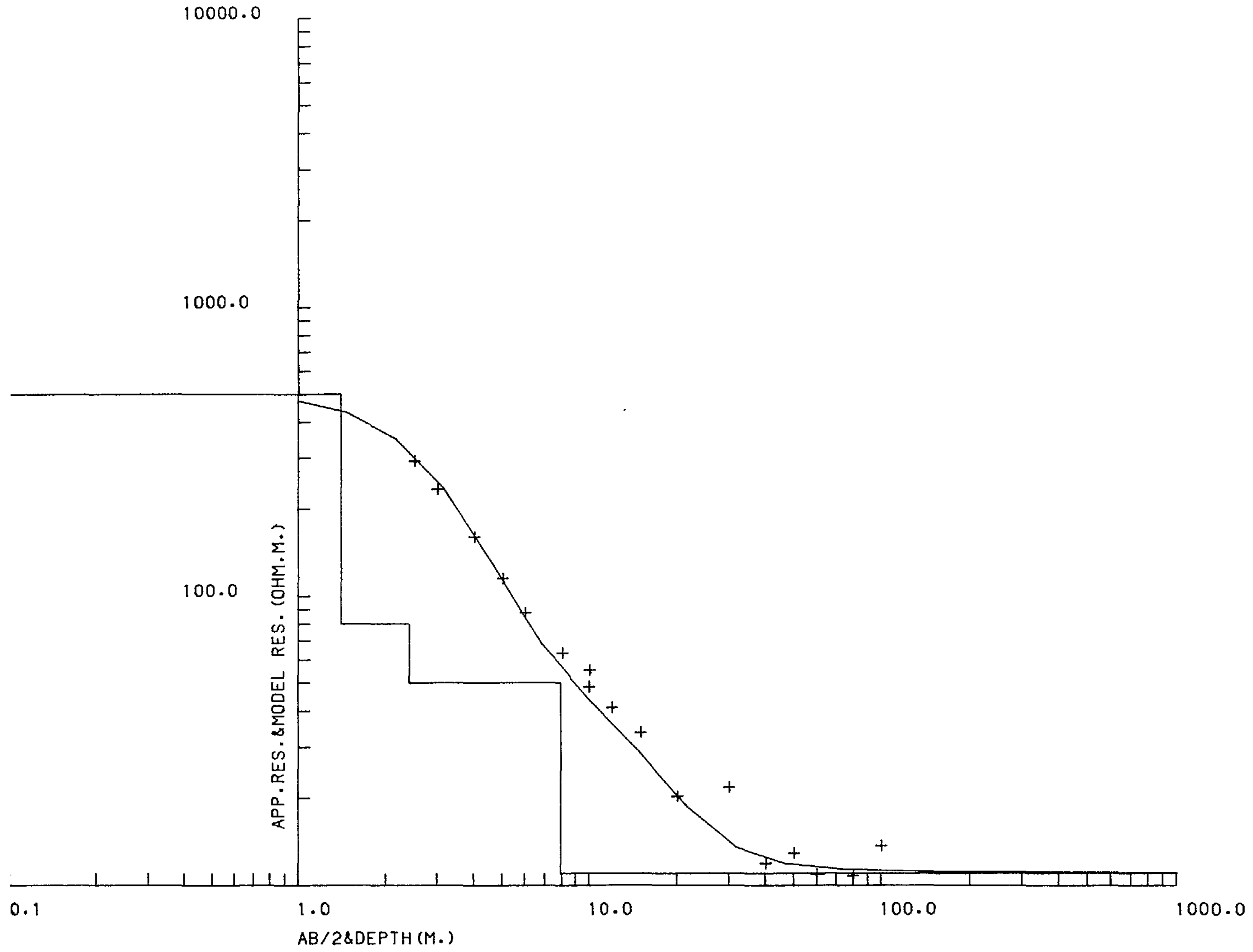
LAYER NO.	RESISTIVITY	THICKNESS
1.	450.	0.6
2.	4000.	0.8
3.	450.	6.5
4.	1700.	3.5
5.	150.	6.0
6.	80.	15.0
7.	40.	

NAURU 2. OCT 1987



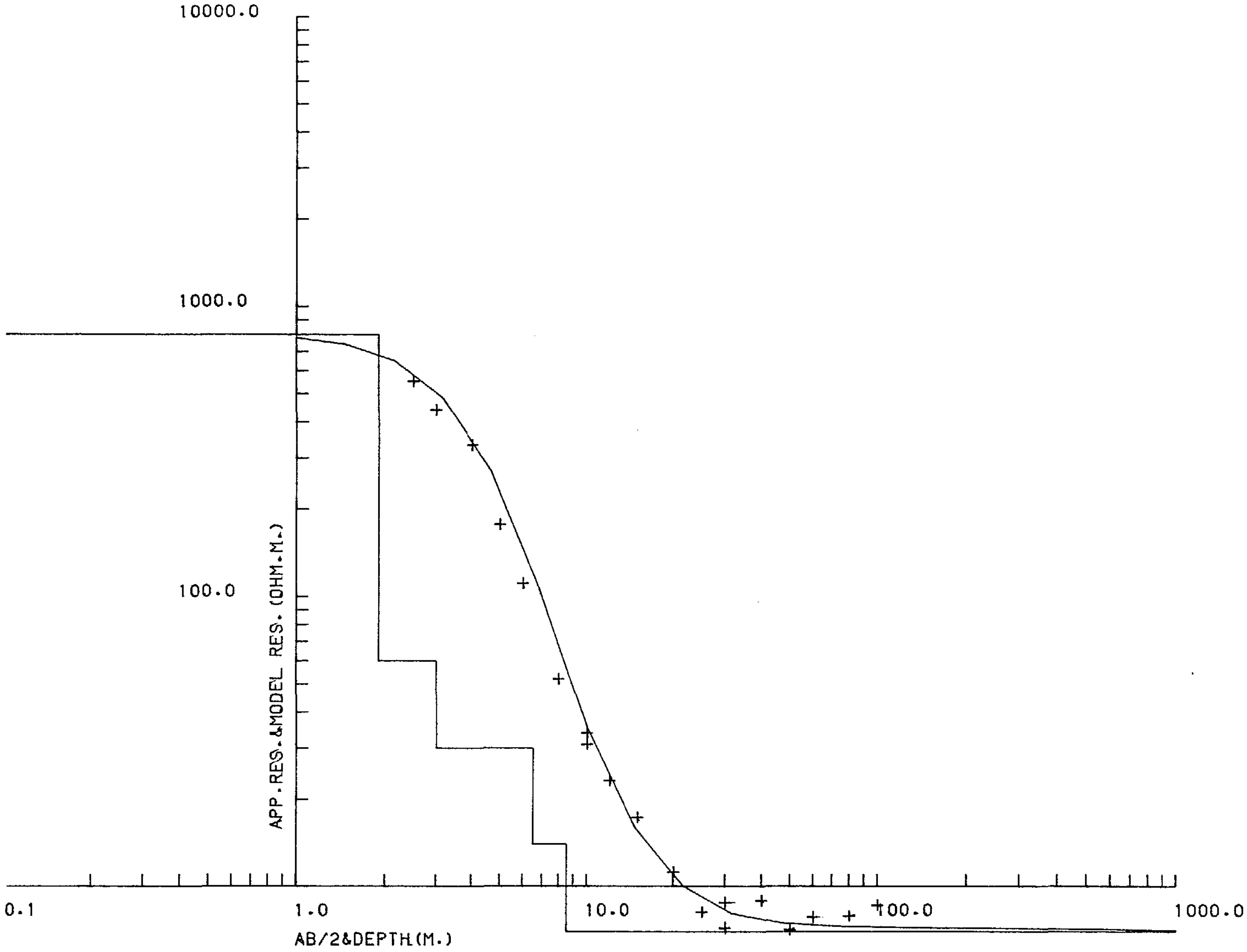
LAYER NO.	RESISTIVITY	THICKNESS
1.	270.	3.2
2.	1100.	7.0
3.	10000.	15.0
4.	1000.	6.0
5.	200.	20.0
6.	6.	

NAURU 3. OCT 1987



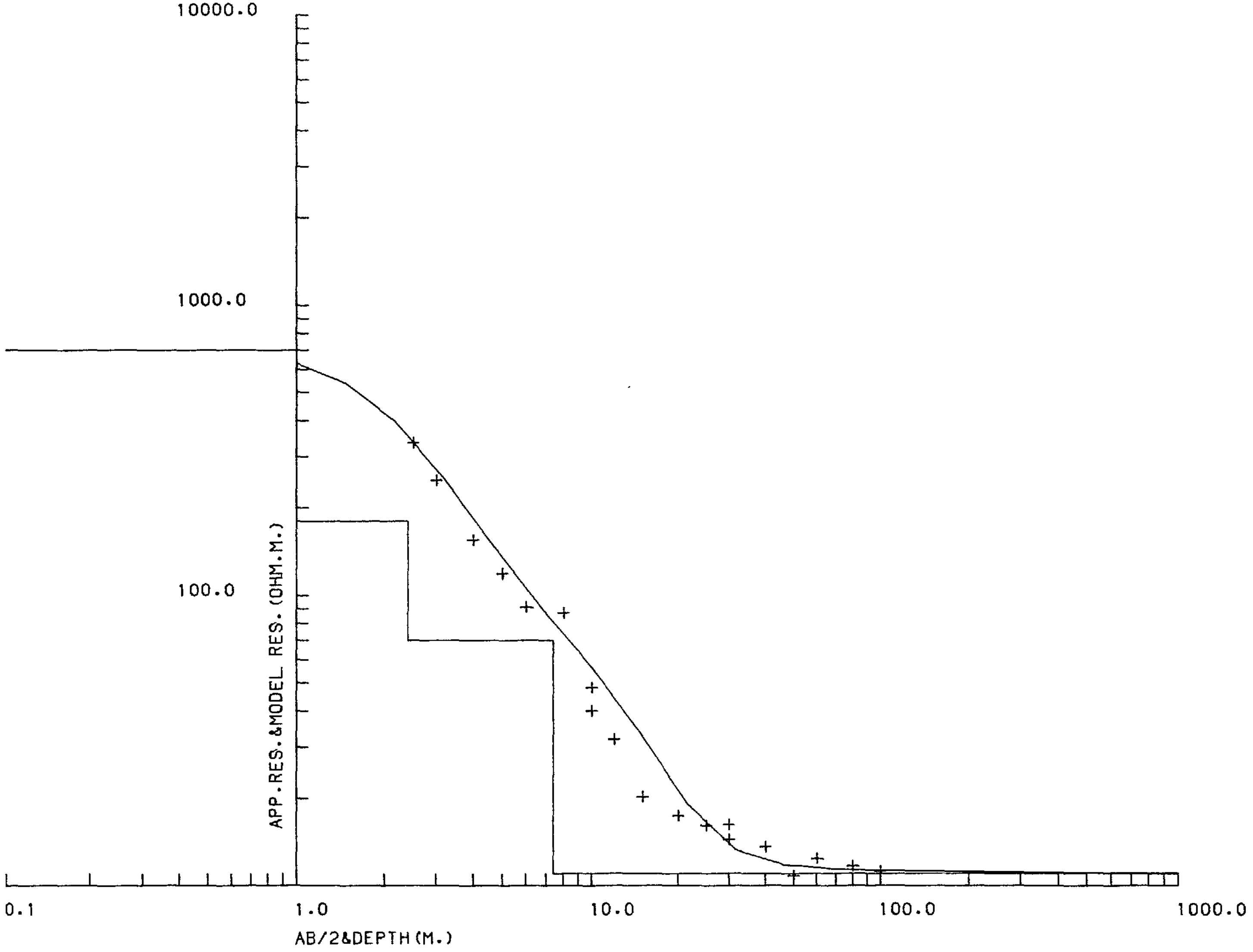
LAYER NO.	RESISTIVITY	THICKNESS
1.	500.	1.4
2.	80.	1.0
3.	50.	5.5
4.	11.	

NAURU 4. OCT 1987



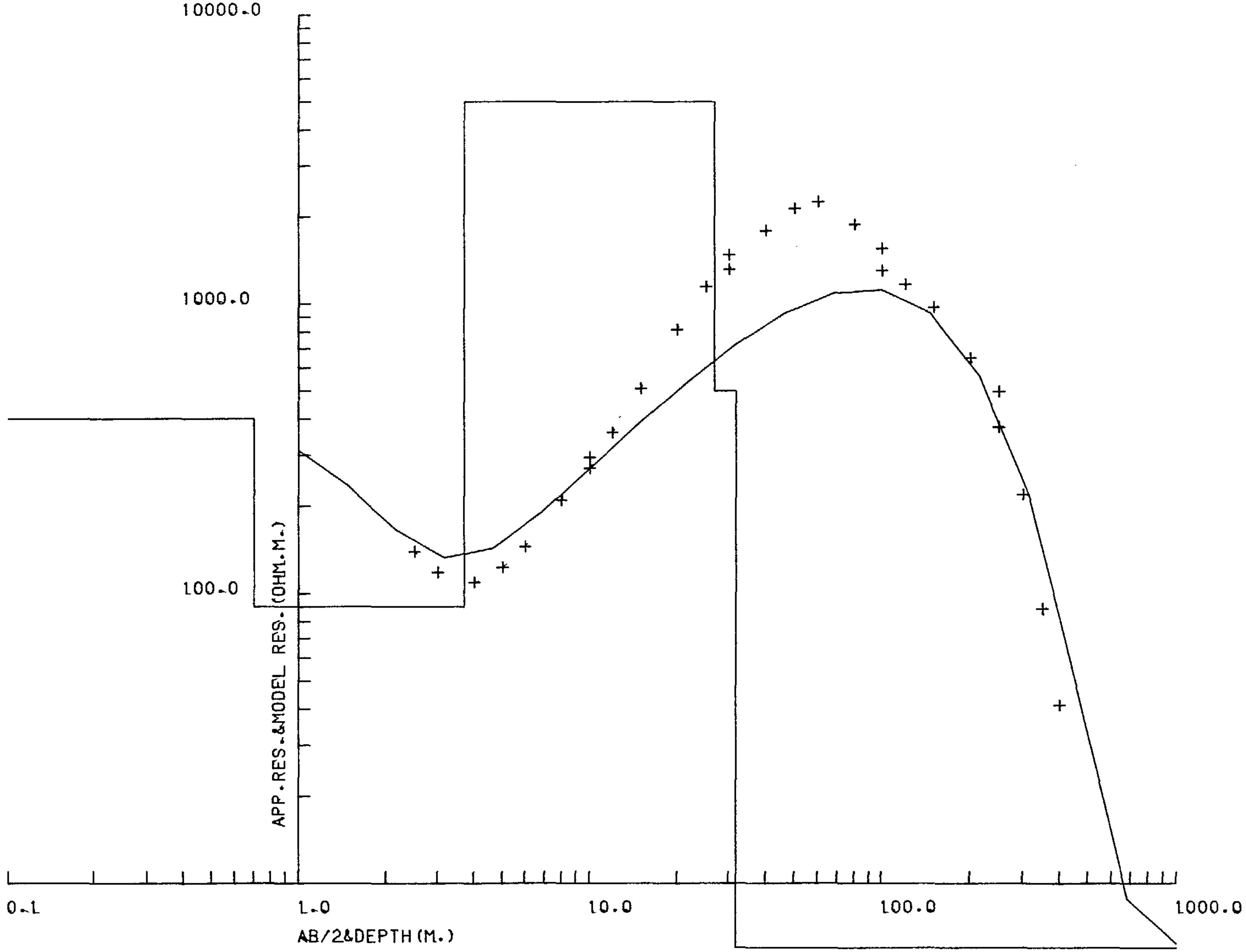
LAYER NO.	RESISTIVITY	THICKNESS
1.	800.	1.9
2.	60.	1.1
3.	30.	3.5
4.	14.	2.0
5.	7.	

NAURU 5. OCT 1987



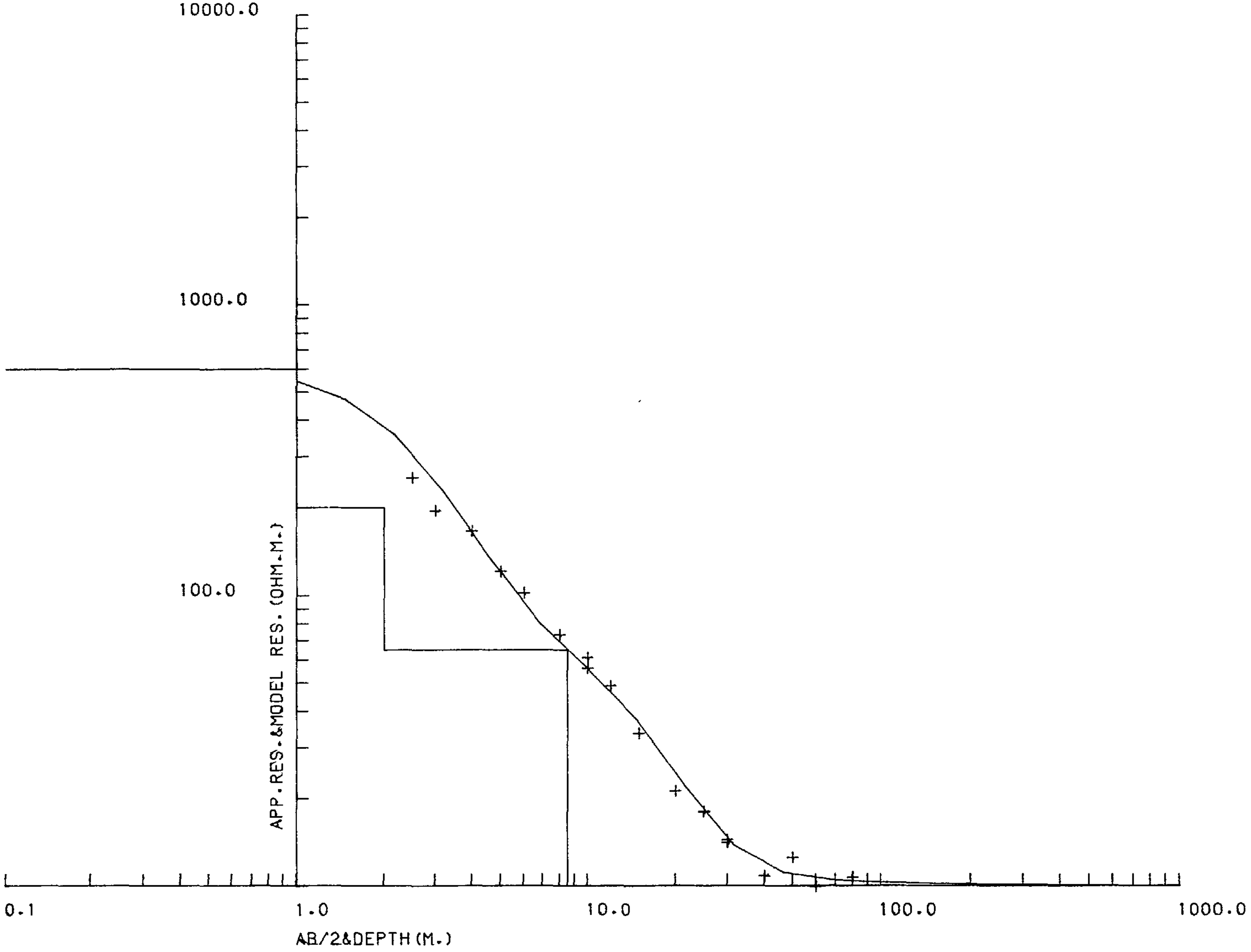
LAYER NO.	RESISTIVITY	THICKNESS
1.	700.	1.0
2.	180.	1.4
3.	70.	5.0
4.	11.	

NAURU 6. OCT 1987



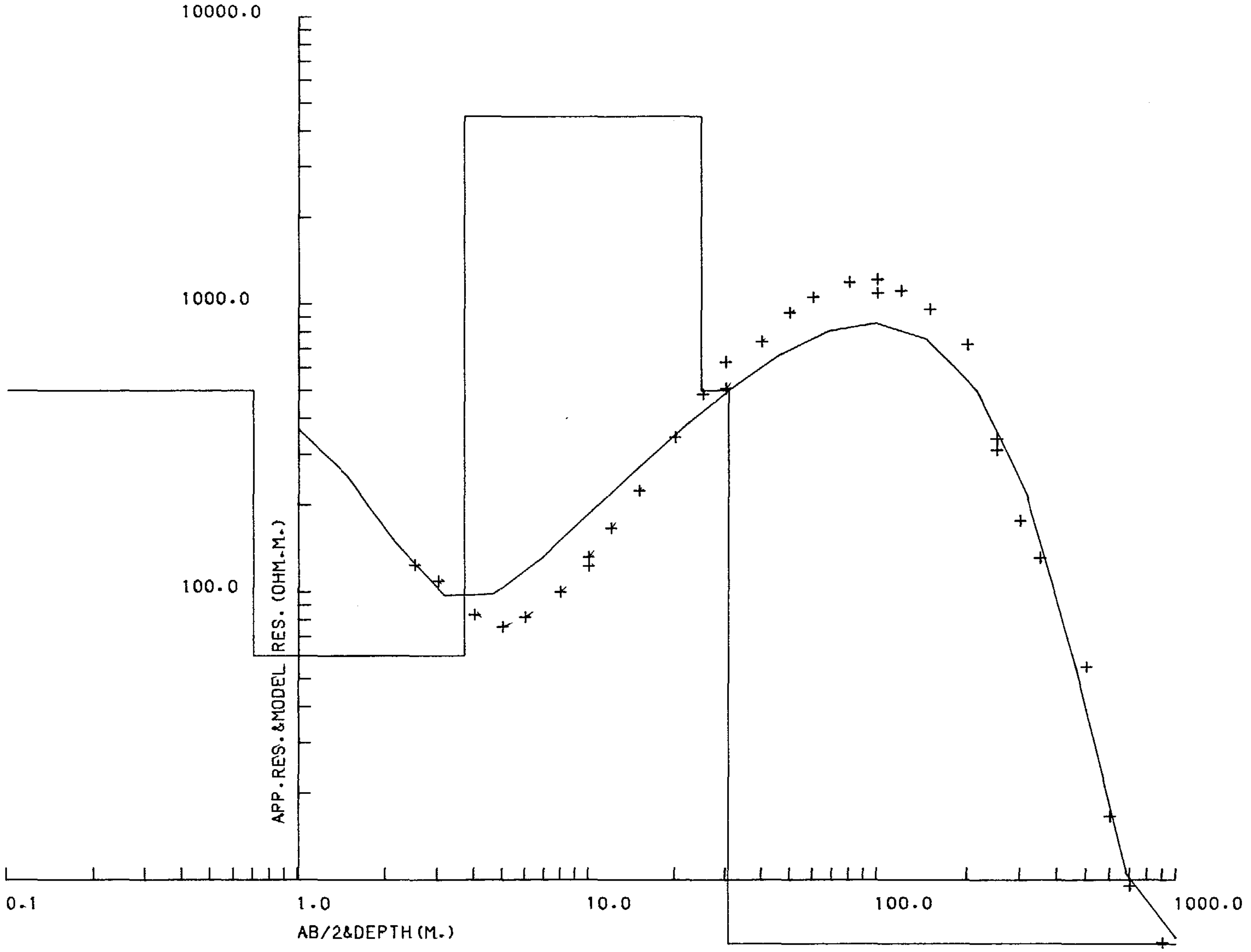
LAYER NO.	RESISTIVITY	THICKNESS
1.	400.	0.7
2.	90.	3.0
3.	5000.	23.0
4.	500.	5.0
5.	6.	

NAURU 7. OCT 1987



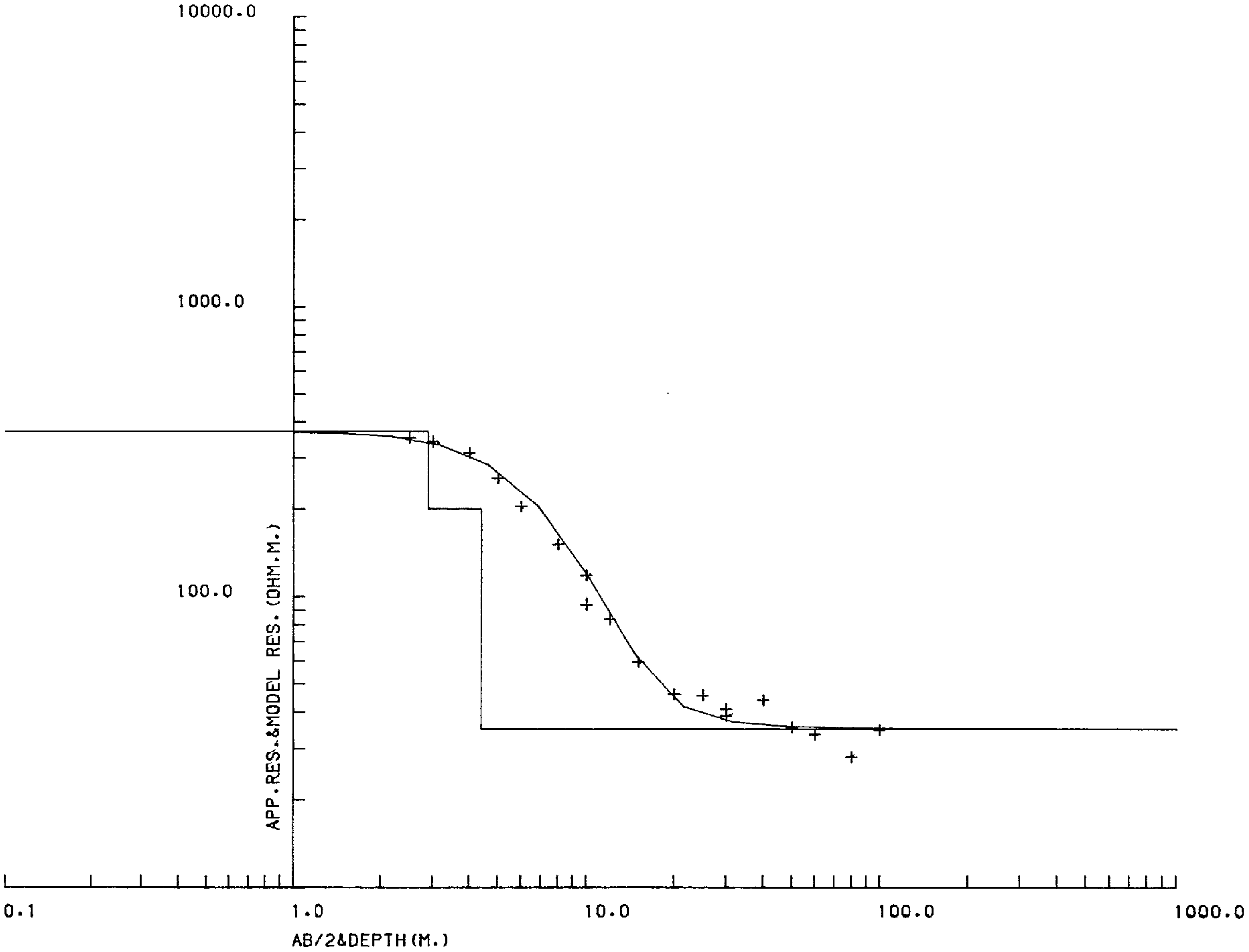
LAYER NO.	RESISTIVITY	THICKNESS
1.	600.	1.0
2.	200.	1.0
3.	65.	6.5
4.	10.	

NAURU 8. OCT 1987



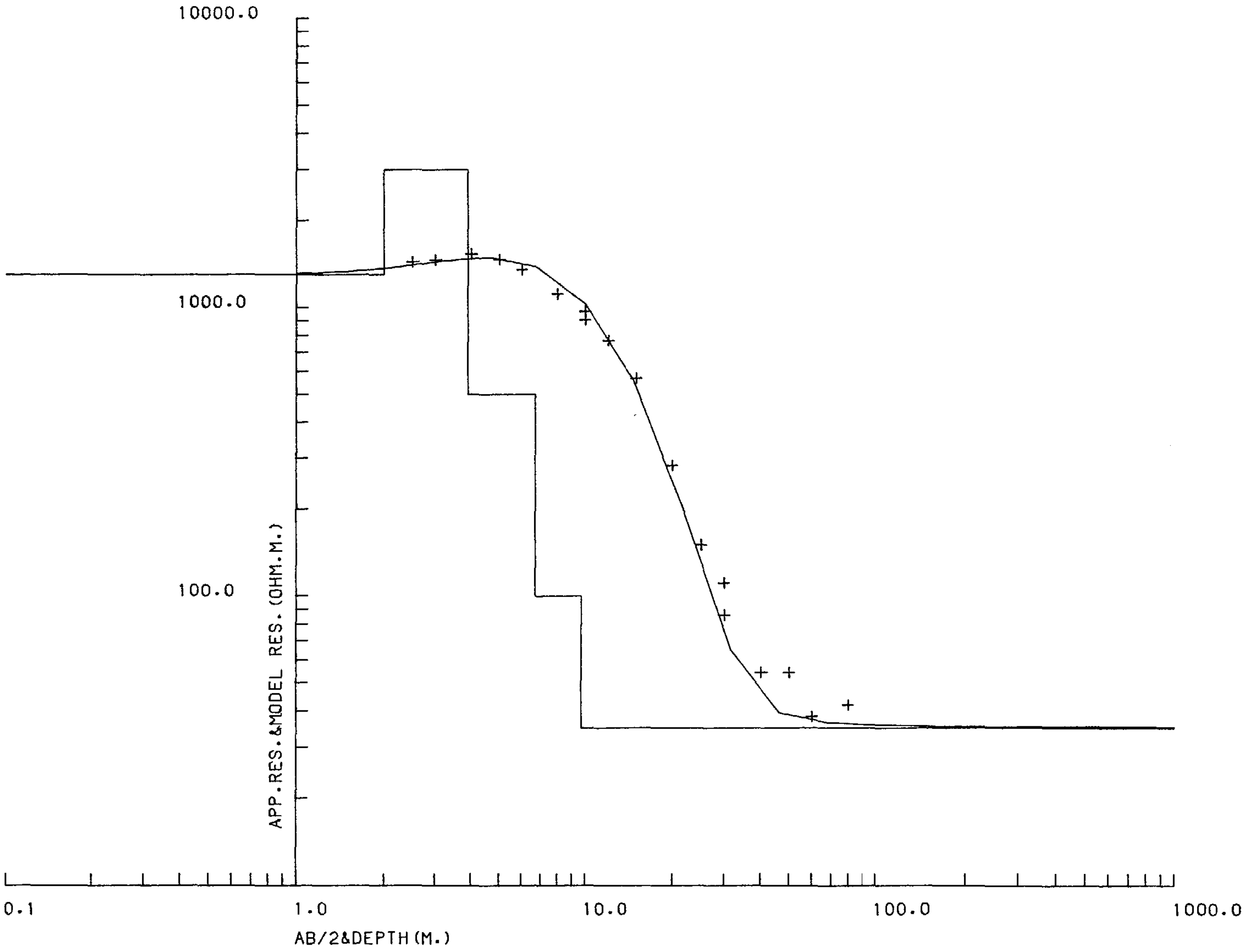
LAYER NO.	RESISTIVITY	THICKNESS
1.	500.	0.7
2.	60.	3.0
3.	4500.	21.0
4.	500.	6.0
5.	6.	

NAURU 9 OCT 1987



LAYER NO.	RESISTIVITY	THICKNESS
1.	370.	2.9
2.	200.	1.5
3.	35.	

NAURU 10. OCT 1987



LAYER NO.	RESISTIVITY	THICKNESS
1.	1300.	2.0
2.	3000.	1.9
3.	500.	2.8
4.	100.	3.0
5.	35.	

APPENDIX 3

MONTHLY AND ANNUAL RAINFALL, NAURU

Information 1915 - 1976 from Bureau of Meteorology, Melbourne (station 200089, 1915-1950; station 200245, 1951-1976). Information 1977-1987 from Nauru Phosphate Corporation.

Follows from p. 75

MONTHLY AND ANNUAL RAINFALL, NAURU

YEAR	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEPT	OCT	NOV	DEC	TOTAL
1915	-	-	-	-	-	92	72	8	23	0	5	35	-
1916	322	26	40	5	4	18	20	20	1	7	0	2	465
1917	10	3	5	73	10	87	57	22	129	12	11	61	480
1918	4	35	383	86	131	164	478	761	305	487	354	326	3514
1919	440	644	512	454	105	133	204	347	329	350	241	293	4052
1920	60	603	479	183	127	223	-	-	-	-	-	-	-
1921	272	75	20	22	12	2	80	114	57	54	94	451	1253
1922	377	208	17	88	86	116	308	277	58	9	165	30	1739
1923	106	88	289	173	32	167	173	357	189	221	673	398	2866
1924	435	153	159	4	61	61	83	84	30	58	15	3	1146
1925	50	113	8	1	47	91	108	244	179	474	-	-	-
1926	-	-	-	-	-	-	-	-	76	25	195	32	-
1927	18	7	4	41	38	98	157	105	72	12	233	396	1181
1928	549	176	26	82	12	14	77	36	125	34	139	483	1753
1929	347	394	22	22	55	74	252	248	110	99	232	528	2838
1930	466	448	561	137	82	261	281	695	688	272	335	364	4590
1931	455	185	446	120	60	183	38	171	19	94	32	173	1976
1932	860	556	438	228	103	101	210	167	80	0	2	6	2751
1933	367	115	81	169	95	162	261	94	6	57	18	0	1425
1934	32	5	34	17	38	163	129	88	18	13	13	354	904
1935	359	223	47	10	100	89	130	13	91	160	76	503	1801
1936	383	265	334	110	29	33	45	108	49	6	392	311	2065
1937	277	403	162	13	33	45	76	126	98	35	12	13	1293
1938	207	121	14	1	2	25	37	17	3	0	41	67	535
1939	37	34	33	9	70	124	182	281	209	52	330	448	1809

YEAR	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEPT	OCT	NOV	DEC	TOTAL
1940	288	374	383	519	308	305	357	263	316	409	450	-	-
1941	-	-	388	449	248	349	338	211	383	-	-	-	-
1942	-	-	-	-	-	-	-	-	-	-	-	-	-
1943	-	-	-	-	-	-	-	-	-	-	-	-	-
1944	-	-	-	-	-	-	-	-	-	-	-	-	-
1945	-	-	-	-	-	-	-	-	-	-	40	129	-
1946	225	258	333	366	309	346	397	195	219	459	395	228	3730
1947	369	292	9	54	24	195	129	71	13	11	186	334	1687
1948	258	387	644	481	428	300	143	111	9	3	265	305	3368
1949	588	113	390	169	44	41	59	58	25	50	30	30	1597
1950	2	36	2	6	7	13	17	51	20	10	25	91	280
1951	322	23	216	267	407	277	234	406	107	286	142	597	3284
1952	258	134	117	117	106	101	186	203	155	35	28	364	1804
1953	410	623	386	-	450	154	239	427	130	411	188	528	-
1954	368	157	221	157	26	22	20	71	82	2	1	16	1143
1955	486	23	95	46	44	33	19	28	78	2	10	41	905
1956	104	121	78	64	53	7	20	44	16	40	82	138	767
1957	157	415	275	176	222	259	273	210	242	357	414	417	3417
1958	257	558	264	469	198	213	316	123	63	44	142	154	2801
1959	385	230	193	99	65	94	28	21	11	31	162	441	1760
1960	576	245	89	190	153	7	173	47	81	98	140	357	2156
1961	238	219	400	269	140	142	148	247	58	50	178	59	2148
1962	22	28	32	68	63	53	104	104	80	2	344	58	958
1963	34	13	26	89	68	100	52	149	272	365	132	452	1752
1964	306	568	126	3	7	4	24	75	18	1	7	282	1421

YEAR	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEPT	OCT	NOV	DEC	TOTAL
1965	400	395	134	316	104	192	345	387	325	385	356	325	3664
1966	332	441	269	302	158	114	215	40	10	106	22	133	2142
1967	64	60	14	406	47	17	81	44	49	11	16	525	1334
1968	455	374	17	51	4	14	141	15	19	6	51	146	1293
1969	-	374	548	333	100	54	32	35	-	77	87	373	-
1970	260	641	380	474	72	105	23	26	3	8	22	0	2014
1971	13	4	1	115	54	108	72	-	18	28	28	160	-
1972	359	175	25	172	293	300	343	287	526	220	183	482	3365
1973	335	432	150	45	24	166	12	12	15	4	1	15	1211
1974	0	1	10	118	125	58	73	129	3	6	70	355	948
1975	781	215	199	70	75	114	96	58	73	3	2	17	1703
1976	5	201	523	320	198	213	258	285	425	275	179	408	3290
1977	369	311	421	310	152	53	315	126	369	191	456	450	3524
1978	163	0	454	377	24	28	28	27	32	16	63	29	1502
1979	204	412	361	21	160	227	119	95	46	303	420	526	2893
1980	258	444	554	300	304	300	235	198	281	493	310	187	3864
1981	277	277	471	535	49	242	49	70	19	91	134	470	2686
1982	445	168	553	311	134	179	403	300	132	354	175	223	3376
1983	175	16	4	80	174	233	407	81	36	7	1	196	1410
1984	41	4	1	31	39	55	5	21	9	165	101	102	576
1985	233	100	174	17	64	52	92	90	17	7	179	247	1275
1986	437	139	2	93	139	190	201	126	203	303	495	476	2805
1987	176	510	290	340	371								

Follows from p. 79

APPENDIX 4

CHEMICAL AND BACTERIOLOGICAL ANALYSES OF NAURU WATER SAMPLES

Chemical analyses by AMDEL, Adelaide;
bacteriological analyses by Nauru
General Hospital

Follows from p. 81

	Anatan well	Clodamar's well	Retow's well	Anatan cave	Benjamin's well	Heine's well	Menke's well	Meneng well	Reweru's well
Calcium	96	68	62	26	52	86	90	71	135
Magnesium	56	65	67	26	33	35	60	70	71
Sodium	358	370	390	52	96	145	400	422	374
Potassium	14	12	16	<0.5	6	4	15	15	12
Carbonate	-	-	-	-	-	-	-	-	-
Bicarbonate	431	282	308	177	284	328	334	296	530
Sulphate	119	110	119	13	36	42	111	144	65
Chloride	567	652	646	79	129	240	703	722	715
Nitrate	24	<0.1	14	4	14	10	30	6	8
pH (laboratory)	7.5	7.3	7.7	7.8	7.7	7.6	7.8	7.7	7.4
pH (field)	6.70	6.89	6.92		6.88	6.84	7.09	6.70	6.81
Conductivity (lab)	2630	2700	2750	560	910	1300	2900	3050	3070
Resistivity	3.80	3.70	3.64	18	11	7.69	3.45	3.28	3.26
Total dissolved solids	1490	1475	1520	310	465	740	1650	1690	1755
Total hardness	470	437	430	172	266	359	472	465	629
Fluoride	0.2	0.2	0.3	<0.1	0.2	0.1	0.2	0.4	0.3
Silica	1.1	1.35	1.8	<0.01	4.5	2.5	4.3	1.6	5.2
Phosphorus	0.09	0.07	0.06	0.33	0.02	0.15	0.05	0.03	0.15
Phosphate	0.24	0.17	0.17	0.96	0.06	0.41	0.12	0.07	0.43
Iron	<0.03	<0.03	<0.03	<0.03	<0.03	<0.03	<0.03	<0.03	<0.03
Cadmium	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
Zinc	0.14	0.49	0.30	<0.02	<0.02	0.47	0.02	<0.02	0.04
MPN index	43	23	43	93	0	93	0	4	9

	Drillhole W1 25.5 m	Drillhole P4 36.5 m	Drillhole P4 39.5 m	Drillhole H10 33.0 m	Drillhole H10 50.0 m	Drillhole P5 31.5 m	Drillhole P5 43.5 m	Drillhole P3 11.2 m	Drillhole W3 65.0 m	Seawater
Calcium	22	24	40	66	103	53	103	90	215	364
Magnesium	13	9	84	73	223	100	305	203	680	1220
Sodium	36	23	555	380	1670	685	2500	1605	5500	10500
Potassium	0.5	1	20	17	51	25	60	45	180	320
Carbonate	-	-	-	-	15	-	23	26	20	23
Bicarbonate	121	105	168	169	146	182	144	154	119	113
Sulphate	10	8	114	94	410	143	595	390	1300	2410
Chloride	55	40	1018	715	3138	1291	4583	2905	10160	19611
Nitrate	<0.1	0.2	0.2	160	150	13	4	8	7	<0.1
pH (laboratory)	7.8	7.4	8.3	7.6	8.4	7.9	8.6	8.9	8.9	9.0
pH (field)	-	-	-	7.06	-	6.70	6.87	-	-	
Conductivity (lab)	380	320	3600	2900	10100	4600	14000	9200	29000	51000
Resistivity	26	31	2.78	3.45	0.99	2.17	0.71	1.09	0.34	0.20
Total dissolved solids	295	168	2000	1655	5920	2600	8830	5160	18490	35410
Total hardness	108	98	445	465	1174	544	1512	1060	3334	5927
Fluoride	0.3	0.2	0.3	0.2	0.3	0.5	0.2	0.3	0.4	0.8
Silica	0.4	1.1	0.5	0.5	1.2	1.2	5.0	1.5	2.0	6.1
Phosphorus	0.60	0.01	0.06	0.03	0.02	0.34	0.01	0.12	0.24	0.01
Phosphate	1.80	0.02	0.19	0.09	0.05	0.99	0.02	0.34	0.69	0.02
Iron	< 0.03	<0.03	0.08	<0.03	<0.03	0.08	<0.03	<0.03	<0.03	<0.03
Cadmium	< 0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
Zinc	< 0.02	0.05	<0.02	0.19	<0.02	<0.02	<0.02	0.08	<0.02	<0.02
MPN index	-	-	-	-	-	-	-	-	-	-

	Rainwater 13/10/87	Rainwater 14/10/87	Rainwater 17/10/87	Buada Lagoon 9/10/87	Buada Lagoon 16/10/87	Anabar Lagoon 9/10/87	Anmara Well 9/10/87	Maqua Pool 9/10/87	Maqua Pool 16/10/87
Calcium	1.0	0.5	0.6	29	28	85	15	42	44
Magnesium	0.6	0.2	0.4	6.2	6.5	175	22	68	68
Sodium	1.0	1.0	1.5	32	30	1431	104	466	450
Potassium	<0.5	<0.5	<0.5	0.5	0.5	40	2	16	15
Carbonate	-	-	-	9.5	34.9	15.7	-	-	-
Bicarbonate	9.0	3.5	4.7	91.3	46.8	187	256	186	199
Sulphate	0.3	0.5	0.5	12.0	11.0	353	32	103	101
Chloride	1.0	2.0	4.0	47	48	2540	74	838	801
Nitrate	<0.1	<0.1	<0.1	< 0.1	< 0.1	<0.1	4	7	7
pH (laboratory)	6.5	5.8	5.8	8.7	8.8	8.5	7.4	7.6	7.6
pH (field)	-	-	-	-	-	-	-	-	6.90
Conductivity (laboratory)	21	18	18	343	350	8400	730	3180	3150
Resistivity	487	556	556	29	29	1.19	14	3.14	3.17
Total dissolved solids	10	10	10	200	155	5032	400	1760	1710
Total hardness	5	2	3	98	97	932	128	385	390
Fluoride	<0.1	<0.1	<0.1	0.4	0.3	0.3	0.4	0.2	0.2
Silica	<0.01	<0.01	<0.01	0.01	<0.01	1.5	4.4	0.8	0.9
Phosporus	0.10	0.11	0.16	0.20	0.31	0.05	0.54	0.10	0.10
Phosphate	0.32	0.32	0.46	0.55	0.94	0.11	1.75	0.28	0.34
Iron	<0.03	<0.03	<0.03	<0.03	<0.03	<0.03	<0.03	<0.03	<0.03
Cadmium	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
Zinc	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	0.03	<0.02	<0.02
MPN index	-	-	-	-	0	-	-	-	240

Elemental analyses in mg/L; conductivity in microS/cm; Resistivity in ohm-m: MPN index is Most Probable Number of e coli.

	Odn-aiwo well	Botelenga's well	Kayser's well	Rudy's well	Dannang's well	Ijuh cave	Drillhole P6 25.5 m	Drillhole P6 21.5 m	Drillhole W1 20.5
Calcium	105	93	69	73	90	32	14	20	23
Magnesium	125	22	19	36	40	37	5	7.5	12
Sodium	830	26	44	68	120	182	16	20	18
Potassium	32	3	1.5	0.5	0.5	5	0.5	0.5	0.5
Carbonate	-	-	-	-	-	-	-	-	-
Bicarbonate	403	357	315	467	434	211	71	94	131
Sulphate	195	16	22	52	33	66	5	6	5
Chloride	1532	35	48	36	177	272	23	31	25
Nitrate	8	25	5	3	3	13	0.1	0.1	< 0.1
pH (laboratory)	7.7	7.4	7.7	7.5	7.6	7.6	7.9	7.2	8.0
pH (field)	6.95	6.82	6.91	6.94	6.80	6.80	6.58	6.90	
Conductivity (lab)	5700	710	660	900	1260	1370	200	265	280
Resistivity	1.75	14	15	11	7.94	7.30	50	37	36
Total dissolved solids	3245	430	360	520	730	730	85	145	160
Total hardness	776	323	250	330	389	232	55	81	107
Fluoride	0.3	0.2	0.2	0.3	0.2	0.1	0.1	0.2	0.1
Silica	6.3	3.5	2.6	1.5	0.07	<0.01	4.2	3.9	0.06
Phosphorus	0.06	0.05	0.07	0.03	0.09	0.07	0.02	0.28	0.06
Phosphate	0.12	0.13	0.18	0.04	0.24	0.17	0.04	0.81	0.17
Iron	0.03	0.03	<0.03	<0.03	<0.03	0.03	0.03	0.06	0.07
Cadmium	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
Zinc	<0.02	0.08	0.03	1.12	0.07	0.02	0.10	0.09	<0.02
MPN index	240	43	9	240	0	93	-	-	-

	G. Apad's well	Daniel's well	Rydell's well	Tapau's well	Engar's well	Anabar cemetery well	Jeremiah's well	Itsimera's well	Ijuh well
Calcium	85	72	34	87	37	67	70	96	72
Magnesium	12	23	36	27	36	56	50	51	56
Sodium	6	70	138	103	167	265	253	257	365
Potassium	<0.5	1	8	2	7	8.5	7	10	11
Carbonate	-	-	-	-	-	-	-	-	-
Bicarbonate	338	352	330	319	211	472	345	390	348
Sulphate	2.4	33	88	33	49	133	94	73	163
Chloride	4	80	123	163	268	355	413	424	534
Nitrate	< 0.1	< 0.1	0.2	19	14	1	4	35	12
pH (laboratory)	7.4	7.3	7.5	7.5	7.8	7.5	7.3	7.4	7.6
pH (field)	6.84	6.96	6.92	7.16	6.86	6.78	6.83	6.85	6.88
Conductivity (lab.)	520	840	1070	1080	1310	2000	2000	2080	2550
Resistivity	19	12	9.35	9.26	7.63	5.00	5.00	4.81	3.92
Total dissolved solids	290	460	615	640	730	1140	1090	1195	1420
Total hardness	262	274	233	328	240	398	380	449	410
Fluoride	0.3	0.2	0.2	0.3	0.1	0.2	0.3	0.2	0.3
Silica	0.2	2.6	3.2	5.2	1.3	<0.01	0.7	2.2	0.2
Phosporus	0.03	0.30	0.18	0.05	0.09	0.10	0.04	0.12	0.02
Phosphate	0.06	0.86	0.48	0.09	0.27	0.24	0.09	0.33	0.07
Iron	<0.03	<0.03	0.06	<0.03	0.03	<0.03	0.03	0.03	0.03
Cadmium	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
Zinc	0.46	<0.02	0.13	0.07	<0.02	0.03	0.08	<0.02	0.18
MPN index	1100	93	93	4	0	0	93	0	0