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GROUNDWATER RESOURCES OF NIUE ISLAND

by

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ABSTRACT

Niue Island, in the South Pacific Ocean, is a raised coral atoll. The original atoll rim is preserved as a peripheral ridge at an elevation of about 60 m, and the original lagoon floor now forms an internal basin at an elevation of about 35 m. Limestone of Miocene age occurs to a depth of more than 200 m, and limestone probably overlies volcanic bedrock at a depth of about 300 m below sea level.

There is no surface drainage on Niue. Two-thirds of the rainfall is taken up by evapotranspiration, and one-third infiltrates the ground and maintains a freshwater layer, overlying salt water, within the limestone. The elevation of the water-table is about 1.8 m above sea level in the centre of the island and generally decreases seawards. Electrical resistivity surveys indicate that the freshwater layer is 50-80 m thick in the centre of the island (6 km from the coast), and increases to 100-150 m thick 1-2 km inland from the coast, then disappears within 500 m of the coast, where salt water mixes with the fresh water along fissures in the limestone. Groundwater flow is, in general, radially outwards from the centre of the island.

The annual recharge to groundwater is estimated as 624 mm. Even during a drought, a model freshwater layer 50 m thick and drawn up halfway - i.e., 25 m - would be capable of yielding about 4000 m^3/year/ha of groundwater. Aquifer tests on two specially constructed bores indicate specific capacity (yield-to-drawdown ratio) of about 12 l/s/m of drawdown, and a safe long-term pumping rate of about 8 l/s.

The total dissolved solids content of the fresh water in the interior of Niue ranges from 136 to 261 mg/litre and the water is considered suitable for most agricultural and urban uses. With adequate controls and proper bore construction and development, there is sufficient freshwater to supply Niue's foreseeable needs for irrigation and urban water supply. The aquifer is susceptible to pollution because of rapid groundwater movement along fissures, and cautious management and monitoring will be required for large-scale groundwater development.

INTRODUCTION

On behalf of the Australian Development Assistance Bureau, an investigation of the groundwater resources of Niue Island in the Pacific Ocean (Fig. 1) was undertaken between 30 March and 11 May 1979. The BMR team consisted of G. Jacobson (geologist), P.J. Hill (geophysicist), and A.W. Schuett (groundwater technician).

The investigation followed recommendations for the assessment of Niue's groundwater potential made by D. Kammer, hydrologist, United Nations Development Programme, in 1978. At that time there was some doubt about the availability of water to support both urban use and agricultural irrigation in the future.

The terms of reference were defined in preliminary discussions with Niue government officials as:

1. Estimate the quantity and quality of water available.
2. Ascertain the safe yield and pumping rate.
3. Assess the suitability of the water for agricultural and urban use.
4. Evaluate the danger of groundwater pollution from pesticides and fertilisers, if used in conjunction with irrigation.
5. Assess the feasibility of drawing urban water supplies from a central source.

The field investigation included: inspections of caves and springs; a census of hydrological data of existing water-bores; gravity and magnetic surveys to determine the depth and shape of the island's basement; electrical resistivity surveys to determine the thickness of the freshwater layer; drilling and construction of two water production bores and two observation bores; aquifer testing; measurements of tidal response in bores; and water sampling for electrical conductivity measurement and chemical analysis.

The drilling was done under contract by F.A. Kelly Pty Ltd., Broadmeadow, NSW. Assistance with other aspects of the work was provided by the Directors and staff of the Niue Department of Works; Department of Agriculture; Department of Justice, Lands and Survey; and Department of Health. Geological and survey information from the investigations of Mr. J. Barrie of Avian Mining Pty Ltd, a company which is prospecting for minerals on Niue, was most helpful and was freely provided. Tidal information was obtained from the Hydrographic Office of the New Zealand Navy by courtesy of Mr I. McGregor, the New Zealand Representative on Niue.

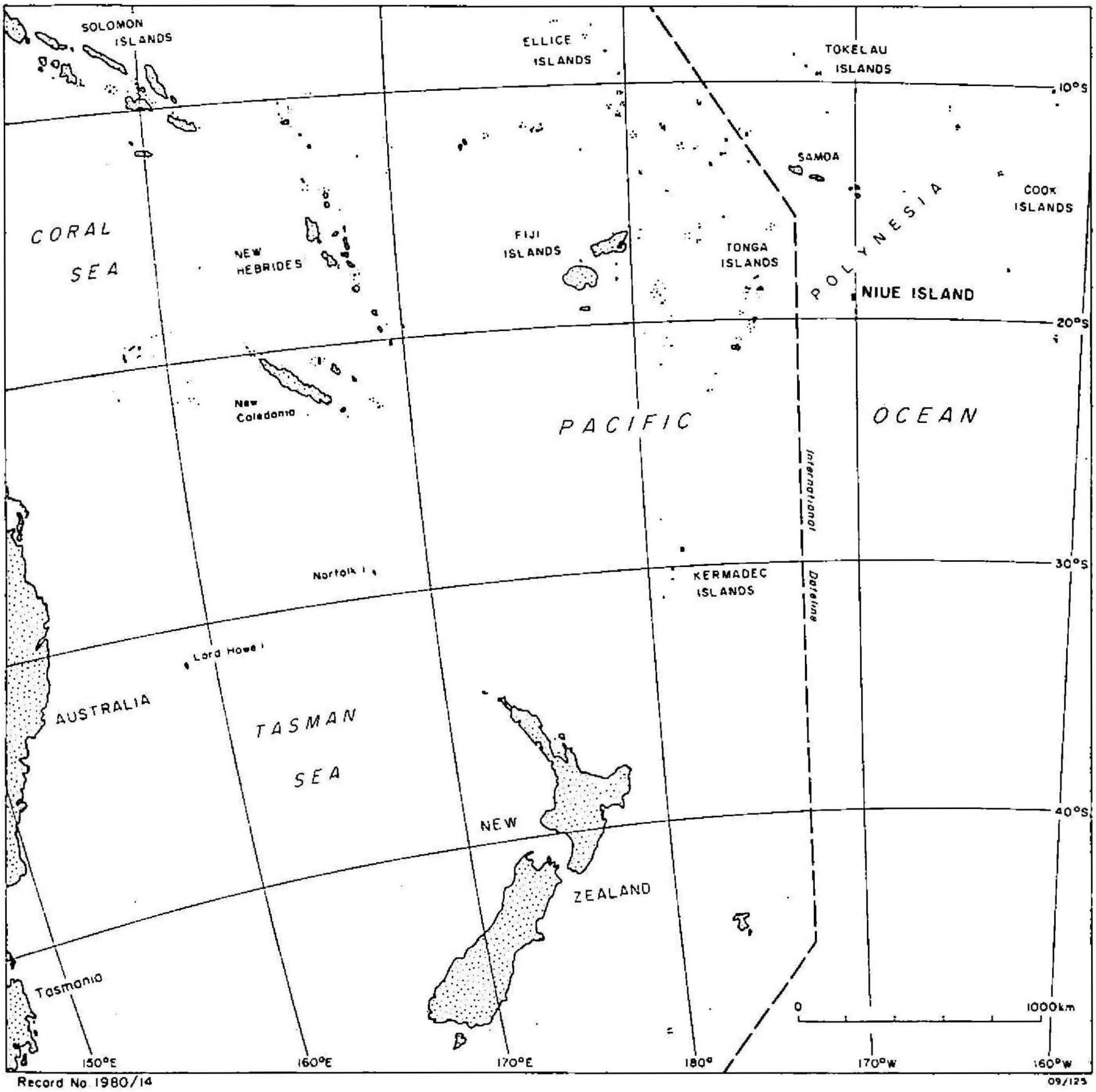

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Fig. 1. Location map

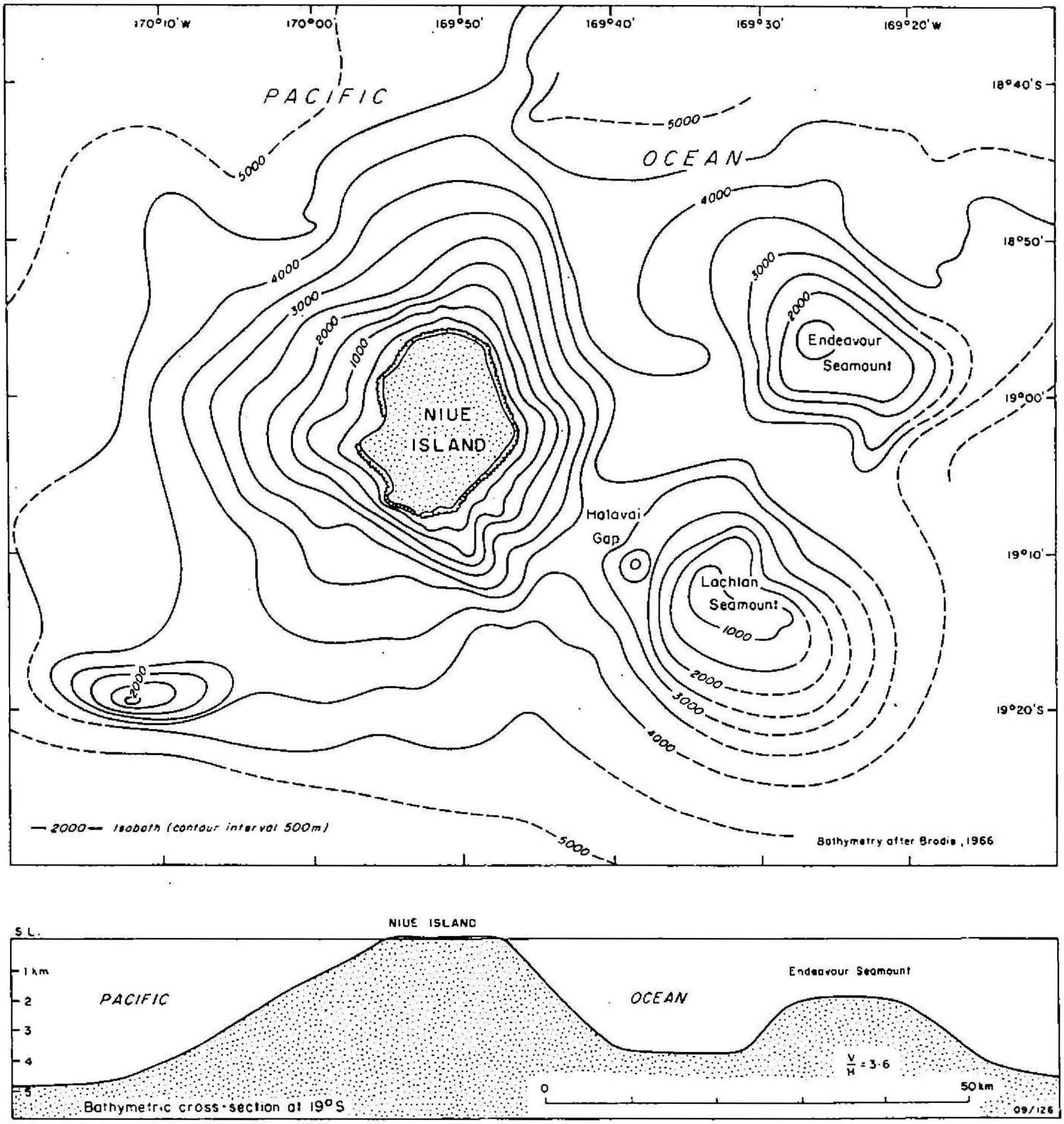

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Fig.2. Bathymetry

The help and co-operation of these people, and of other Niue residents who helped in many ways, is gratefully acknowledged.

GEOLOGY

Niue Island is a raised coral atoll which is underlain by a volcanic seamount that rises 4000 m from the floor of the Pacific Ocean (Fig. 2). The area of the island is about 259 km^2. Limestone and coral sand are exposed on the island; the volcanic substructure has been deduced from the bathymetry (Fig. 2) and the magnetic contours that indicate a caldera structure (Schofield, 1959). The gravity and magnetic surveys of the present investigation have confirmed the basal volcanic structure of the island (Hill, in prep.); preliminary results indicate that the volcanic rock is generally at a depth of about 300 m below sea level, and that a core of dense volcanic rock underlies the southwest of Niue (Fig. 3).

The coral limestone sequence has been proved to a depth of more than 200 m in mineral exploration drillholes (Fig. 4). The rock varies in texture from hard and dense to soft and chalky or sugary; the sequence includes beds of unconsolidated sand and of hard, recrystallised dolomite. The limestone is jointed and cavernous to great depths.

Palaeontological determinations on drill-core samples by G.C.H. Chaproniere of BMR (Table 1) indicate that most of the limestone sequence to a depth of 170 m below sea level is of middle to late Miocene age. Fossils from surface localities in the interior of Niue have previously been dated as Plio-Pleistocene (Schofield, 1959), but they may have been taken from a thin veneer of younger sediments.

Figure 5 shows the broad geomorphological elements of Niue. The original atoll topography is preserved. The flat-bottomed floor of the former Mutalau Lagoon (Schofield, 1959) is now an internal basin at an elevation of about 35 m. What was formerly a narrow atoll rim, the Mutalau Reef, is now a peripheral ridge around the island at an elevation of about 60 m. The former lagoon passage is now a dry valley to the south of Alofi at an elevation of about 42 m. A narrow terrace, the Alofi Terrace, is preserved at an elevation of about 25 m along most of the coast line. Younger coral terraces, 2-4 m above sea level, fringe parts of the east and south coast. A fringing coral reef about 100 m wide encircles the island at sea level (Fig. 6), and solution notches are developed at the base of the cliffs. The concentric photolineaments in the southwest of the island (Fig. 5) are probably strandlines of the former Mutalau Lagoon.

TABLE 1

AGES OF FOSSILS IN SAMPLES RECOVERED FROM DRILLHOLES

by G.C.H. Chaproniere

Drillhole	Sample depth (m)	Age
PB 1	4.00	middle Miocene to Recent
	7.95	Eocene to Recent
	9.90	middle Miocene to Recent
	12.40	middle to late Miocene
	14,05	Miocene
	16.15	middle to late Miocene
DH 4	42.70	Miocene to Recent
	48.00	middle Miocene to Recent
	54.00	early Miocene to Recent
	60.30	early Miocene to Recent
	75.10	middle to late Miocene
	82.00	Eocene to Recent
	102.00	early Miocene to Recent
	113.20	Miocene to Recent
	122.30	Miocene
	200.30	middle to late Miocene, probably middle Miocene
	212.10	middle Miocene to Recent
	220.25	middle Miocene to Recent
PB 2	4.25	middle Miocene to Recent
	9.95	not determinable
	17.00	Miocene
	26.80	Miocene to Recent
	36.00	Eocene to Recent
	46.90	early Miocene to Recent

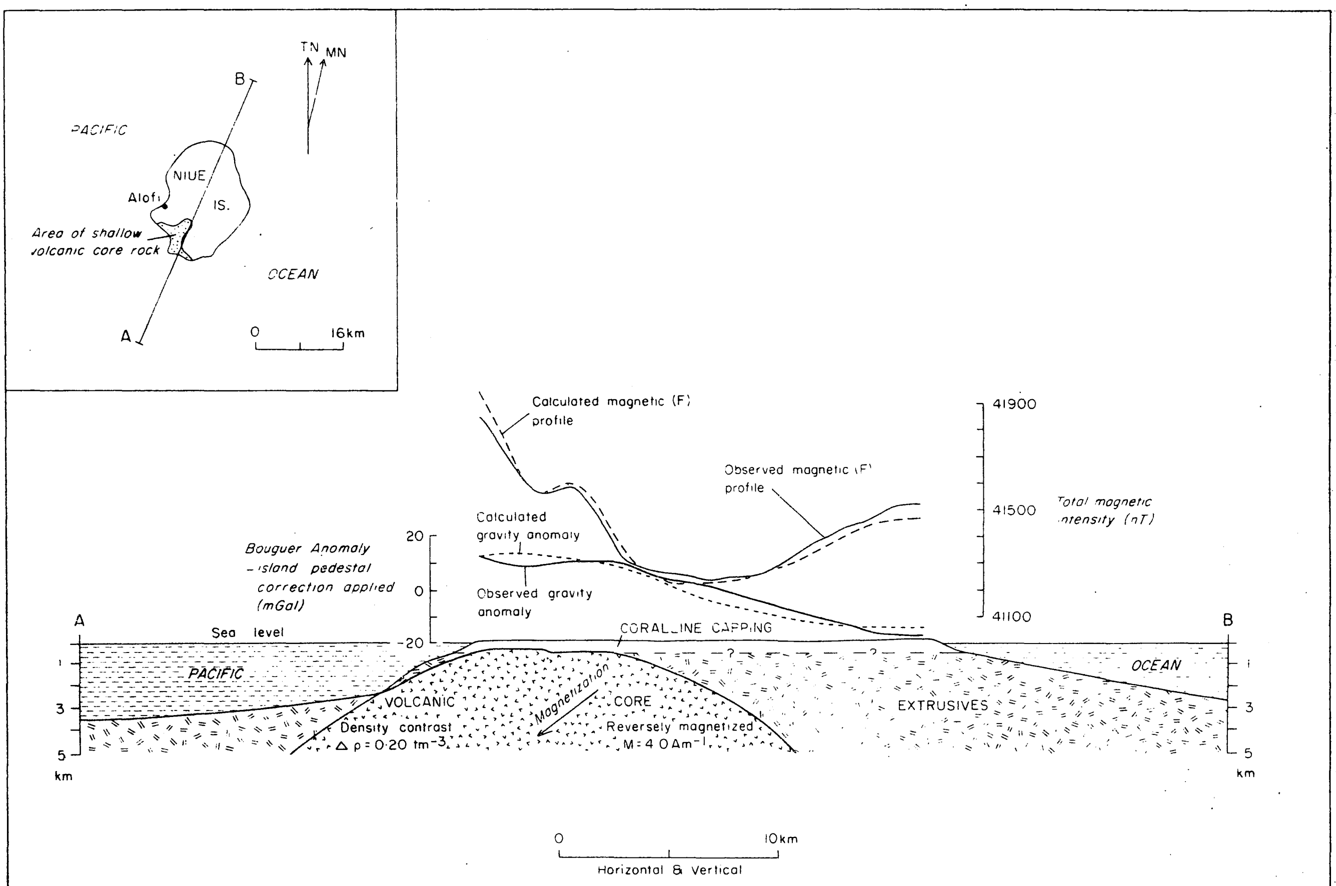

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Fig.3. Interpreted volcanic substructure of Niue Island

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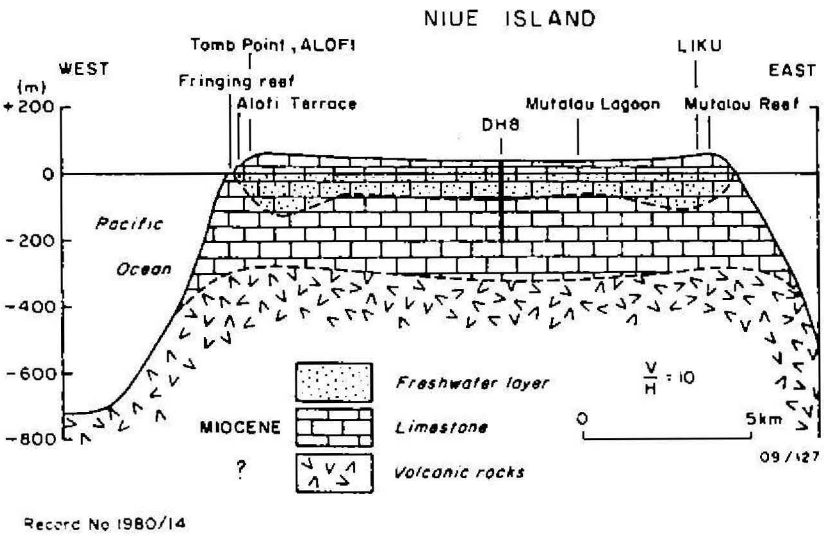

Fig. 4. Geological section through Tomb Point

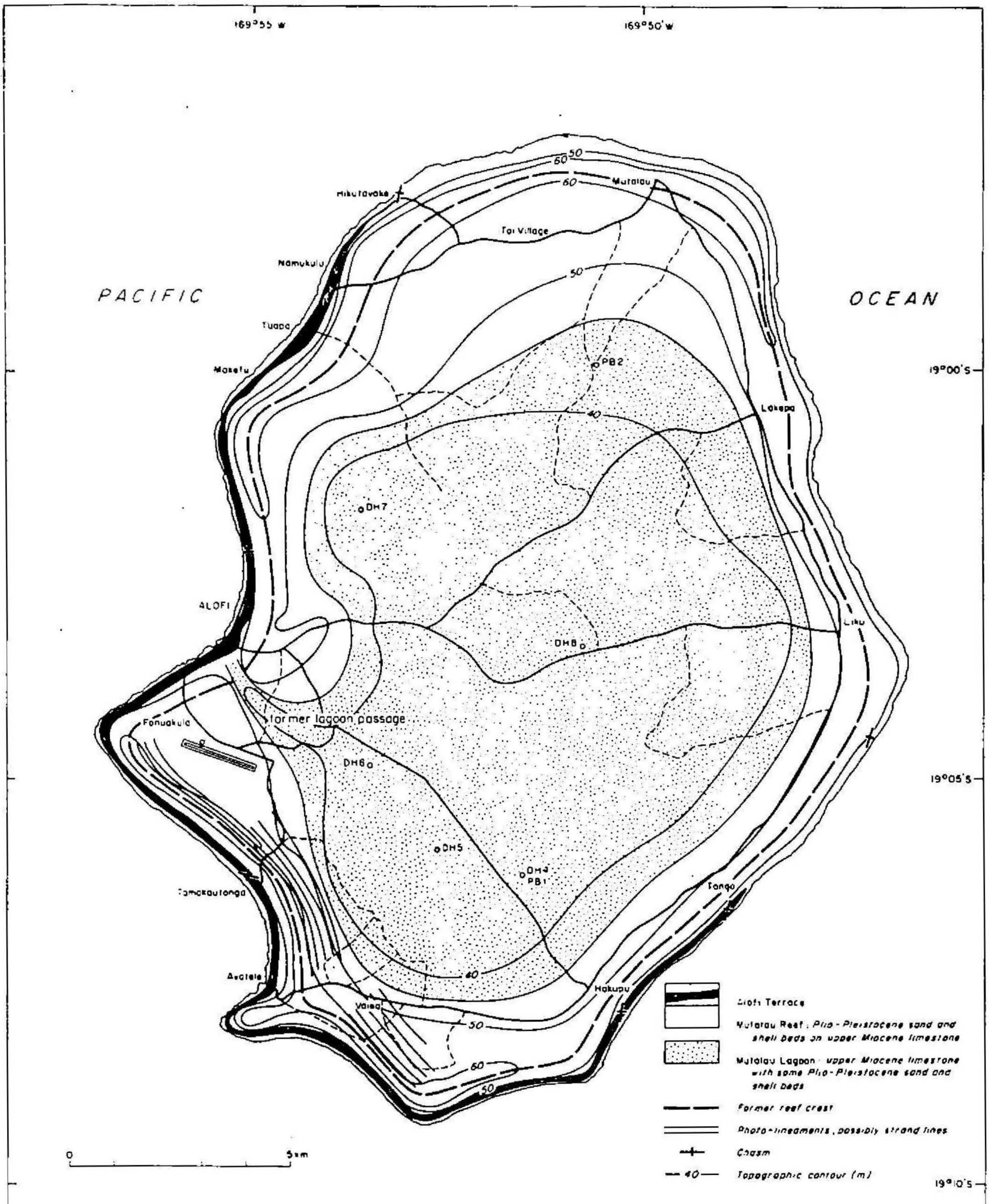

Fig. 5. Geomorphology

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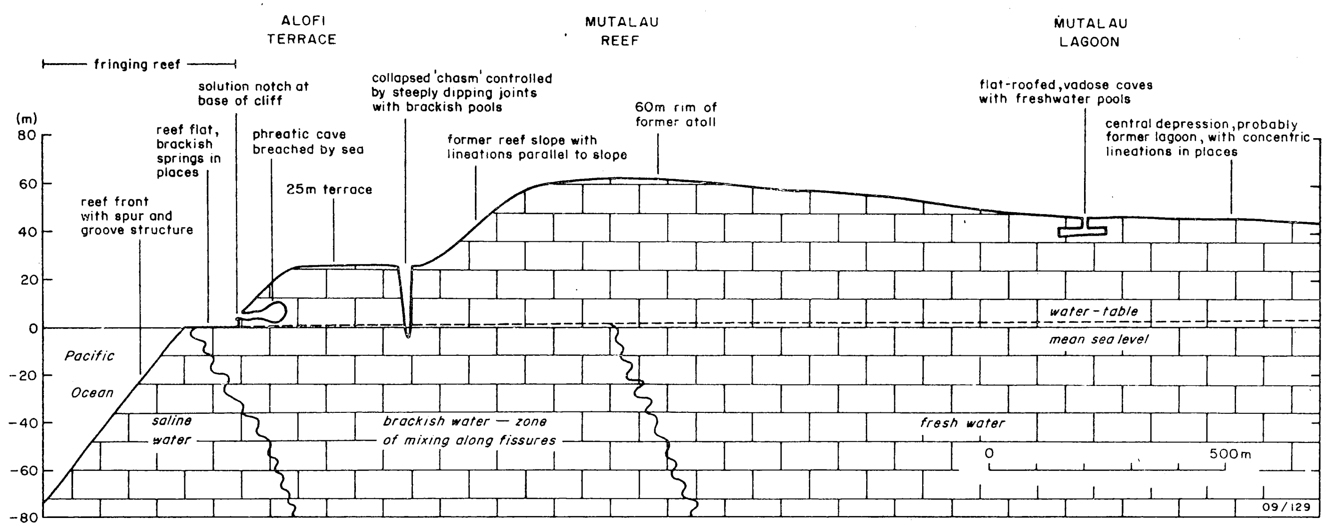

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Fig. 6. Cross-section showing geomorphological features, west coast of Niue Island

Caves of three types are commonly developed in the limestone (Fig. 6). Along the coast, marine erosion has exposed many caves close to or just above present sea level. These caves exhibit the rounded shapes and intricate solution features which indicate phreatic, below water-table, origin.

Chasms have developed subparallel to the coast on the inner side of the Alofi Terrace (Schofield, 1959). The chasms in some locations form interconnected systems up to 500 m long and 25 m deep; they have steep sided walls leading down to brackish pools which are part of the basal groundwater body. The pools have been used by the Niueans as a water source in times of drought.

In the interior basin of Niue, many small dolines give access to flat-roofed caves consisting of branching passages a few metres below ground level. These vadose caves commonly contain soil washed in through fissures, and freshwater pools are found in places on either a rock or a soil floor. Many of these caves were traditionally used by the Niueans for burial.

Soils on Niue have been mapped by Wright & van Westerndorp (1965). Soil covers only 52 percent of the surface of Niue, and is generally thin. Much of the soil is radioactive, containing ionium and radium-226. The origin of the radioactivity has been variously ascribed to volcanic ash fallout (Wright & van Westerndorp, 1965); radioactive elements trapped from sea water in the former lagoon (Fieldes & others, 1960); and hydrothermal emanation from the volcanic substructure (Schofield, 1967). The last hypothesis has been a main reason for the mineral exploration program currently being conducted on Niue by Avian Mining Pty Limited.

The main elements of the geological history of Niue are similar to those of the Cook Islands (Wood & Hay, 1970). Niue was probably a volcano undergoing erosion at the start of the Miocene, 24 million years ago. During the Miocene, 5-24 million years ago, the island subsided and a platform reef developed to a thickness of at least 300 m. Uplift during the Pliocene, 1.8-5 million years ago, led to some erosion of the reef limestone by solution. Changing sea levels during the Pleistocene led to further reef growth. Niue was an atoll consisting of the Matalau Reef surrounding the Mutalau Lagoon, probably about 400 000 years ago. Sea level subsequently fell and the lagoon was drained. Schofield & Nelson (1978) constructed a detailed history of the effects of sea-level changes and considered that the isolated central lagoon would have held a salt-water lake for some time. However, in view of the high infiltration rate under present conditions on Niue, it seems unlikely that a closed lagoon would have held water.

An overall fall of sea level relative to the land has probably continued to the present day, except during a stillstand - probably about 150 000-120 000 years ago - when the Alofi Terrace was formed. The raised coral terraces 2-4 m above sea level in the southeast of Niue possibly indicate relatively recent upward tilting of this part of the island.

HYDROLOGY

There is no surface runoff on Niue and the water balance is:

RAINFALL = EVAPOTRANSPIRATION + GROUNDWATER RECHARGE.

The annual rainfall recorded at Alofi has ranged from 1065 mm to 3185 mm; the mean is 2041 mm. Figure 7 shows the variations from the long-term mean. The worst recorded drought was 1940-44, when the annual rainfall was 23.6 percent below the mean for a 5-year period. In two other droughts, 1925-6 and 1976-7, the annual rainfall was more than 32 percent below the mean for a 2-year period.

The rainfall is seasonal; most rain falls between December and April (Fig. 8). The mean monthly rainfall ranges from 84 mm in June to 307 mm in March (Table 2).

Evapotranspiration is the sum of evaporation from soil and transpiration by plants. It may be considered as actual evapotranspiration, which is the real rate of water-vapour return to the atmosphere, or as potential evapotranspiration, which is the rate of water-vapour return under ideal conditions. No pan evaporation measurements are available for Niue, so evapotranspiration has been calculated by the climatological method of Thornthwaite (1948). Using Niue temperature data and allowing for latitude, potential evapotranspiration has been estimated as 1417 mm annually (Table 2). Monthly potential evapotranspiration ranges from 83 mm in July to 153 mm in January.

Figure 8 shows that there is a water surplus for 11 months of the year when rainfall is greater than potential evapotranspiration, and a water deficit for one month. If the water deficit of 9 mm in June is assumed to be made up by soil moisture recharge in July, then the soil moisture budget balances (Table 2), and actual evaporation equals potential evapotranspiration.

Monthly groundwater recharge has been calculated by subtracting potential evapotranspiration from the mean monthly rainfall (Table 2). Recharge is estimated as 624 mm annually, of which 85 percent is available between December and April.

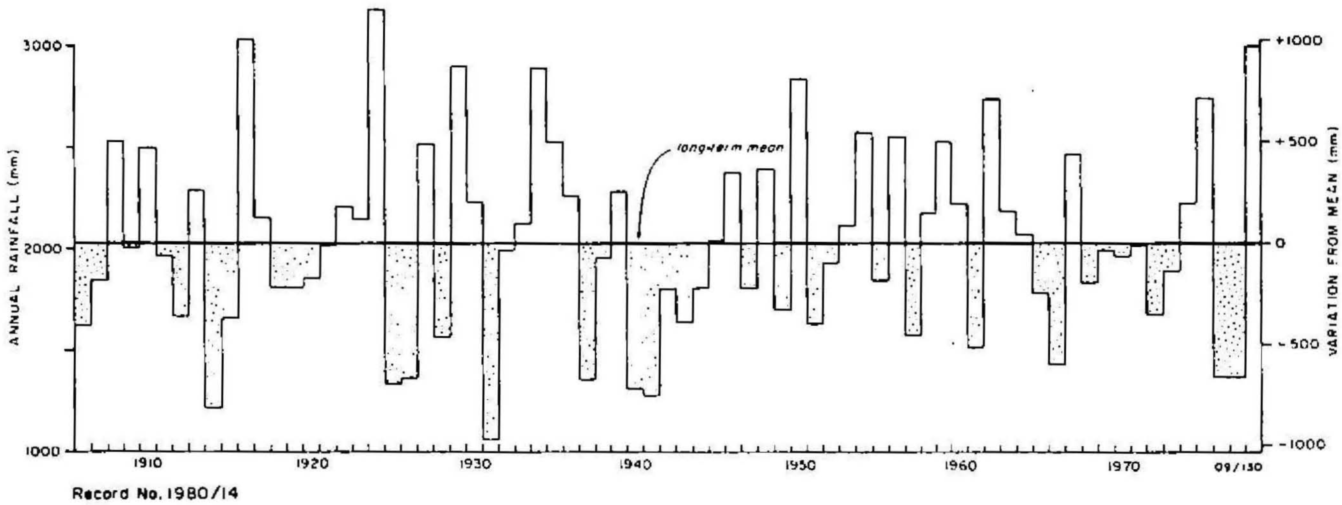

Fig. 7. Rainfall variation from mean, 1906-78

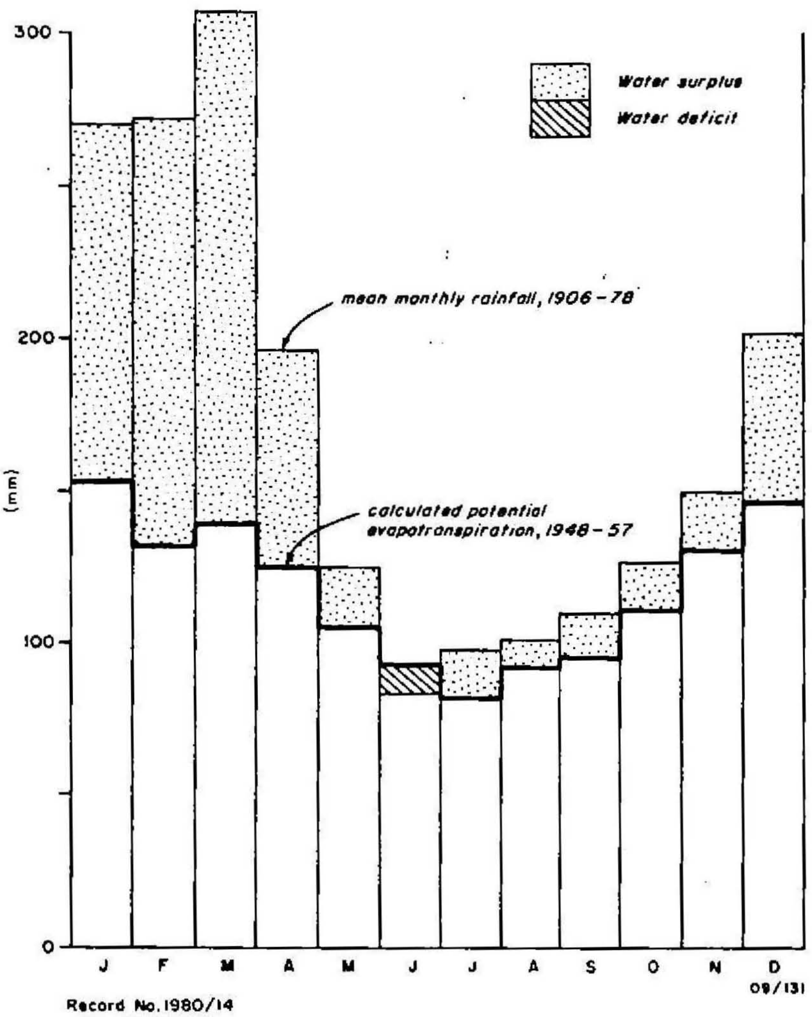

Fig. 8. Monthly rainfall and evapotranspiration
(Potential evapotranspiration calculated by method of Thornthwaite, 1948)

TABLE 2

MONTHLY WATER BALANCE

	Mean monthly temperature* °C	Potential evapo-transpiration mm	Soil moisture balance mm	Ground-water recharge mm	Mean monthly rainfall mm
January	26.3	153		117	270
February	26.2	132		139	271
March	26.2	139		168	307
April	25.8	125		71	196
May	24.6	106		19	125
June	24.0	93	-9	0	84
July	22.9	83	+9	6	98
August	23.3	92		9	101
September	23.6	96		14	110
October	24.6	119		8	127
November	25.2	131		19	150
December	25.8	148		54	202
		1417	0	624	2041

* Mean monthly temperature, 1948-57, from Wright & van Westerndorp (1965).

Recharge to the basal groundwater body takes place through a zone of porous and fissured limestone 30-60 m deep - the vadose zone. The porosity of the limestone is variable, but tests on drill core indicate that it averages 22 percent (Table 3). Permeability tests on drill core indicate a horizontal permeability of 732 millidarcy, equivalent to about 0.6 m/day, and a vertical permeability of 233 millidarcy, equivalent to about 0.2 m/day. Very rapid infiltration can be observed everywhere on Niue; after prolonged heavy rainfall the ground is dry in a few minutes. It is likely that groundwater recharge in the vadose zone takes place mainly along vertical fissures and solution channels. Beneath the water-table, groundwater movement is probably by a combination of intergranular and fissure flow.

TABLE 3

POROSITY, PERMEABILITY, AND DENSITY OF CORES

Drillhole	Sample depth (m)	Average effective porosity of two plugs (% bulk volume)	Absolute permeability (millidarcy)		Average density (g/cm^3)	
			V	H	Dry bulk	Apparent grain
PB 1	9.70	18.4	730	1023	2.16	2.66
	16.80	23.9	656	750	2.09	2.74
	28.40	21.2	1	1978	2.01	2.55
	39.50	33.4	34	808	1.81	2.73
PB 2	4.30	19.6	84	626	2.22	2.76
	12.40	15.3	551	1469	2.20	2.60
	17.90	13.5	0	10	2.20	2.54
	26.40	14.6	414	2303	2.11	2.47
	29.40	33.5	127	92	1.84	2.76
	35.70	30.9	617	793	1.85	2.67
	36.70	19.3	2	11	2.15	2.67
	42.40	30.3	3	3	1.88	2.71
	45.50	21.6	1	0.1	2.15	2.74
DH 4	33.60	14.6	0	192	2.32	2.72
	35.60	2.9	0	0.5	2.67	2.74
	75.40	42.0	502	1617	1.59	2.73
Mean of 16 samples		22.2	233	732	2.08	2.67

Determinations by BMR Petroleum Technology Laboratory, Canberra

EXISTING WATER SUPPLY

The existing water supply consists of rainwater tanks, one dug well, and 45 operating bores spread around the rim of the island. The bores are 70(mm diameter and are uncased. They are equipped with low-yielding electric or diesel pumps, or windmills, which deliver 600-800 l/hour. The bores supply the town of Alofi, the villages, and agricultural development projects. Details of existing bores are given in Appendix 1, and their locations are shown in Figure 9, in which the bore numbers are arbitrary. The bores have been constructed at various times since 1964 (Schofield, 1968), before which the island's water supply came from the dug well at Fonuakula, rainwater catchments, and cave pools.

The Alofi town water supply is at present derived from the dug well and seven bores, but is felt to be inadequate; the Niue government proposes to improve it by extending the borefield. In addition there is a possibility of introducing agricultural irrigation for passionfruit and lime plantations if high-yielding bores can be developed.

Six bores that are listed in Appendix 1 have been abandoned; three on the Alofi Terrace were abandoned because of high salinity, and two village bores were abandoned because of bacteriological contamination.

Bores supplying domestic water are regularly monitored by the Department of Health for chloride and bacteria content. The freshwater supply system developed since 1964 is generally safe from pollution; the modest pump yields ensure no upconing of salt water, and the bores are generally sited well away from possible sources of contamination.

RESISTIVITY SURVEY

Evaluation of the groundwater resources of Niue in terms of the quantity and distribution of freshwater has been based on a determination of the thickness of the freshwater layer mapped by resistivity depth probing techniques, which are applicable because of the contrast in electrical resistivity between the overlying dry coralline limestone and the underlying freshwater and salt-water saturated rock.

Electric current may be propagated in rocks and minerals by electronic, electrolytic, and dielectric conduction. The greatest contribution to the current flow comes from electrolytic conduction. This is because the rock matrix is, in the vast majority of cases, highly resistive, and also the low frequencies usually employed in electrical prospecting preclude significant

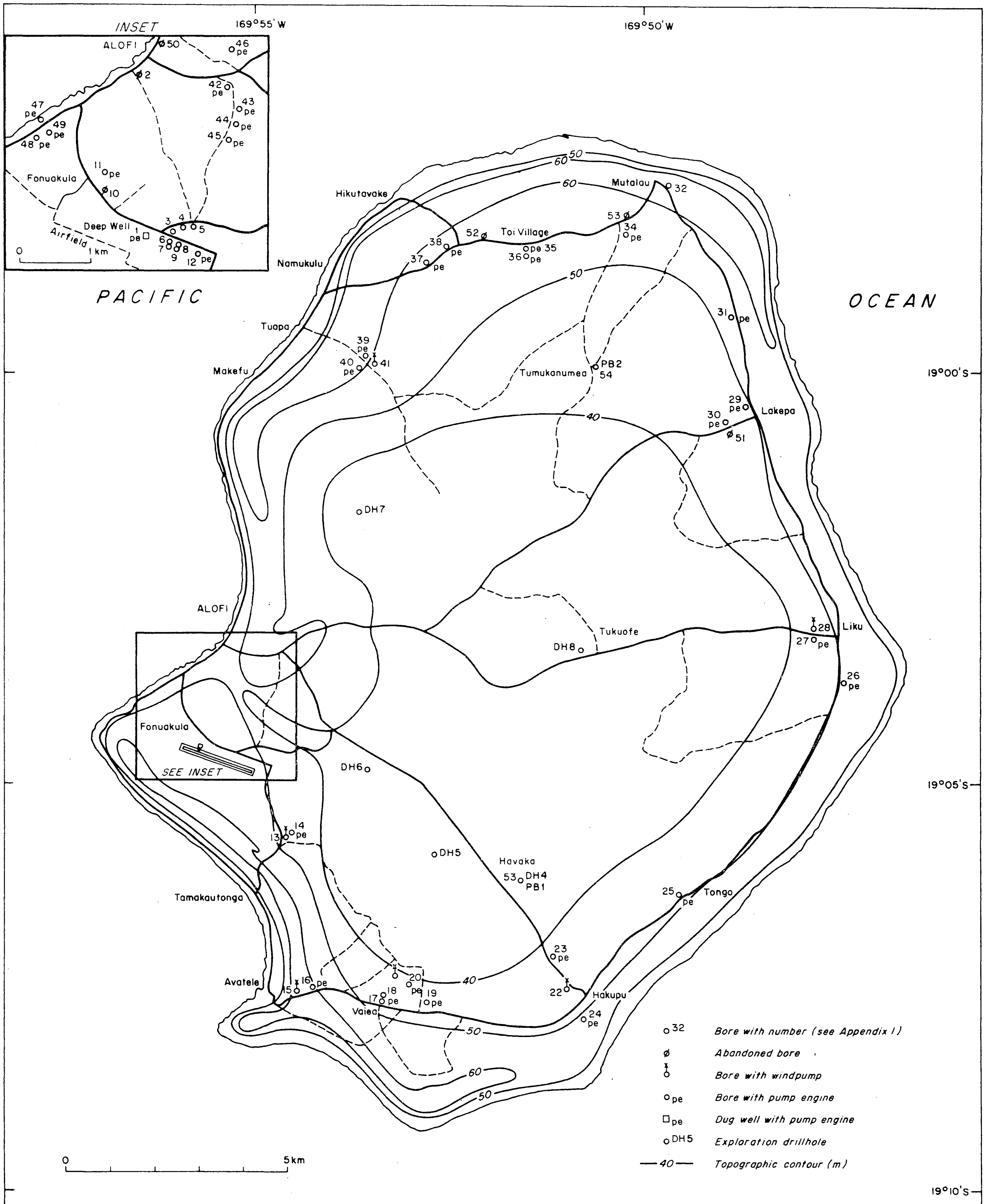

Fig. 9. Water-bore locations

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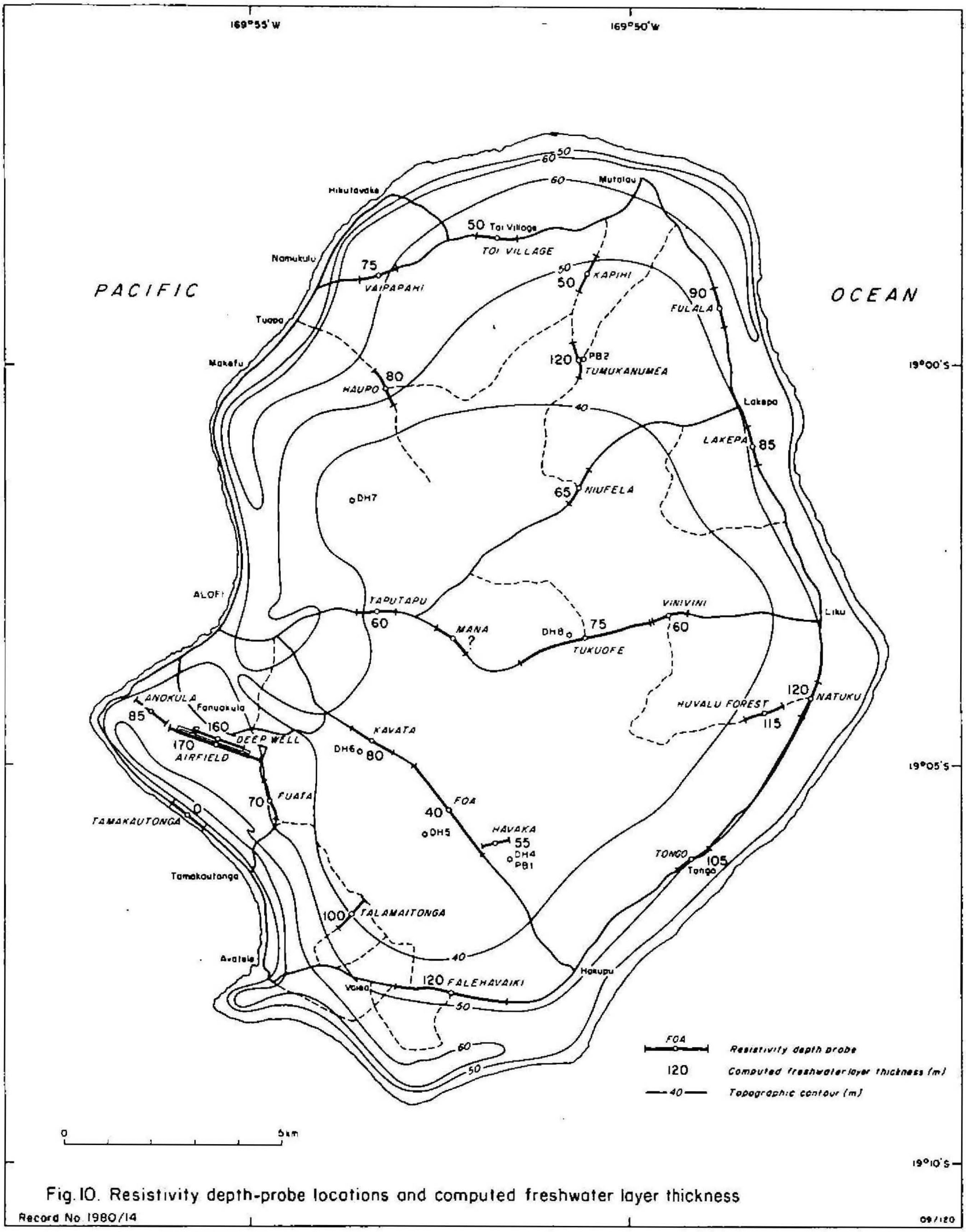

Fig. 10. Resistivity depth-probe locations and computed freshwater layer thickness

dielectric current flow. The bulk resistivity of a rock depends primarily on the properties of the interstitial electrolyte such as the amount, conductivity or salinity, and distribution relative to the pore/matrix internal structure.

Generally, four-electrode arrays are used for resistivity depth probing. Current is driven through one pair of electrodes; the potential established in the earth of this current is measured with the second pair of electrodes. From the variation of apparent resistivity with array dimension, it is possible to deduce rock resistivities as a function of depth. The vertical resistivity profile can then be interpreted in hydrogeological terms.

FIELD INVESTIGATION

For the Niue investigation a 'Yew' hand-driven AC generator was used for Wenner probes. This instrument has a scale of 30 ohms and ranges X0.01, X0.1, X1, and X10. The current source for Schlumberger probes was a bank of 13 heavy-duty 12V dry-cell batteries which provided about 160V when in series. To conserve power, a switching arrangement was used to reduce the voltage, and therefore the current, for small electrode spacings.

Current and potentials were measured by 'Data Precision' digital multimeters, which are capable of measuring up to 2A (current) and down to 0.1 mV (potential). Non-polarising electrodes, consisting of porous pots containing saturated copper sulphate solution, were used for the potential contacts to eliminate time-varying electrochemical potentials.

The depth-probe sites were distributed over the island so as to give as complete a coverage as possible (Fig. 10). A total of 21 Wenner and four deep Schlumberger sounding were made. The Wenner arrays were expanded from an electrode separation of 1.0 m out to a maximum ranging from 292 to 400 m at the various sites. The ratio of expansion was about 1.20, so that the electrode separation was 1.0 m, 1.2 m, 1.4m, 1.7 m, 2.0 m, etc. A similar ratio of expansion (about 1.25) was chosen for the current electrodes of the Schlumberger arrays, but these were expanded out to 1100-1600 m for the half-current electrode separations (AB/2, where AB is the current electrode spacing). The Schlumberger soundings were commenced with AB/2 = 2.5 m.

Most of the work was done along roads and tracks because dense tropical bush or jagged limestone terrain covers most of the island. With a team of five local assistants provided by the Department of Public Works, a full working day was required for each of the deep soundings, for which cable spreads up to 3200 m long were needed. On the other hand, three of the shorter Wenner probes on average were completed per day.

Sea water was poured around electrodes so as to reduce the contact resistance. For large AB/2 values of the Schlumberger soundings it was essential to get maximum current into the ground so that the potentials could be read with reasonable precision. Multiple electrodes (up to six or seven) were used at the current electrode positions. Though adequate, it was never possible to drive more than about 400 mA into the ground.

LABORATORY MEASUREMENTS

Seven representative sections of core taken from drillholes PB 1, PB 2, and DH4 at or below the water-table were selected for tests of resistivity and porosity. The 3.6-cm diameter samples in Figure 11 illustrate the variations in texture.

The resistivity of each sample was determined while saturated with saline (NaCl) water of about 24 ohm-m resistivity; this was followed, after flushing and drying, by a second measurement using an 8.62 ohm-m salt solution. Niue groundwater typically has a conductivity of 400 microsiemens/cm (μS/cm)* which is equivalent to 25 ohm-m resistivity. Thus the first set of measured resistivity values should indicate values to be expected for the freshwater aquifer (Table 4).

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* The unit of conductivity used in this report is microsiemens/cm (μS/cm). Ten microsiemens/cm is equivalent to one millisiemen/metre.

TABLE 4

POROSITY AND RESISTIVITY MEASUREMENTS ON DRILL-CORE SAMPLES

SAMPLE NO.	DRILL-HOLE	DEPTH (m)	POROSITY (%)	RESISTIVITY OF SATURATED ROCK (Ro) FOR DIFFERENT WATER RESISTIVITIES (Rw)		FORMATION FACTOR
				Rw(ohm-m)	Ro(ohm-m)	
1	PB 1	32.30-32.55	27.0	23.8	1100	46.2
				8.62	302	35.0
2	"	36.99-37.20	34.2	23.8	724	30.4
				8.62	225	26.1
3	"	39.65-39.85	31.8	23.8	2140	90.1
				8.62	731	84.8
4	PB 2	38.70-38.90	14.8	23.8	4790	201
				8.62	1860	215
5	"	45.90-46.25	29.3	23.8	1560	65.7
				8.62	462	53.6
6	"	46.25-46.45	28.0	23.8	2780	117
				8.62	854	99
7	DH4	75.40	44.0	23.3	94.5	4.1
				8.62	36.6	4.4

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Fig. 11. Typical core sections from the aquifer tested for resistivity and porosity (see text)

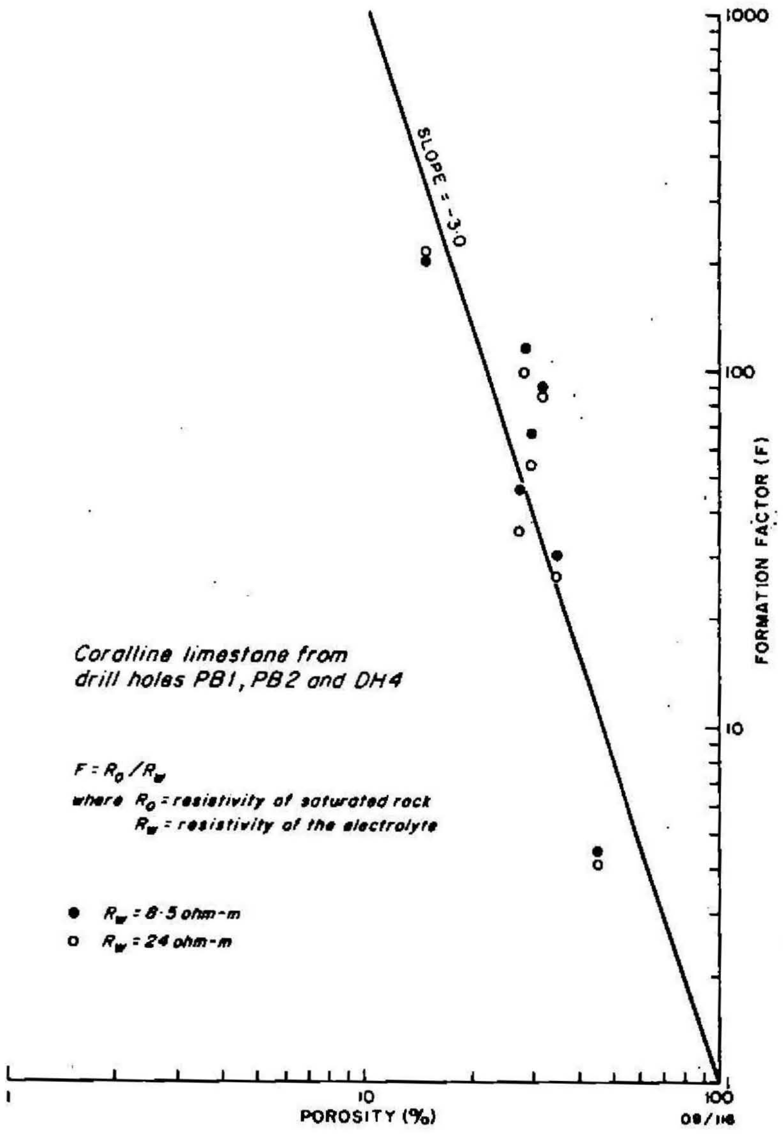

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Fig.12. Formation factor as a function of porosity
(laboratory measurements)

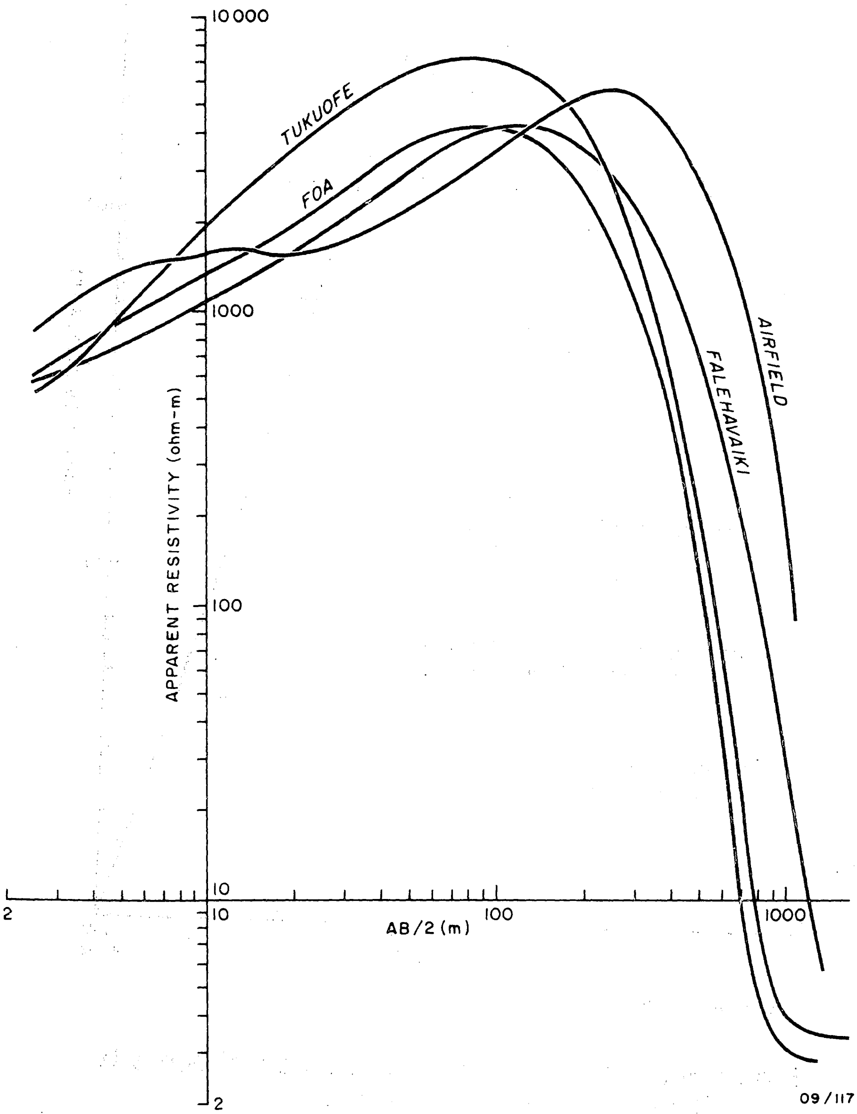

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Fig. 13. Schlumberger resistivity depth-probe curves

In fact the tests show a range of values from about 95 to about 4800 ohm-m, and the average aquifer resistivity is about 1900 ohm-m. These values are compatible with the findings of Dolan & others (1975) at Kavieng, Papua New Guinea, where freshwater saturated coral limestone gave resistivity values ranging from 20 to 6000 ohm-m and the water resistivity was inferred to range from 12 to 100 ohm-m.

According to the empirical formula of Archie (1942), the formation factor, F, for saturated rock is given by

$$F = R_o/R_w = p^{-m}$$

where R_o = resistivity of saturated rock,
R_w = resistivity of the electrolyte,
P = porosity,
and m = cementation factor (constant).

The logarithmic plot of the laboratory measurements (Fig. 12) shows that Archie's relation holds approximately for the Niue coralline limestone, for which m = - 3.0. Therefore, where the aquifer resistivity and the resistivity of the water at a particular location are known, an aproximate value for the porosity can be derived from this graph.

DEPTH PROBE RESULTS AND INTERPRETATION

The Schlumberger apparent resistivity curves for Tukuofe, Foa, Falehavaiki, and the airfield are shown in Figure 13. The Wenner curves are shown in Figure 14 (Deep Well, Anokula, Fuata, Tamakautonga, Kavata, Talamaitonga, and Havaka) and Figure 15 (Tongo, Taputapu, Mana, Vinivini, Huvalu Forest, Natuku, Niufela, Lakepa, Tumukanumea, Haupo, Vaipapahi, Toi Village, Kapihi, and Fulala).

Some of the field curves were smoothed to remove obvious distortions, particularly those due to heterogeneities in the surficial zone. The original field data are held by the Bureau of Mineral Resources and will be made available to the Niue government on request.

Apart from minor variations all the sounding curves show a similar pattern. With increased electrode spacing, apparent resistivity increases to a maximum at an electrode spacing of about 100 m. Further increase in electrode spacing leads to a gradual, then a rapid, decrease in apparent resistivity. This pattern is consistent with the variation of resistivity expected with depth, based on drilling results and water-table measurements, which is:

Layer	Thickness	Description	Expected resistivity
1 (top)	0-2 m	Soil	Low resistivity
2	20-65 m	Unsaturated coralline limestone/dolomite	High resistivity
3	0-100 m	Freshwater-saturated limestone/dolomite	Moderate resistivity
4	?	Salt-water saturated rock	Very low resistivity
5 (bottom)	3 km?	Volcanic complex at unknown depth	Very low to moderate resistivity

Interpretation of the sounding curves is limited in accuracy for several reasons:

1) Local variations in the thickness, and probably also the resistivity, of the low-resistivity soil layer are a source of noise and distortion on the curves.
2) The extremely high resistivity contrasts encountered often mean that asymptotic approaches by the curve are disrupted, thereby preventing precise resistivity determinations.
3) The principle of suppression applies to the freshwater layer since it is bounded by layers of higher and lower resistivities.

Extra control is needed if the geoelectric section, particularly the freshwater layer, is to be adequately defined. Two assumptions were made: (a) that the water-table lies about 1 m above mean sea level in the interior of the island; and (b) that the freshwater is underlain by a zone of diffusion, about 30 m thick, in which the water is half as saline as sea-water - e.g., has a resistivity of 0.4 ohm-m. This means that the layer beneath the freshwater layer is about 60 times more conductive, since the freshwater resistivity is about 25 ohm-m.

With the additional assumptions of horizontal stratification and isotropic layers, solutions to the sounding curves were obtained by Cyber 76 computer using a resistivity inversion program written by D.L.B. Jupp of Macquarie University. Interpreted resistivities and thicknesses for all the depth-probe locations, and the inferred thicknesses of the freshwater layer, are shown in Appendix 2. The estimates of the layer thickness are considered to be accurate to within about 20 m.

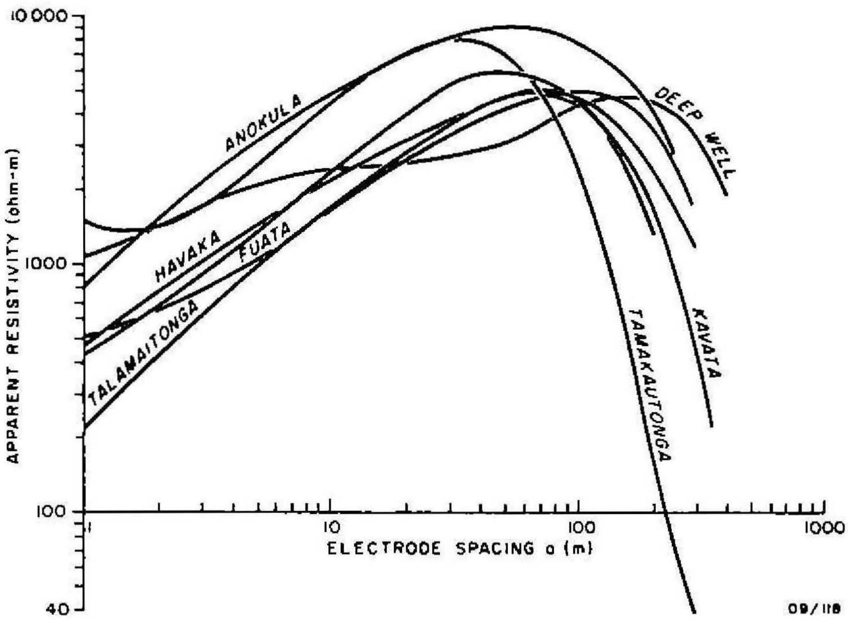

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Fig. 14. Wenner resistivity depth-probe curves

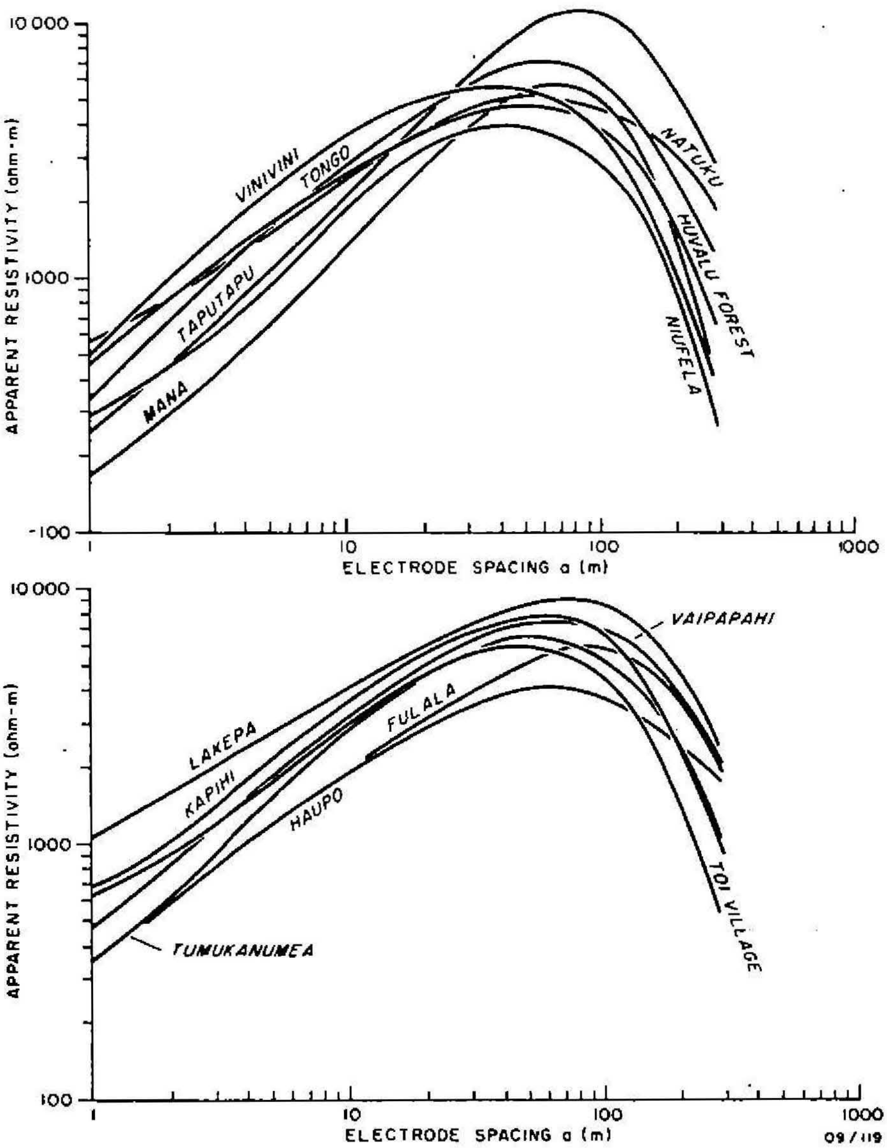

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Fig.15. Wenner resistivity depth-probe curves

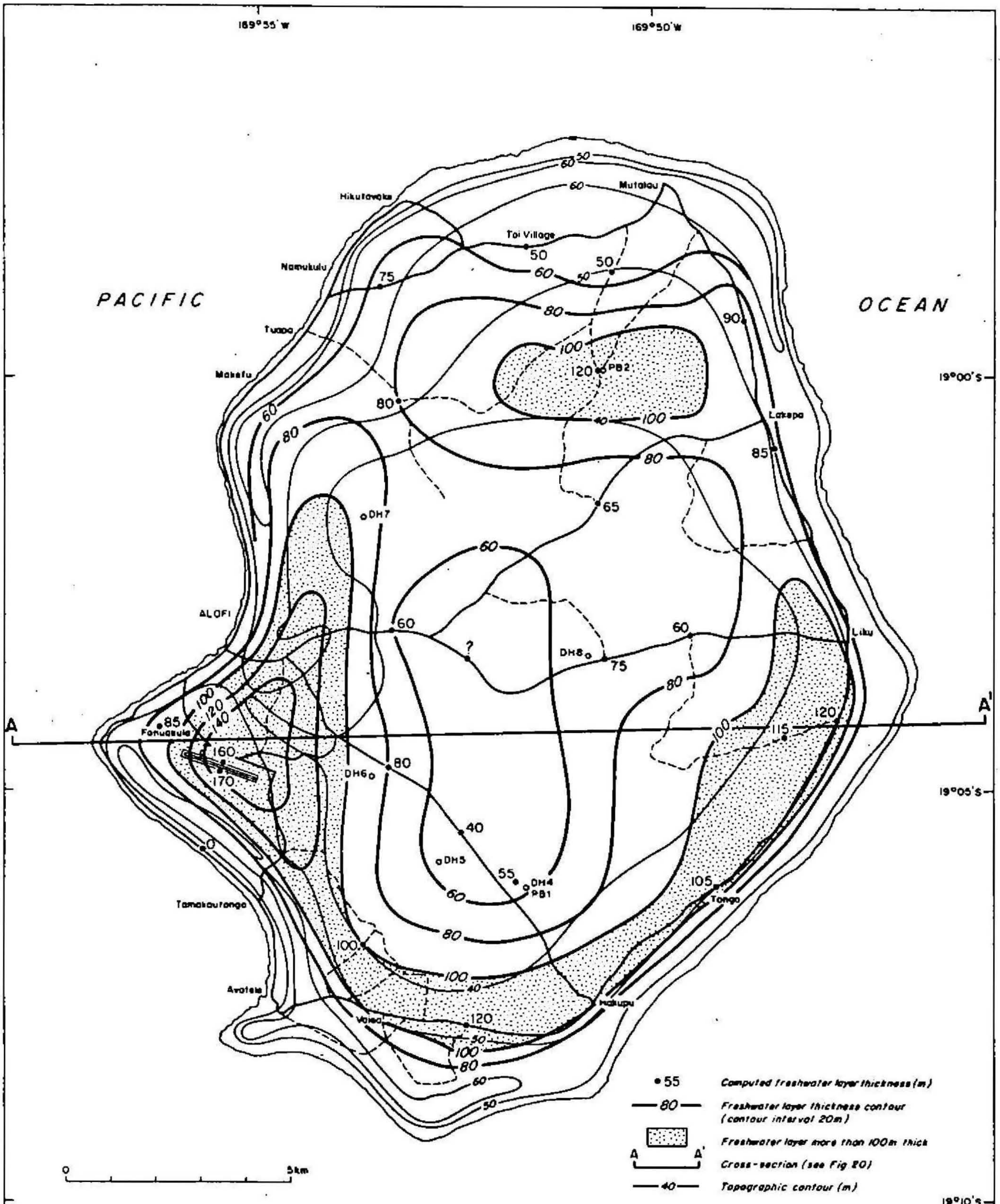

Fig. 16. Thickness of the freshwater layer inferred from resistivity data

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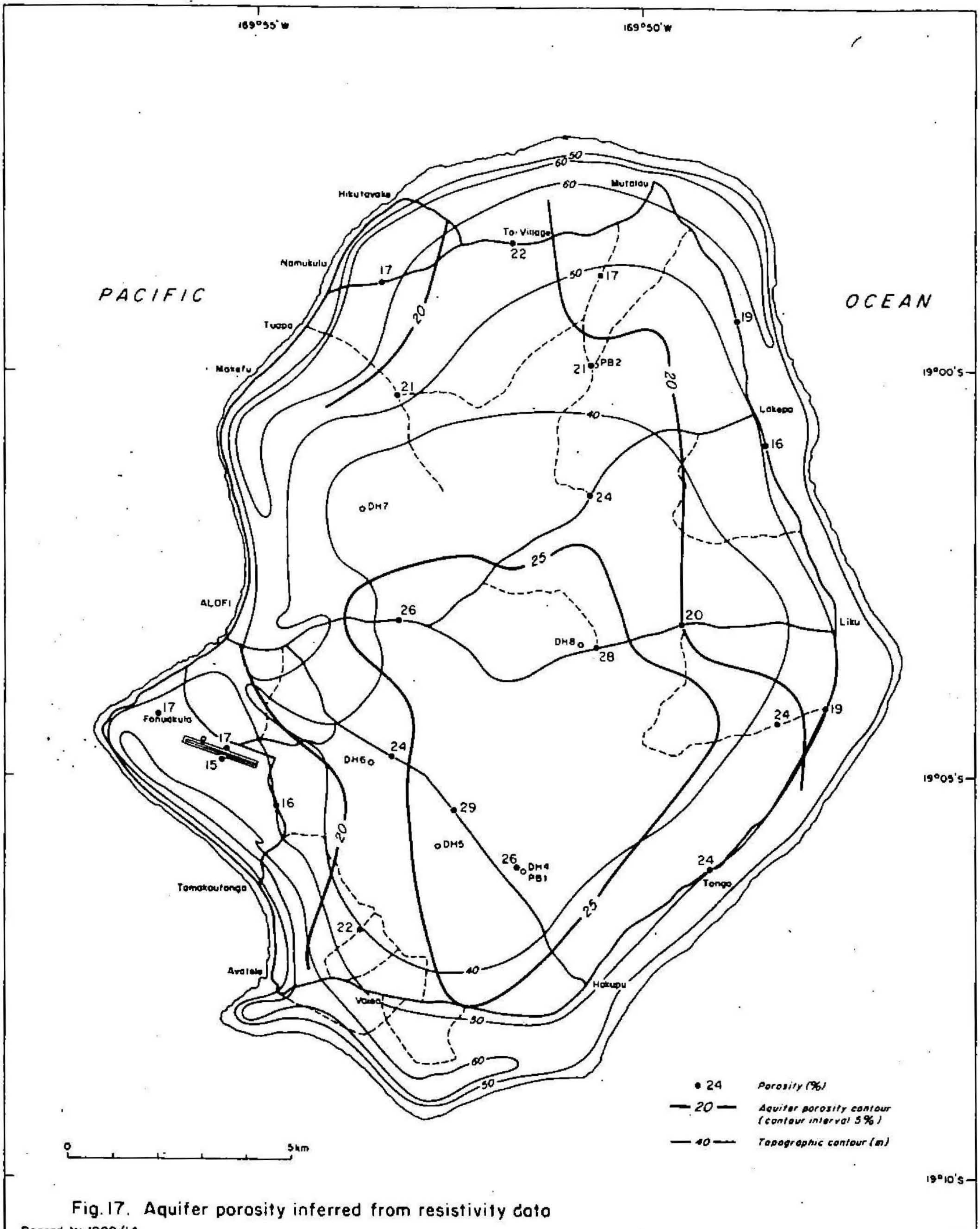

Fig. 17. Aquifer porosity inferred from resistivity data

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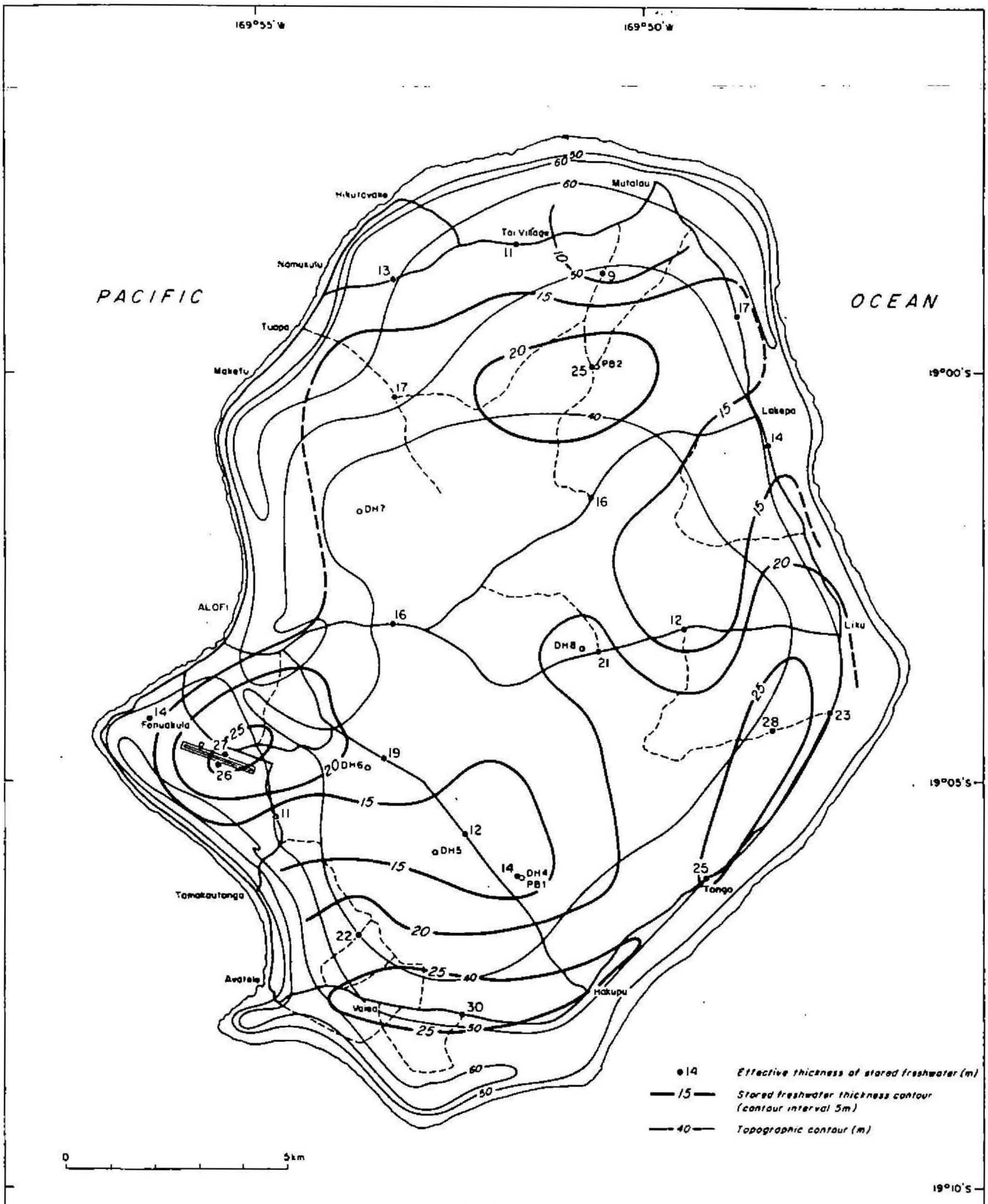

Fig.18. Freshwater storage inferred from resistivity data

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Figure 16 shows contoured thicknesses of the freshwater layer.

FRESHWATER STORAGE

From the freshwater layer resistivity values, and if an average resistivity of 25 ohm-m (460µS/cm conductivity) is assumed for the water, the relation in Figure 12 can be used to deduce an approximate porosity for the aquifer, and therefore freshwater storage in terms of effective water thickness. This has been done for all the depth-probe locations (Table 5).

Aquifer porosity inferred from the resistivity data is shown in Figure 17; porosity is greatest - more than 25 percent - in the central and southern interior of Niue. Freshwater storage in terms of effective water thickness is shown in Figure 18; storage is greatest - more than 25 m - beneath parts of the rim of the island, and has a mean value of 17.6 m. Multiplying this by the area of island (259 km^2) leads to the conclusion that the freshwater layer contains about 4.6 km^3 of water.

TABLE 5 FRESHWATER LAYER PARAMETERS

DEPTH PROBE	FRESHWATER LAYER THICKNESS (m)	FRESHWATER LAYER RESISTIVITY (ohm-m)	INFERRED POROSITY (%)	STORAGE (m)
Tukuofe	75	1200	28	21
Foa	40	1100	29	12
Falehavaiki	120	1600	25	30
Airfield	170	7500	15	26
Deepwell	160	5500	17	27
Anokula	85	5500	17	14
Fuata	70	6400	16	11
Tamakautonga	0	-	-	0
Kavata	80	1800	24	19
Talamaitonga	100	2500	22	22
Havaka	55	1500	26	14
Tongo	105	2000	24	25
Taputapu	60	1500	26	16
Mana	?	-	-	-

TABLE 5 FRESHWATER LAYER PARAMETERS (continued)

DEPTH PROBE	FRESHWATER LAYER THICKNESS (m)	RESISTIVITY (ohm-m)	INFERRED POROSITY (%)	STORAGE (m)
Vinivini	60	3500	20	12
Huvalu Forest	115	2000	24	28
Natuku	120	3600	19	23
Niufela	65	1900	24	16
Lakepa	85	7000	16	14
Tumukanumea	120	2700	21	25
Haupo	80	2700	21	17
Vaipapahi	75	5000	17	13
Toi Village	50	2600	22	11
Kapihi	50	5000	17	9
Fulala	90	4000	19	17

THE FRESHWATER AQUIFER

Perched freshwater aquifers occur in the vadose zone in the form of cave pools. The basal freshwater aquifer extends throughout the island and is unconfined, its top surface being the water-table.

AQUIFER CONFIGURATION AND GROUNDWATER FLOW

Levelling of the water-table with respect to mean sea level has been undertaken in those bores which were accessible (Appendix 1). Mean sea level on Niue was determined by New Zealand naval hydrographers in 1955, and is related to a steel pin on the Alofi wharf. A tide gauge was set up on the wharf during the present investigation, and it was found that mean tide level on 13 April 1979 was 0.55 m above the mean sea-level datum (Fig. 21).

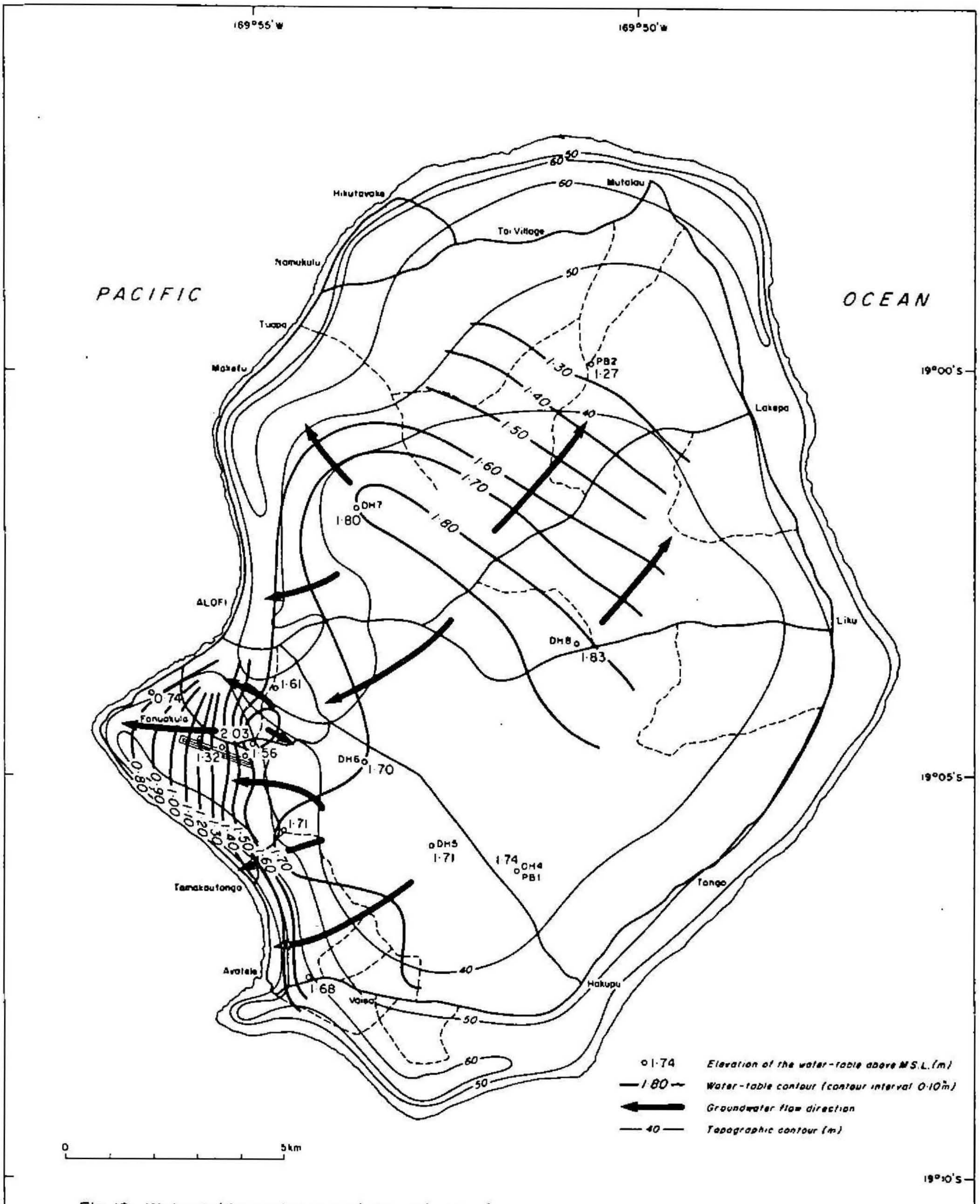

Fig. 19. Water-table contours and groundwater flow

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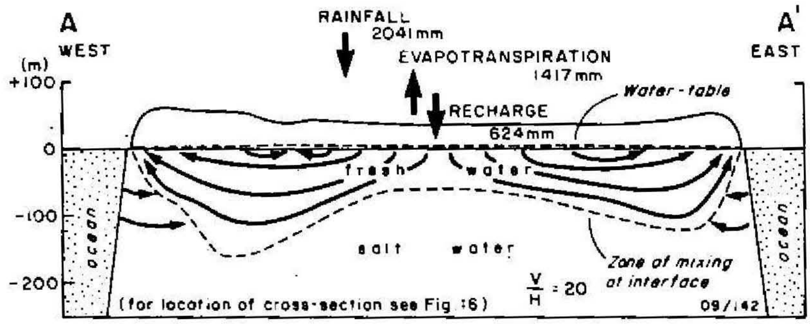

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Fig. 20. The freshwater layer. Diagrammatic cross-section showing groundwater flow

Contoured water-table elevations (Fig. 19) show that the top surface of the aquifer in the centre of Niue is at a maximum 1.83 m above mean sea-level datum. Groundwater flow is inferred to be radially outwards from the centre of the island, although there is some indication of local reversals of this trend. Thus the water-table in bore 5, near the airport, was about 2.03 m above mean sea-level datum when measured on 13 April 1979 (Fig. 19). The groundwater flow system is shown diagrammatically in Figure 20.

The thickness of the basal freshwater layer as determined by resistivity depth probes is between 50 and 80 m in the centre of Niue, between 100 and 150 m beneath the former atoll rim, and 0 at the coast (Fig. 16). Thus the freshwater aquifer is roughly doughnut-shaped (Fig. 20), unlike the classical freshwater lens of small oceanic islands.

According to the Ghyben-Herzberg equation for a typical freshwater lens on a small oceanic island, the depth of the salt-water interface is given by

$$h_s = \frac{\rho_f}{\rho_s - \rho_f} h_f$$

where h_s is the depth of the salt-water interface below sea level, h_f is the height of the water-table above sea level, ρ_s is the salt-water density, and ρ_f is the freshwater density (Herzberg, 1901). Density measurements on Niue waters show that the salt-water density is 1.0233 g/cm^3 and the freshwater density is 0.9977 g/cm^3. The equation then becomes

$$h_s = 38.97 \; h_f.$$

Thus the maximum freshwater lens thickness would be 38.97 x 1.83 = 71.32 m in the centre of the island, and this would decrease steadily to 0 at the coast. This is markedly different from the freshwater layer configuration as determined by the resistivity survey (Fig. 16), and it is concluded that the Ghyben-Herzberg theory does not apply. This theory was developed for homogeneous sand aquifers, but the Niue aquifer is fissured and porous limestone with varying directional permeability.

In Bermuda, Vacher (1978) has described an asymmetric freshwater layer beneath the island, which is composed of two types of limestone with different permeabilities; the freshwater layer is thicker within the younger, less permeable, limestone. It is likely that the 'doughnut' shape of the freshwater

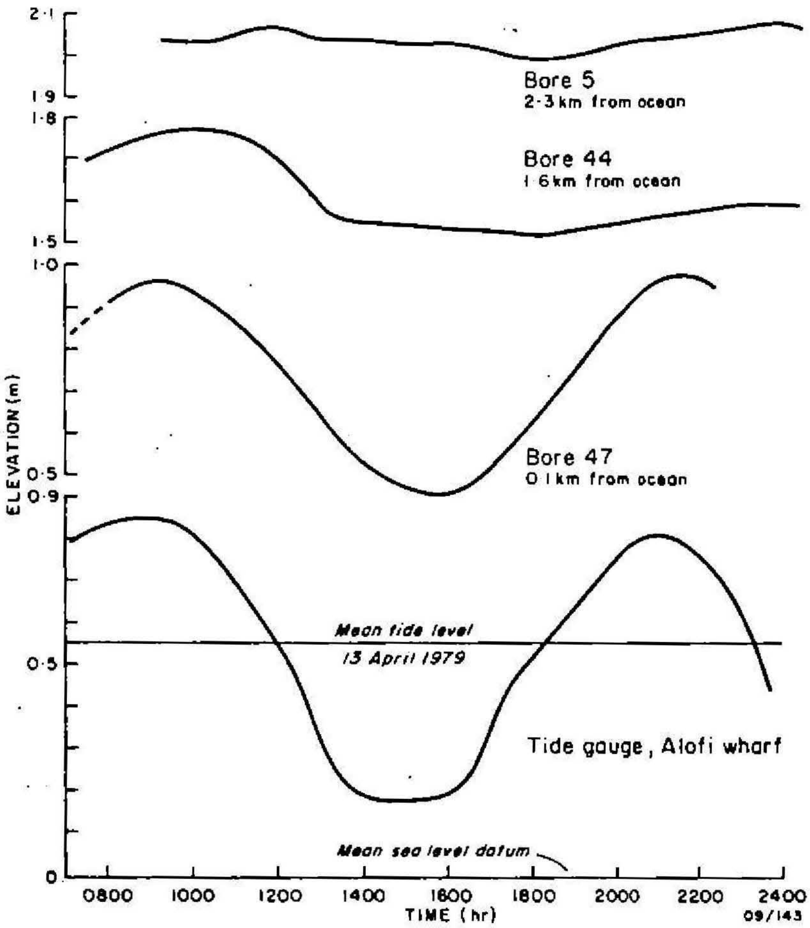

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Fig.21. Tidal fluctuations in groundwater levels, 13 April 1979

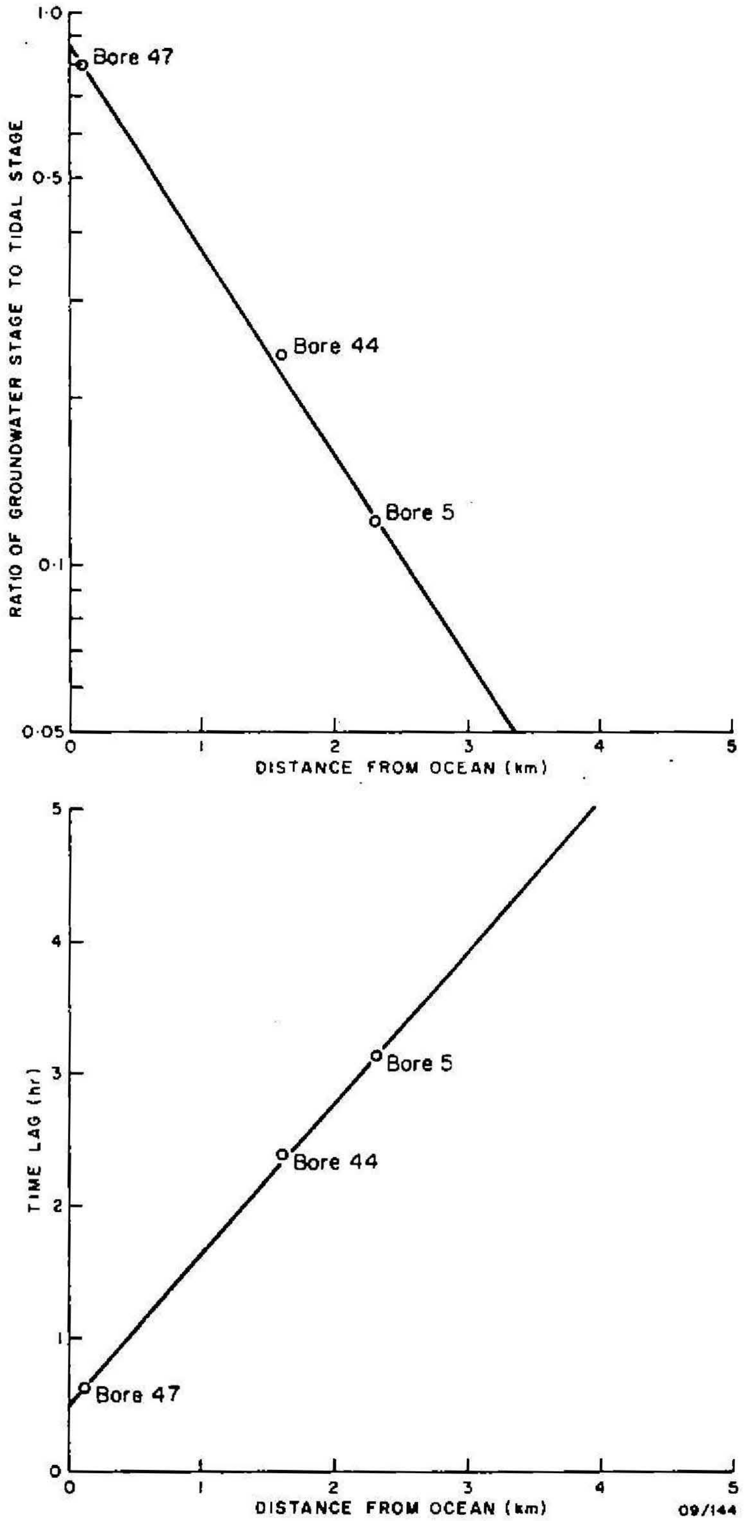

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Fig. 22. Tidal stage ratio and time lag plotted against distance from ocean

layer on Niue is due to a variation of permeability within the limestone, which - by analogy with the Bermuda limestone - would be less permeable beneath the rim of the island. This could be so if the former lagoonal sediments are porous calcarenites, and the former atoll rim consists of recrystallised or cemented reef limestone with lower permeability.

The groundwater is recharged by infiltrating rainwater over the entire island. If lateral flow of groundwater towards the coast is restricted by the lower permeability of the rock nearer the coast, then equilibrium conditions require a deeper section of rock for the lateral transmmssion of groundwater. The freshwater layer will therefore be thicker in the less permeable rocks, which act as an underground dam. Groundwater is forced to flow downwards throug fissures, creating a downward bulge in the freshwater/salt water interface.

TIDAL FLUCTUATIONS

Tidal fluctuations in the water-table were measured in three bores on 13 April and compared with tide gauge measurements at the Alofi wharf. These observations (Fig. 21), and additional observations made during aquifer tests in drillhole DH4, show that tidally induced fluctuations in groundwater-level extend throughout the island.

Tidal stage ratio, which is the ratio of groundwater stage to tidal stage, has been plotted against distance from the ocean in Figure 22. This shows that the amplitude of tidally induced fluctuations in groundwater-levels decreases with distance from the ocean. The time lag for the tidal fluctuation in groundwater level increases with distance from the ocean (Fig. 22). The apparent velocity of the wave is 900 m/hour.

All three of the observation bores, 5, 44, and 47, are drilled roughly to sea level and only partly penetrate the aquifer. Observations of a fully penetrating drillhole, DH4, and an adjacent partly penetrating bore, OB2, were made simultaneously during a pumping test on 20-21 April (Fig. 23 and 24). The observations showed greater tidal fluctuations and shorter time lag in the fully penetrating bore than in the partly penetrating bore.

It seems likely that the amplitude and time lag of the tidal response are controlled by the permeability of the penetrated strata. The deeper hole probably penetrated a more permeable section of limestone aquifer.

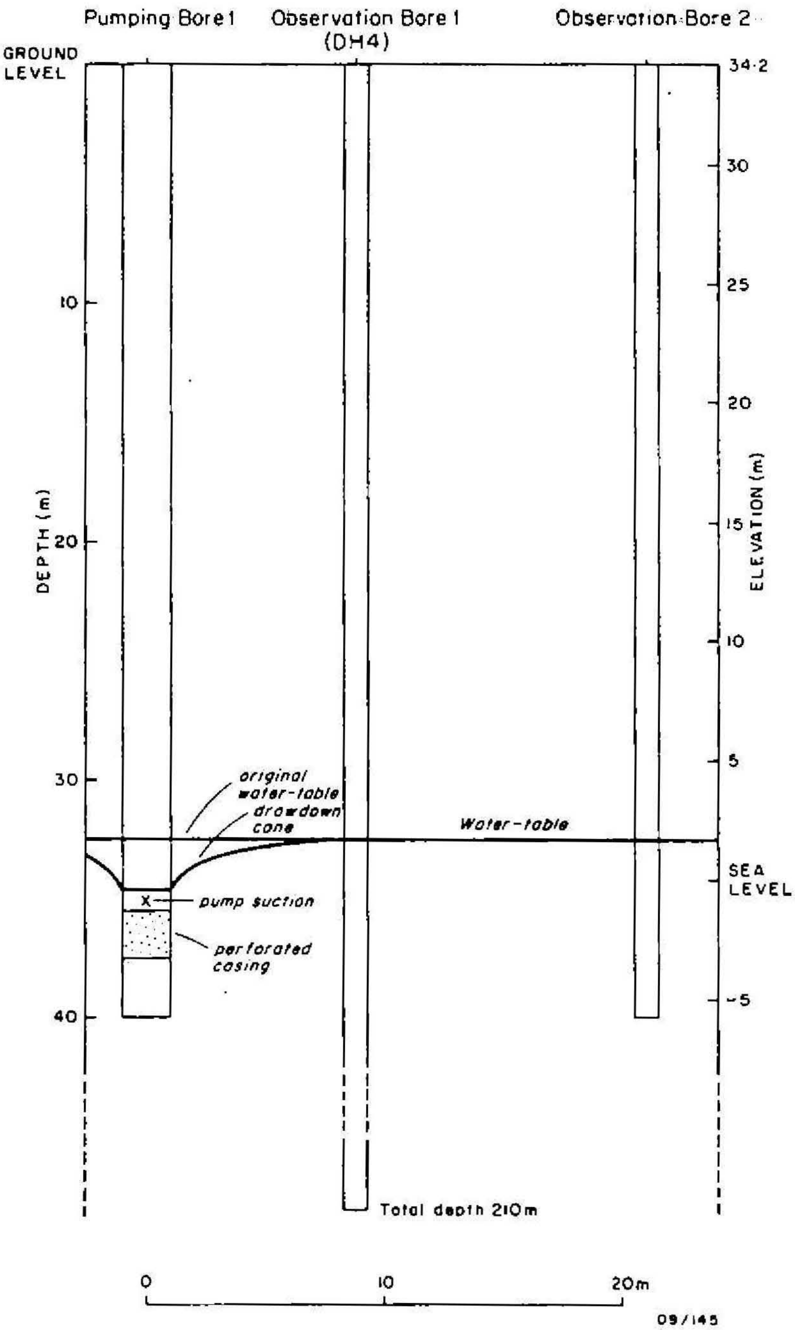

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Fig. 23. Arrangement of bores for pumping test, southern test site

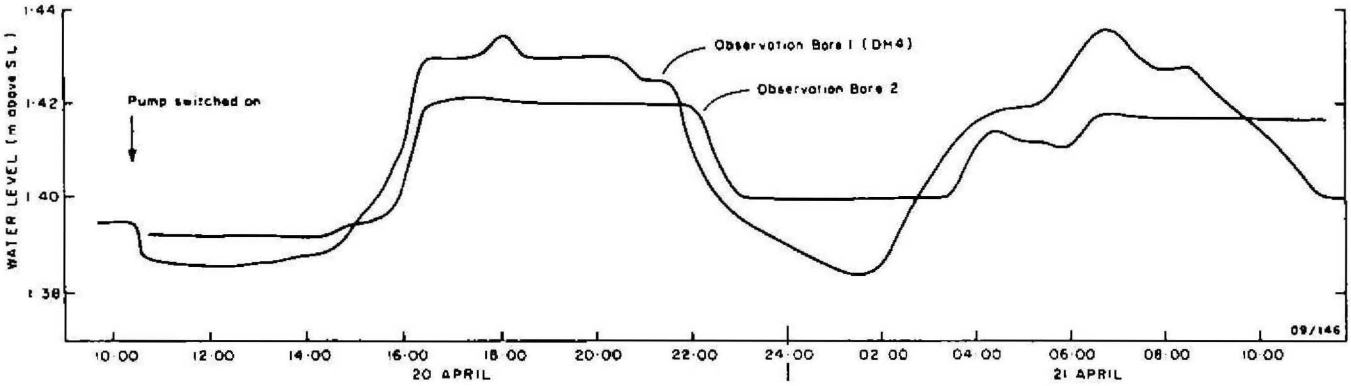

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Fig. 24. Water levels in observation bores during pump test PB1, 20-21 April 1979

The effect of tidal fluctuations is to thicken the transition zone of salt-water mixing at the base of the freshwater layer. The transition zone is about 40 m thick where measured in drillhole DH4 (Fig. 25). This drillhole, however, penetrates the entire transition zone into salt water; mixing may be due to the hydraulic connection afforded by the hole itself, and its salinity distribution may be different from that in the undisturbed aquifer (Mather & Buckley, 1973). Around the coast of Niue, the transition zone is 500-800 m wide (Fig. 6) and mixing is facilitated by large fissures.

AQUIFER TESTS

Aquifer tests were carried out at two sites in the interior of Niue: PB1 in the south, and PB2 in the north. In addition a recovery test was done on the dug well at Fonuakula. A proposed test at a site in the centre of Niue was not carried out because of time limitations.

Southern site

At the southern site, a production bore (PB1) and an observation bore (OB2) were constructed; Avian's drillhole DH4 was also used as an observation bore (OB1). The layout of bores is shown in Figure 23. The production bore was equipped with 12-cm-diameter galvanised iron casing, which was perforated below the water-table. The production bore was developed with compressed air. The observation bores were equipped with 5-cm-diameter plastic pipe.

A submersible bore hole pump was used for a 24-hour pump test with a constant discharge of 3.82 l/s. In the production bore, drawdown of the water-table was 1.4 m after one hour's pumping, the limit imposed by the length of tube on the air-pressure device used. The water-level then remained below this level until the end of the test; the greatest possible drawdown was the level of pump suction, 2.1 m. Water-levels were measured in two observation bores (Fig. 24). An initial drawdown of 1 cm was observed in OB1; however, subsequent movement of the water-table in both observation bores also recorded tidal fluctuations with an amplitude of several centimetres that masked the effects of pumping. Recovery of the water-level was measured at the cessation of pumping; full recovery was achieved in 6 minutes.

Analysis of the time-drawdown relation for the pumping bore indicates a coefficient of transmissivity of 68 m^2/day. Analysis of the recovery data indicates a coefficient of transmissivity of 93 m^2/day. The specific capacity, or yield-to-drawdown ratio, of the bore was 1.82 l/s/m of drawdown during the pump test. Specific capacity is an index of productivity, in part related to permeability and in part related to efficient well construction. At the time of the pump test, it was considered that the use of compressed air in developing the bore may have clogged the perforated casing with fine particles of rock, and that the productivity of the bore could be improved by better development. Instructions were left with the driller for the bore to be deepened a few metres and redeveloped. This was subsequently done (October, 1979) and an aquifer test by the Department of Public Works showed no detectable drawdown in 4 hours pumping at 3.90 l/s. The hydraulic characteristics of the redeveloped bore are therefore much better than those obtained during the first aquifer test and a more powerful pump would be required to measure them. The coefficient of transmissivity is probably of the order of 1000-10 000 m^2/day.

Figure 25 shows the results of conductivity probes in the observation bore OB1 before and after pumping. After 22 hours pumping the base of the freshwater layer had moved up about 4 m.

Conductivity of the pump discharge ranged from 330 to 390 µS/cm during the aquifer test.

<u>Northern site</u>

At the northern site, a production bore (PB2) was drilled to a depth of 46 m and equipped with 12-cm-diameter galvanised iron casing, perforated below the water-table. An observation bore was constructed 3 m away and equipped with 5-cm-diameter plastic pipe. The production bore was pumped for 12 hours at a constant discharge of 3.52 l/s. Drawdown of the water-table was 0.28 m after one minute's pumping and remained constant thereafter for the duration of the test. Recovery was immediate at the cessation of pumping. No drawdown attributable to pumping was observed in the observation bore, but a tidal fluctuation with an amplitude of 6 cm was recorded.

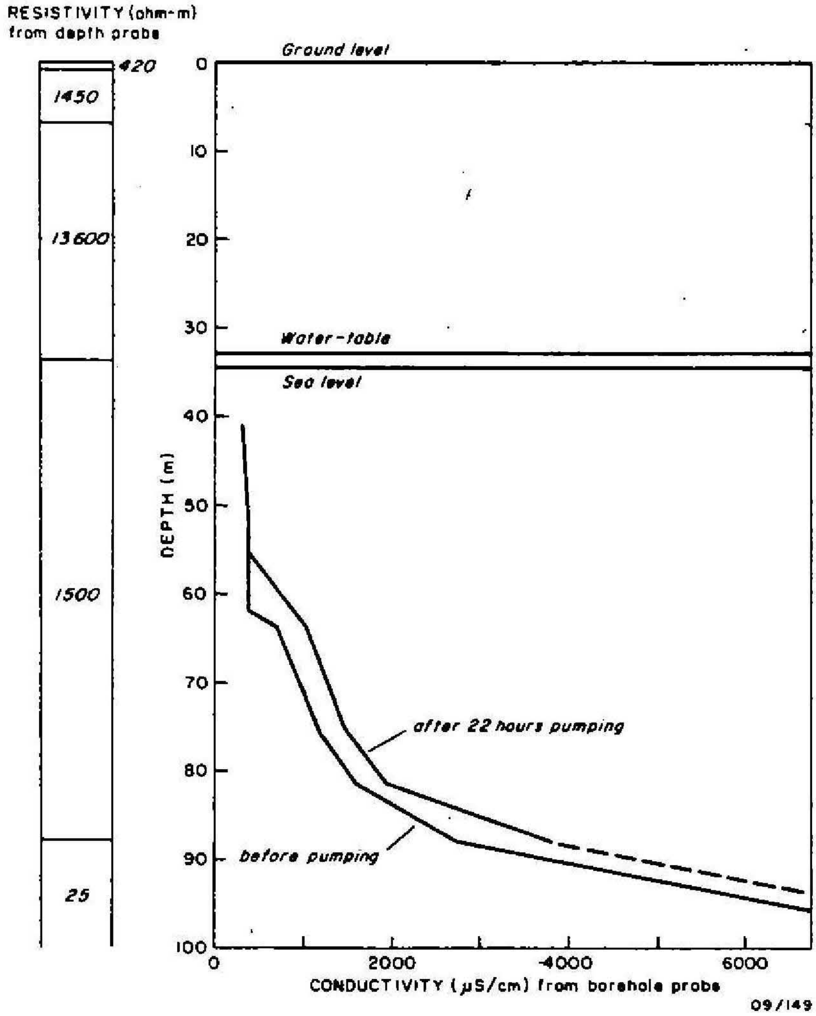

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Fig. 25. Conductivity profile in observation bore 1 (DH4) before and during pump test on PB1, 20–21 April 1979

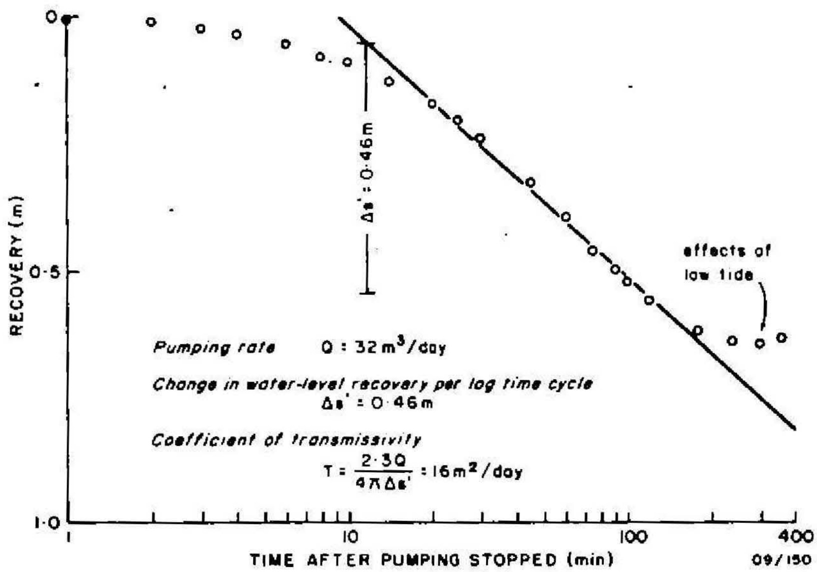

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Fig. 26. Time-recovery graph for town well, Fonuakula, 11 April 1979

The specific capacity of this bore was 12.64 l/s/m of drawdown during the 12 hour test. The pump capacity was insufficient to achieve the drawdown necessary for an analysis of transmissivity, which is probably of the order of 1000-10 000 m^2/day.

Conductivity of the discharged water was constant at 500 µS/cm throughout the test.

Fonuakula well

A recovery test was conducted on the dug well at Fonuakula (no. 1, Fig.9) on 11 April when the pump was switched off for several hours. The water level in the well recovered by 0.65 m in 3 hours. Analysis of the time-recovery graph (Fig. 26) indicates that the coefficient of transmissivity was 16 m^2/day. Resistivity depth probes suggest that the Fonuakula well is an area of relatively low-permeability rock but thick aquifer section (Fig. 16). The well penetrates only a small part of the aquifer section.

SAFE YIELD

A method has been developed by Mather (1975) for computing the freshwater lens thickness on an oceanic island. This method is based on an equation by Henry (1964) which gives the relationship between the co-ordinates of the base of the freshwater lens for a sharp freshwater/salt-water interface. From this equation, the depth below sea level to the interface is proportional to the square-root of the rate of uniform vertical recharge per unit area. Thus

$$y \propto \sqrt{Vo}$$

where y is the depth below sea level to the interface, and Vo is the rate of uniform vertical recharge per unit area.

For Niue the annual water balance has been determined (Table 2) as Rainfall (2041 mm) = Evapotranspiration (1417 mm) + Groundwater Recharge (634 mm). If the average depth below sea level to the interface is 50 m in the interior of Niue then the above relation becomes

$$50 \propto \sqrt{624}$$

that is $$50 \propto 25$$

which gives a proportionality constant of 2.

The abstraction of groundwater from the freshwater layer can be considered as equivalent to reducing the annual vertical recharge. Then, from the above relation, the depth to the interface can be calculated for various abstraction rates. For example, if the amount of effective annual recharge is reduced from 624 mm to 500 mm by abstracting 124 mm of recharging rainfall, then the depth of the interface below sea level under new equilibrium conditions will be

$$y = 2 \sqrt{Vo}$$

that is $$y = 2 \times \sqrt{500}$$

$$= 44.8 \text{ m.}$$

Table 6 shows the depths of the interface calculated for various annual abstraction rates, for a model freshwater layer on Niue with an original depth of 50 m below sea level.

The effects of drought can be assessed by considering the annual rainfall deficit as a loss of effective recharge to the aquifer. During the worst historical drought on Niue, 1940-44, the annual rainfall was 23.6 percent below the mean for the 5-year period (Fig. 7). This effective annual recharge would have been reduced from 624 mm to 476 mm during this time. The total rainfall deficit would have been 5 x 148 = 740 mm over 5 years and this can be considered equivalent to a reduction in recharge. If a specific yield of 15 percent is assumed then the rainfall deficit would be stored in approximately 4.9 m of aquifer; this must be subtracted from the estimated depths to the interface (Table 6) to allow for the drought period.

During a drought, the freshwater/salt-water interface could be maintained at 25 m below sea level-that is, at about half the original freshwater layer thickness-with 222 mm of annual rainfall as effective recharge (Table 6). This would leave the equivalent of 402 mm of rain available for abstraction annually. This is equivalent to a safe yield of about 4000 m^3/year, or 11 000 l/day/ha.

TABLE 6

EFFECT OF GROUNDWATER ABSTRACTION ON

DEPTH OF FRESHWATER/SALT-WATER INTERFACE

Effective recharge (mm)	Equivalent abstraction (mm)	Depth of interface below sea level (m)	Depth of interface for 5-year drought (m)
624	0	50.0	45.1
500	124	44.8	39.9
400	224	40.0	35.1
300	324	34.6	29.7
222	402	29.9	25.0
200	424	28.2	23.3
100	524	20.0	15.1

EFFICIENT ABSTRACTION OF GROUNDWATER

If drawing up the lens to half its original thickness is acceptable, then the safe pumping rate can be estimated from specific capacity data. Drawdown must be controlled in order to prevent the upward coning of salt water beneath abstraction points.

Control of drawdown can be achieved by operating the pump at a specified level and rate such that drawdown never exceeds one-half of the elevation of the water-table above mean sea level. If a borefield is in operation, a level of maximum operational drawdown should be determined for each bore and precautions taken to ensure that this drawdown is never exceeded, even when all pumps are in operation.

Measurements of PB2, at the northern site, showed that the elevation of the water-table is 1.27 m above sea level. The permissible drawdown would be half of this - that is, 0.63 m. The specific capacity of the bore was 12.64 l/s/m of drawdown. Thus, for a drawdown of 0.63 m, the safe pumping rate would be 7.98 l/s or 690 m^3 per day. Applying the figure previously derived for safe yield of a model aquifer - 11 m^3/day/ha - then the area of land required to maintain the discharge of this bore would be 63 ha.

As a first approximation, groundwater development in the interior of Niue could be by a borefield with one bore - producing about 8 l/s - to every 63 ha. However, local variations in permeability, and thickness of the freshwater layer, mean that every individual bore will have to be to ascertain its safe yield. The closer spacing of lower-yielding bores would be a suitable option.

Properly constructed and developed bores will be necessary to achieve the required production. Bores should be constructed to take casing of at least 100 mm internal diameter. Purchase of a drilling rig with a capability of drilling 200 mm diameter holes is recommended.. All bores should be cased to protect the pumps, and the casing should be perforated below the water-table. The bores should be developed by surging and/or bailing.

In general, turbine pumps with a capacity of 1.5 to 2.5 l/s will be suitable for Niue and could be used in bores spaced about every 15 ha.

WATER QUALITY

The results of chemical analyses of twelve Niue groundwater samples are given in Table 7. Eleven of the twelve samples had a total dissolved solids content in the range 136-261 mg/l, well below the World Health Organisation's (1963) maximum acceptable limit for drinking water; the other sample, from a bore near the coast, had a total dissolved soldis content of 500 mg/l. The electrical conductivity of the twelve samples was in the range 256-919 µS/cm.

Field conductivity measurements are shown in Figure 27. The coastal strip up to 1 km wide shows evidence of salt-water mixing and conductivity above 500 µS/cm.

Figure 28, a Piper trilinear diagram, shows the ionic composition of Niue groundwater. The inland bores have bicarbonate waters with calcium and magnesium the dominant cations. Groundwater from a perched aquifer in the Tukuofe cave is of similar composition except that the ratio Mg/Ca (in milliequivalents per litre) is slightly higher, 0.73, compared with 0.25-0.70 for the inland bores. Water from a bore near the coast southwest of Alofi had a chloride content of 192 mg/l, indicating sea-water mixing.

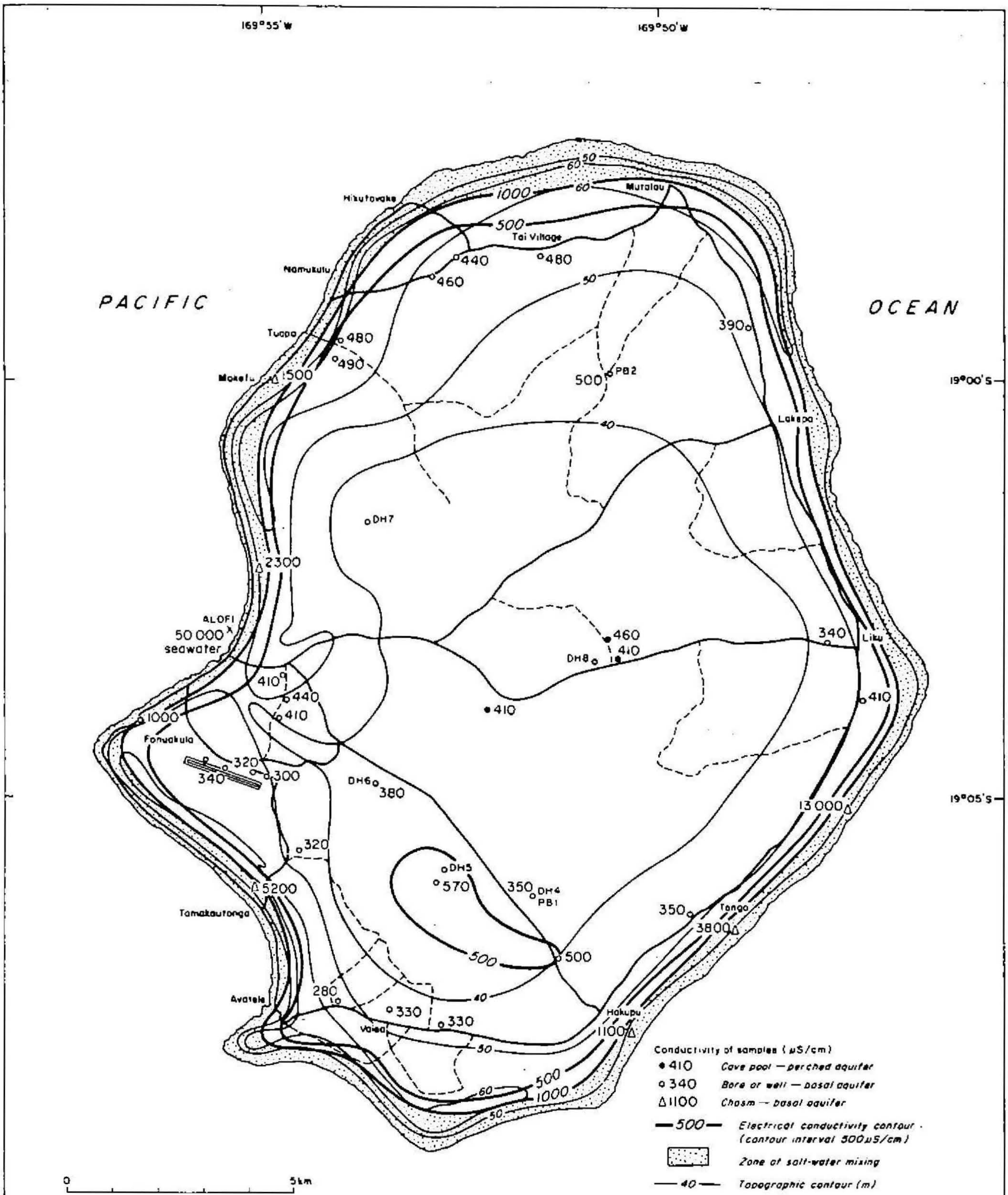

Fig. 27. Groundwater quality

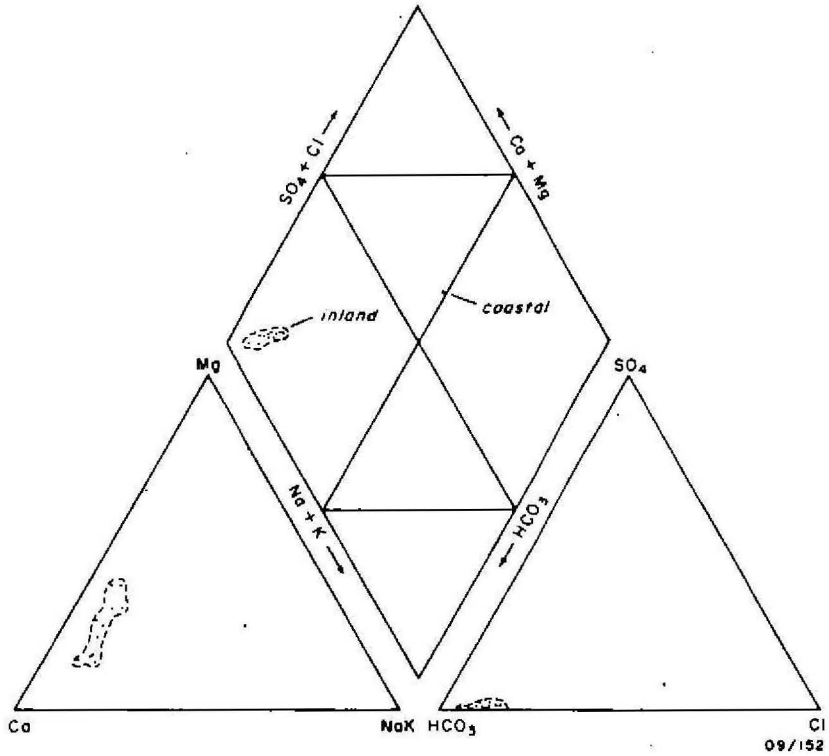

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Fig. 28. Ionic composition of Niue groundwater plotted on a Piper trilinear diagram

TABLE 7

CHEMICAL ANALYSES OF GROUNDWATER SAMPLES

(For sample locations see Fig. 9)

	PB1 Havaka	PB2 Tumukanumea	Bore 30 Lakepa	Bore 48 Amanau	Deep Well Fonuakula	Bore 16 Avetele	Bore 26 Liku	Bore 42 Tuila	Bore 22 Hakupu	Bore 39 Tuapa	Bore 34 Toi	Cave Tukuofe	World Health Organisation (1963) - limit of general acceptability for drinking water
Calcium	42	63	61	54	44	39	59	56	51	56	53	47	75
Magnesium	18	21	16	24	9	6	8	15	7	20	8	21	50
Sodium	5	11	10	99	6	7	12	7	6	13	9	8	
Potassium	0.3	0.5	0.4	5	2	0.4	0.7	0.5	1	1	1	0.6	
Bicarbonate	207	286	255	202	163	143	215	245	182	261	195	239	
Sulphate	2	4	3	27	4	2	4	3	3	5	5	2	200
Chloride	7	21	20	192	10	12	22	14	11	25	16	12	200
Nitrate	0	0	0	0	23	0	0	0	0.8	0	0.4	0	45
Conductivity	331	474	429	919	321	256	403	399	316	462	349	382	
Total dissolved solids	175	261	236	500	179	136	212	215	168	249	188	208	500
Total hardness	179	244	217	234	149	121	180	202	155	221	166	203	
Carbonate hardness	170	235	209	166	134	117	176	201	149	214	160	196	
Non-carbonate hardness	9	9	8	68	15	4	4	1	6	7	6	7	
Total alkalinity	170	235	209	166	134	117	176	201	149	214	160	196	
pH	7.6	7.8	8.0	7.8	7.7	7.6	7.7	7.6	7.5	7.7	7.5	7.9	7-8.5
Radium-226		1.0		0.5	1.0						1.0	0.6	3*

Conductivity in µS/cm at 25°C
Chemical composition in mg/l
Hardness as $CaCO_3$ in mg/l
Radium 226 in picocuries/l
* Maximum limit, United States Public Health Service (1962)

Nitrate was determined as generally less than 1 mg/l except for the dug well at Fonuakula. A sample from the well had 23 mg/l nitrate which is within the limits of acceptability for drinking water, but indicates some contamination, probably from livestock. Because of the delay between sampling and analysis, and the fact that the samples were not treated to preserve them, the nitrate concentrations could be greater than the analyses indicate.

The Niue waters are classified as hard to very hard, and softeners could be required for some industrial applications. The water is slightly alkaline with a hydrogen ion concentration, pH, of 7.5-8.0.

Guidelines for the interpretation of water quality for irrigation have been formulated by Ayers (1975). No problems with salinity effects on crop yield are expected with irrigation water having electrical conductivity below 750 μS/cm. The chloride and sodium concentrations in the inland bores are well below those which could cause toxicity problems for plants. Bicarbonate concentrations, however, are above 90 mg/l in all the Niue waters; this could lead to white carbonate deposits on the fruit or leaves of plants with overhead sprinkler irrigation. Nitrogen concentrations in the bores appear to be below the level at which they could interfere with the production or quality of crops; however, more analyses with better sample preservation are required to evaluate this. The sodium absorption ratio ranges from 0.2 to 0.4 for the inland bores; this is a low value, indicating that problems connected with the deflocculation of clay will not occur.

The possibility of radioactive elements being present in harmful concentrations in groundwater has been raised (Schofield, 1967). Five samples taken during the present investigation were analysed for radium-226 (Table 7). All had radium-226 concentrations of 1 picocurie/l or less, which is below the maximum limit of 3 picocuries/l specified by the United States Public Health Service (1962).

The groundwater is bacteriologically clean unless some contamination from outside sources occurs. At present, water-supply bores are carefully monitored by the Niue Health Department and are closed down if contamination does occur. Two bores which were abandoned because of bacteriological contamination, at Toi village and Mutalau, are believed to have been polluted by cave lavatories situated several hundred metres away. The aquifer is susceptible to pollution because of the fissured and permeable limestone, and the lack of soil cover. Waste disposal in the outer 500 m coastal strip is less hazardous because groundwaters flow towards the coast, and the present restriction of waste disposal to this coastal zone should continue. The current restrictions on latrines and on livestock close to bores used for drinking water, should be maintained.

The possibility of groundwater being polluted by agricultural development needs consideration. The use of fertilisers would add phosphate and nitrate to the soil. Phosphate is expected to become fixed in the soil and the limestone. Nitrate, however, would be leached and would percolate to the water-table, and could lead to contamination of the groundwater.

Inorganic pesticides would be fixed in the limestone; organic pesticides would not be fixed but may be biodegradable. Any pesticides used should have either of these properties.

Regular monitoring of water quality will be necessary with future groundwater development on Niue. At the close of the team's visit to Niue, instructions were left with the drilling contractor for three of the Avian Mining Company's deep exploration drillholes to be cased with perforated, 30-mm diameter galvanised water pipe so that they serve as permanent observation bores. Changes in salinity of the freshwater layer can be monitored in these bores. In addition observation bores will be required close to high-yielding bores in order to monitor salinity, and in the case of irrigation bores, nitrate and pesticide concentrations.

CONCLUSIONS AND RECOMMENDATIONS

1. Niue Island is a raised coral atoll with about 300 m of mainly Miocene limestone overlying a volcanic seamount.

2. Groundwater on Niue is contained in a freshwater layer overlying salt water. The thickness of the freshwater layer is 50-80 m beneath the central basin of the island, and over 100 m beneath the peripheral rim. Salt-water intrusion is evident for 500 m inland from the coast, where mixing has been facilitated by fissures in the limestone.

3. The elevation of the water-table is 1.8 m above sea level in the centre of Niue, and freshwater generally flows radially outwards to the sea.

4. Water-balance calculations for a model freshwater layer 50 m thick drawn up to 25 m indicate that the safe yield of the Niue aquifer is about 11 000 l/day/ha.

5. Aquifer tests carried out on specially constructed bores in the interior of Niue indicate that safe long-term pumping rates could be up to about 8 l/s. To avoid upconing of salt water, drawdown should be controlled to be no more than one-half the elevation of the water-table above the mean sea level datum.

6. The present Niue water supply is based on low-yielding, uncased, narrow diameter bores. The supply could be improved by the development of larger-diameter cased bores whose casing was perforated below the water-table. A drilling rig capable of constructing bores with 12.5-15-cm casing should be procured.

7. The use of turbine pumps yielding 1.5-2.5 l/s is recommended, and bores of this capacity could be spaced one per 15 ha.

8. Groundwater in the interior of Niue has a total dissolved solids content of 136-261 mg/l, and is a bicarbonate water. The water is suitable for drinking, and, if bores are protected from bacteriological contamination, urban water supplies can be developed from a central source.

9. The fresh groundwater is generally suitable for irrigation; however, the high bicarbonate content might cause white carbonate deposits to form on fruit and leaves where irrigation is by overhead sprinklers.

10. There is a possibility of groundwater pollution occurring as a result of the application of pesticides and fertilisers. Groundwater quality, especially nitrate concentrations, should be monitored in irrigation areas.

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<u>APPENDIX 1</u>

<u>LIST OF WATER-BORES</u> (For bore locations, see Figure 9)

No.	Location	Date drilled	Elevation above mean sea level datum (m)	Depth (m)	Water-level (m)	Yield (m^3/hour)	Electrical conductivity (μ/S/cm)	Equipment	Use
1	Fonuakula	-	55.45	-	54.13	1.33	321	Two electric pumps	Dug well, town supply
2	Halamahaga School	1964	-	25.9	-	-	-	Abandoned, saline	-
3	Kiamisi	1971	-	57.1	-	-	-	-	-
4	Kiamisi	1978	-	57.9	-	-	-	Electric pump	Town supply
5	Kiamisi	1976	55.20	58.5	53.17	-	-	Electric pump	Town supply
6	Viaola	-	-	-	-	-	-	Electric pump	Town supply
7	Viaola	-	-	-	-	-	-	Electric pump	Town supply
8	Viaola	1977	55.37	-	53.81	-	-	-	-
9	Viaola	-	-	-	-	-	320	Electric pump	Town supply
10	Fonuakula	1967	-	57.3	-	-	-	Abandoned, close to septic tank	
11	Fonuakula	1965	-	64.0	-	0.7	-	Electric pump	Domestic, industrial
12	Toa Farm	1970	-	56.9	-	0.7	300	Electric pump	Stock
13	Fuata	1964	-	49.5	47.11	-	-	Windmill	Village supply
14	Fuata	1977	-	51.8	-	0.9	320	Electric pump	-
15	Avesele	1964	62.73	63.4	61.05	-	-	Windmill	Village supply
16	Avesele	1970	-	56.7	-	-	256	Diesel pump	Village supply
17	Vaiea	1964	-	50.9	-	-	-	Windmill	Village supply
18	Vaiea	1977	-	52.4	-	-	330	Electric pump	Village supply
19	Vaiea Farm	1964	-	51.2	-	-	330	Diesel pump	Stock
20	Vaiea Farm	1965	-	48.8	-	-	-	Diesel pump	Stock
21	Vaiea Farm	1965	-	49.7	-	-	-	Windmill	Stock
22	Hakupu	1967	-	49.0	-	-	316	Windmill	Village supply
23	Hakupu	1964	-	40.2	-	0.8	500	Diesel pump	Village supply
24	Hakupu	-	-	56.1	-	-	-	Electric pump	Stock
25	Vani	1970	-	53.6	-	-	350	Diesel pump	Stock
26	Liku	-	-	-	-	-	410	Electric pump	Stock
27	Liku	1964	-	44.5	-	-	340	Electric pump	Village supply
28	Liku	1968	-	44.5	-	-	-	Windmill	Village supply
29	Lakepa	-	-	50.9	-	-	-	Electric pump	Stock
30	Lakepa	1964	-	43.6	-	-	429	Electric pump	Village supply
31	Fulala	1971	-	50.9	-	-	390	Electric pump	Stock
32	Mutalau	1976	-	58.5	-	-	-	-	Agriculture
33	Mutalau	1964	-	57.9	-	0.4	-	Abandoned, bacterial contamination	

LIST OF WATER-BORES (For bore locations, see Figure 9)

No.	Location	Date drilled	Elevation above mean sea level datum (m)	Depth (m)	Water-level (m)	Yield (m^3/hour)	Electrical conductivity (μS/cm)	Equipment	Use
34	Mutalau	1969	-	55.3	-	-	349	Electric pump	Village supply
35	Toi	1977	-	58.8	-	-	480	Electric pump	Village supply
36	Toi	1971	-	57.0	-	-	-	Electric pump	Village supply
37	Vaipapahi Farm	1965	-	63.4	-	-	460	Electric pump	Agriculture
38	Makaunga	1977	-	60.5	-	-	440	Electric pump	Village supply
39	Omea	1971	-	58.9	-	-	480	Diesel pump	Village supply
40	Omea	1964	-	62.9	-	-	490	Diesel pump	Village supply
41	Omea	-	-	-	-	-	-	Windmill	Village supply
42	Tuila power station	1966	-	54.2	-	-	400	Electric pump	Industrial
43	Tuila road	1971	-	51.8	-	-	440	Electric pump	Town supply
44	Tuila road	-	50.84	-	49.23	-	-	-	Town supply
45	Tuila road	1971	-	51.7	-	-	410	Electric pump	Town supply
46	Paliati school	1965	-	54.9	-	-	-	Electric pump	School supply
47	Amanau	1965	23.29	22.9	22.55	-	10 000	Electric pump	Industrial
48	Amanau	1975	-	27.7	-	-	919	Electric pump	Industrial
49	Amanau	1976	-	27.4	-	-	-	Electric pump	Industrial
50	Alofi	1967	-	24.7	-	-	-	Abandoned, saline	
51	Lakepa	1967	-	43.6	-	-	-	Abandoned	-
52	Toi	1964	-	61.0	-	-	-	Abandoned, bacterial contamination	
53	Havaka	1979	34.20	40.0	32.46	8.0	350	Capped	Current investigation production bore 1
54	Tumukanumea	1979	37.53	50.0	36.26	8.0	500	Capped	Current investigation production bore 2
DH4	Havaka	1979	34.20	230.0	32.46	-	-	Capped	Exploration drillhole (Avian Mining)
DH5	Foa	1979	33.62	204.0	31.91	-	-	Capped	Exploration drillhole (Avian Mining)
DH6	Kavata	1979	38.37	153.8	36.37	-	380	Capped	Exploration drillhole (Avian Mining)
DH7	Fatamanu	1979	47.15	205.4	45.35	-	-	Capped	Exploration drillhole (Avian Mining)
DH8	Tukuofe	1979	33.74	214.5	31.91	-	-	Capped	Exploration drillhole (Avian Mining)

APPENDIX 2

INTERPRETATION OF RESISTIVITY DEPTH PROBES

DEPTH-PROBE NAME	SURFACE ELEVATION (m)	LAYER PARAMETERS (in order of depth) RESISTIVITY (ohm-m)	THICKNESS (m)	INFERRED THICKNESS OF FRESHWATER LAYER (m)
TUKUOFE	34.1	270	1.3	75
		22100	31.5	
		1200	75	
		20	30?	
		3.3		
FOA	33.2	370	1.0	40
		1400	9	
		18000	22	
		1100	40	
		20	30?	
		2.8		
FALEHAVAIKI	47.8	410	0.8	120
		820	7	
		11000	39	
		1600	120	
		35	30?	
		3.5		
AIRFIELD	55.4	650	1.0	170
		1650	26	
		7500	195	
		130	30?	
		3		
DEEP WELL	55.4	940	1.0	160
		2600	26	
		5500	185	
		90	30?	
		3		
ANOKULA	56.4	820	1.0	85
		6200	4.0	
		11000	50.5	
		5500	85	
		90		
FUATA	49.4	540	3.0	70
		6400	115	
		80		

APPENDIX 2 (continued)

INTERPRETATION OF RESISTIVITY DEPTH PROBES

DEPTH-PROBE NAME	SURFACE ELEVATION (m)	LAYER PARAMETERS (in order of depth)		INFERRED THICKNESS OF FRESHWATER LAYER (m)
		RESISTIVITY (ohm-m)	THICKNESS (m)	
TAMAKAUTONGA	23.3	1700 270 23000 6000 25	1.0 0.4 14.3 5	0
KAVATA	37.6	200 2500 12000 1800 30	0.6 4.0 32 80	80
TALAMAITONGA	39.1	170 9700 2500 40	1.0 37 100	100
HAVAKA	34.2	420 1450 13600 1500 25	0.8 6.0 26.5 55	55
TONGO	47.4	300 11500 2000 35	1.0 45.5 105	105
TAPUTAPU	42.4	240 31000 1500 20	1.0 40.5 60	60
MANA	36.3	95 27000 4500 1000 15	0.6 15 19 20?	?

APPENDIX 2 (continued)

INTERPRETATION OF RESISTIVITY DEPTH PROBES

DEPTH-PROBE NAME	SURFACE ELEVATION (m)	LAYER PARAMETERS (in order of depth) RESISTIVITY (ohm-m)	THICKNESS (m)	INFERRED THICKNESS OF FRESHWATER LAYER (m)
VINIVINI	35.4	320 15000 6300 3500 60	0.8 6.0 27.5 60	60
HUVALU FOREST	39.8	500 1850 8100 2000 30	1.0 4.0 34.0 115	115
NATUKU	50.0	460 2000 7000 3600 60	1.0 2.0 46 120	120
NIUFELA	35.0	210 5000 13000 4050 1900 30	1.0 4 8 21 65	65
LAKEPA	50.3	1100 2900 12300 7000 120	1.0 4 44.5 85	85
TUMUKANUMEA	37.7	220 20000 6650 2700 45	1.0 12 24 120	120
HAUPO	51.3	300 3200 5650 2700 1000	1.0 8 41.5 80	80

APPENDIX 2 (continued)
INTERPRETATION OF RESISTIVITY DEPTH PROBES

DEPTH-PROBE NAME	SURFACE ELEVATION (m)	LAYER PARAMETERS (in order of depth) RESISTIVITY (ohm-m)	THICKNESS (m)	INFERRED THICKNESS OF FRESHWATER LAYER (m)
VAIPAPAHI	62.5	480 9900 5000 85	1.3 60.5 75	75
TOI VILLAGE	58.7	550 3500 7700 2600 45	1.3 1.5 54.5 50	50
KAPIHI	48.8	500 11300 5000 80	1.2 46.5 50	50
FULALA	52.0	410 1050 9500 4000 70	1.0 3 47 90	90

? denotes ill-defined

APPENDIX 3

GLOSSARY OF HYDROGEOLOGICAL TERMS

Aquifer: groundwater-bearing formation sufficiently permeable to transmit and yield water in usable quantities,

Draw down: the distance that the water-level in a bore is lowered from the standing water-level by pumping.

Evapotranspiration: evaporation from soil and transpiration by plants. Actual evapotranspiration is the real rate of water-vapour return to the atmosphere from the ground and its plant cover. Potential evapotranspiration is the water vapour flux under ideal conditions.

Perched aquifer: a temporary unconfined aquifer formed where the downward movement of infiltrated water is restricted by a layer of relatively low permeability.

Permeability: hydraulic conductivity, i.e. the factor of proportionality between groundwater velocity and the hydraulic gradient.

Phreatic zone: the groundwater zone, below the water-table.

Porosity: the percentage of the total volume of the material that is occupied by pores or interstices.

Sodium Absorption Ratio: the sodium absorption ratio is defined by

$$SAR = \frac{Na}{\sqrt{(Ca + Mg)/2}}$$

where concentrations are expressed in equivalents per million.

Specific capacity: the well flow per unit drop of water-level in the well.

Specific yield: the volume of water released from a unit volume of saturated aquifer material drained by a falling water-table.

Transmissivity: the rate at which water is transmitted through a unit width of aquifer under a unit hydraulic gradient.

Unconfined aquifer: an aquifer with no clay or restricting material at the top of the groundwater, so that groundwater levels are free to rise or fall. The top of an unconfined aquifer is the water-table.

Vadose zone: the zone between ground surface and the top of the groundwater, where water pressures are less than atmospheric pressure.

Water-table: the plane where groundwater pressures are equal to atmospheric pressure; the phreatic surface.

APPENDIX 4

LOGS OF DRILL CORE

BUREAU OF MINERAL RESOURCES, GEOLOGY & GEOPHYSICS

GEOLOGICAL LOG OF DRILL HOLE

PROJECT NIUE ISLAND
LOCATION Observation bore 2 at site of Producton bore I, Havaka
ANGLE FROM HORIZONTAL (θ) 90° DIRECTION
COORDINATES R.L. OF COLLAR 34·20m

HOLE NO

SHEET 1 OF 2

Rock Type and Degree of Weathering	Description Lithology, colour, strength, etc.	Lift and % core recovery	Depth and size of Core	Fracture Log (0 6 12 18+)	Structures Joints, veins, seams, fault, etc.
NO	CORE	0			
Limestone	Cemented, sandy, shelly fossils	20			
Limestone	White, sandy, shelly fossils	25			Porous
Limestone	White, sandy, medium-coarse grained	80	10m		Shelly fossils etched out by solution. Secondary calcite in cavities
Limestone	White, sandy, dense, fine grained to 11·45m becoming coarser	100		←Middle to late Miocene	
Limestone	White, sandy, dense, medium grained	100		←Middle to late Miocene	Some small shelly fossils etched out. Broken core 16·30–16·60m
Limestone	White, sandy	20			Shells and coral fragments etched out
NO	CORE	0	20m		Soft ground, probably cavernous
Limestone	White, sandy				Shells and coral
Limestone	Sandy	2	30m		
NO	CORE	0			
Limestone	White, fine sandy				Porous where fossils etched out
Limestone	White, medium sandy	50	40m		

Water Level: ▽ (near 33 m)

Drill type
Feed
Core barrel type
Driller F.A. Kelly
Commenced 17/4/79
Completed 19/4/79
Logged by G. Jacobson
M(Pf) 221

Notes

Fracture Log — Number of fractures per 25cm of core. Zones of core loss blacked in.

Bedding & Joint Planes — Angles are measured relative to a plane normal to the core axis.

Water Level Measurements — ▼ Level when hole in progress at specified depth
▽ Level in completed hole on specified date.

Checked by

Record No. 1980/14

Core Photograph Negative No.

Depth(m)	Black & White	Colour

09/A/158

BUREAU OF MINERAL RESOURCES, GEOLOGY & GEOPHYSICS

GEOLOGICAL LOG OF DRILL HOLE

PROJECT NIUE ISLAND

LOCATION Observation bore 2 at site of Production bore 1, Havaka

ANGLE FROM HORIZONTAL (θ) ________ DIRECTION ________

COORDINATES ________ R.L. OF COLLAR ________

HOLE NO ____

SHEET 2 OF 2

Rock Type and Degree of Weathering	Description Lithology, colour, strength, etc.	Casing	Graphic Log	Lift and % core recovery	Depth and size of Core	Fracture Log (0 6 12 18+)	RQD	Structural Log	Structures Joints, veins, seams, fault, etc.	Water Level
					40m					
Limestone	White, fossiliferous 39·65–40·20 m								Vugs where large shells etched out	

This observation bore was cored and completed at 40·20m, and equipped with 5cm diameter plastic casing. The production bore 8m away was drilled to 40m, and equipped with galvanised casing, which was perforated below the water table.

Drill type ________

Feed ________

Core barrel type ________

Driller ________

Commenced ________

Completed ________

Logged by ________

M(Pf) 221

Notes

Fracture Log — Number of fractures per 25cm of core. Zones of core loss blocked in.

Bedding & Joint Planes — Angles are measured relative to a plane normal to the core axis.

Water Level Measurements — ▼ Level when hole in progress at specified depth

▽ Level in completed hole on specified date.

Checked by ________ Record No. 1980/14

Core Photograph Negative No.

Depth(m)	Black & White	Colour

09/A/158

BUREAU OF MINERAL RESOURCES, GEOLOGY & GEOPHYSICS

GEOLOGICAL LOG OF DRILL HOLE

PROJECT NIUE ISLAND
LOCATION Observation bore at site of Production Bore 2, Tumukanumea
ANGLE FROM HORIZONTAL (θ) 90° DIRECTION
COORDINATES R.L. OF COLLAR 37·53 m

HOLE NO
SHEET 1 OF 2

Rock Type and Degree of Weathering	Description Lithology, colour, strength, etc.	Casing	Graphic Log	Lift and % core recovery	Depth and size of Core	Fracture Log (0 6 12 18+)	RQD	Structural Log	Structures Joints, veins, seams, fault, etc.	Water Level
	NO CORE			0						
Limestone	Off white calcarenite, dense, fine sand size			30					Shelly fossils etched out by solution	
Limestone	Off white, fine sandy			85					Highly fossiliferous	
Limestone	Off white, sandy / Cave travertine / Recrystallised			100	10m					
Limestone	Coarse, sandy, porous			100						
Limestone	Medium – coarse grained calcarenite, porous			80					A few shelly fossils etched out	
Limestone	Fine – grained, sandy, recrystallised			90		←Miocene			Jointing dips 55° 2cm calcite vein dip 55° at 18·00m	
Limestone	Fine – grained, sandy			70	20m					
NO	CORE recrystallised, shelly			0					Cave	
Limestone	coarse, porous, sandy / coarse, sandy			100					Numerous shelly fossils	
Limestone	Medium – coarse grained calcarenite			100					Shelly fossils	
Limestone	Medium—coarse grained calarenite				30m				Broken core	
Limestone	Medium – coarse grained calcarenite			40						
Limestone	Shelly, highly fossilierous / Medium sandy, some shelly fossils			100						▽
Limestone	Recrystallised, shelly			100					Vugs where shells etched out	
Limestone	Recrystallised, shelly				40m				Secondary calcite in vugs	

Drill type
Feed
Core barrel type
Driller F.A. Kelly
Commenced 1/5/79
Completed 3/5/79
Logged by G. Jacobson
M(Pf) 221

Notes

Fracture Log – Number of fractures per 25cm of core. Zones of core loss blacked in.

Bedding & Joint Planes – Angles are measured relative to a plane normal to the core axis.

Water Level Measurements – ▼ *Level when hole in progress at specified depth*
▽ *Level in completed hole on specified date.*

Checked by

Record No. 1980/14

Core Photograph Negative No. Depth (m)	Black & White	Colour

09/A/159

BUREAU OF MINERAL RESOURCES, GEOLOGY & GEOPHYSICS

GEOLOGICAL LOG OF DRILL HOLE

PROJECT NIUE ISLAND

LOCATION Observation bore at site of Production bore 2, Tumukanumea

ANGLE FROM HORIZONTAL (θ) ________ DIRECTION ________

COORDINATES ________ R.L. OF COLLAR ________

HOLE NO ____

SHEET 2 OF 2

Rock Type and Degree of Weathering	Description Lithology, colour, strength, etc.	Casing	Graphic Log	Lift and % core recovery	Depth and size of Core	Fracture Log (0 6 12 18+)	RQD	Structural Log	Structures Joints, veins, seams, fault, etc.	Water Level
					40m					
Limestone	Recrystallised, sandy			70						
Limestone	Medium grained calcarenite			100					Shelly fossils etched out	
Limestone	Fine grained, dence			90		← Early Miocene to Recent				

This observation bore was cored and completed at 46·95m, and equipped with 5cm diameter plastic casing. The production bore 3m away was drilled to 50m and equipped with galvanised casing, which was perforated below the water table.

Drill type ________

Feed ________

Core barrel type ________

Driller ________

Commenced ________

Completed ________

Logged by ________

M(Pf) 221

Notes

Fracture Log — Number of fractures per 25cm of core. Zones of core loss blacked in.

Bedding & Joint Planes — Angles are measured relative to a plane normal to the core axis.

Water Level Measurements — ▼ Level when hole in progress at specified depth

▽ Level in completed hole on specified date.

Checked by ________

Record No. 1980/14

Core Photograph Negative No.

Depth(m)	Black & White	Colour

09/A/159

SHEET 2 OF 2