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BUREAU OF MINERAL RESOURCES, GEOLOGY AND GEOPHYSICS

RECORD

RECORD 1981/78

HYDROGEOLOGICAL AND GEOPHYSICAL INVESTIGATIONS
ON NORFOLK ISLAND 1981

by

R.S. Abell and F.J. Taylor
with
Appendices by P.G. Duff and E.M. Truswell

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SUMMARY

Norfolk Island is an erosional remnant of a volcanic complex consisting of relatively flat-lying interbedded basaltic lava and tuff built on a submarine pile of pillow lavas and hyaloclastite deposits. Quaternary calcareous aeolinite occurs on the south side of the island. A deep weathering profile has developed in the volcanic succession since eruptive activity ceased during the late Pliocene, 2.3 my ago.

The investigation was undertaken to assess whether a deep potable groundwater supply can be developed from bedrock aquifers as an alternative to locally polluted, shallow groundwater currently exploitated from perched aquifers in weathered volcanic rocks. Detailed resistivity traversing led to the selection of four drill sites in the Broken Bridge - Mission Creek valleys. Low resistivity values are interpreted as zones of saturated deep weathering which, if co-incident with fractures, may contribute to the recharge of deeper aquifers. Beneath the Kingston lowland a depth probe confirmed the existence of a freshwater layer 2 m thick overlying a brackish water zone 15 m thick. The recorded magnetic data are a typical response to a basaltic lava and tuff sequence; the high noise levels in the profiles are due to variations in remanent magnetism and other magnetic inhomogeneities in the rock sequence rather than man-made interference.

The current hydrogeological model proposed for Norfolk Island is a two-component groundwater storage system connected by fractures. The upper storage is a perched water table aquifer in the porous weathered mantle, presently exploited but currently threatened by pollution from septic tank effluent and livestock waste. The lower storage is thought to be a basal groundwater aquifer in hyaloclastite rocks and perhaps pillow lavas at and below sea level as yet unexploited. Groundwater recharge to the basal aquifer is accomplished through a complex distribution of bedrock fractures beneath the weathered mantle. If accessible to recharge, basaltic tuff beds may act as semi-confined aquifers with the capacity to yield additional groundwater between the weathered mantle and basal aquifer. Where recharge is cut off locally dry permeable pockets in bedrock may form where deep weathering has penetrated sufficiently to clay-seal the fractures.

The permeability characteristics of the hyaloclastite rocks underlying Norfolk Island is still imperfectly known. Basal groundwater is thought to occur in permeable pockets sealed by impermeable rock, or in fractures. The anisotropic permeability distribution suggests that the classical geometrical lens-shape of a freshwater body commonly occurring on most oceanic islands is likely to be distorted on Norfolk Island with the liklihood of a thick brackish water zone. The zone of mixing between freshwater and seawater will be greater along zones such as fractures and permeable pockets.

The prospects for developing shallow groundwater from alluvium along Mission Creek are discussed in terms of second class water supply. Chemical analyses of rainwater samples collected during 1979-80 show rainwater is a weak solution of NaCl, having a similar S04:Cl ratio to seawater. A recharge estimate of 17.7% using the ratio of chloride ions in rainwater and shallow groundwater is given for the upper weathered mantle storage.

An outline is given of the cost estimates and methods for drilling and equipping production bores in the Broken Bridge - Mission Creek valleys. Drilling logistics are discussed with regard to methods and costs of transporting drilling equipment to Norfolk Island. The main recommendation is a deep drilling program to prove or otherwise the existence of deep groundwater for development as a long-term primary water resource for domestic use. The drilling program needs to be formulated in co-ordination with water supply and sewage scheme proposals that will best serve the long-term needs of Norfolk Island.

INTRODUCTION

In June 1980 the Department of Housing and Construction (DHC) completed a report on the proposed water supply and sewerage project for Norfolk Island (Goldfinch & Cross, 1980). This report requested that the Bureau of Mineral Resources, (BMR) implement the following recommendations:-

(1) Undertake hydrogeological investigations on Norfolk Island as recommended in a groundwater report on Norfolk Island (Abell, 1976).

(2) Undertake investigations, drilling and testing as appropriate to provide observation and production bores in either or both of the Broken Bridge/Mission Creek valleys. A sufficient number of bores are to be drilled so that a production rate of not less than 10.4 L/sec is achieved with at least one bore in excess of minimum requirements to provide stanby capacity. Each production bore is to be cased and fitted with screens.

To implement the first of these recommendations Messrs R.S. Abell, F.J. Taylor and P. Swan of BMR visited Norfolk Island over a three-week period between May and June 1981. The main objective of the survey was a hydrogeological/geophysical investigation in the Broken Bridge - Mission Creek valleys leading to the selection of drill sites and recommendations on drilling to ascertain whether a groundwater supply at deeper levels on the island can be developed free of pollution from human or other agencies.

Responsibility for funding and administration of the investigation was undertaken by the project manager Mr R. Howes of the Department of Housing and Construction (NSW region).

The following activities were undertaken by the survey party:

(1) Detailed resistivity and magnetometer traverses in the Broken Bridge/Mission Creek areas with additional reconnaissance traverses on the Kingston Lowland, Anson Bay and Steels Point areas.

(2) Detailed hydrogeological assessment of the Broken Bridge/Mission Creek areas supplemented by further observations of the general hydrogeology of the island, in particular the waterbearing properties of the volcanic rock sequence.

(3) An assessment of the capability of the drilling rig on the island to drill bores in excess of 100 m, a requirement for developing groundwater in bedrock aquifers.

(4) Other activities included the selection of a bore site at the Norfolk Island school, inspection of the evaporimeter at the Meteorological station, examination of drill core recovered from the quarry site investigations in 1980 and stream gauging facilities.

(5) Discussions were held from time to time with the Acting Administrator and the Chief Minister and their staffs on various aspects of the survey.

Opportunity is taken in this report to discuss some of the broader aspects of the hydrogeology of Norfolk Island and to include a section on the water quality aspects of rainwater collected from 1978-1980. Appendices relate to brief reports of support investigations arising out of the senior author's visit (RSA) to the island. This report supplements in more detail information contained in an interim report submitted to the Department of Housing and Construction (NSW region) in September 1981 (Abell & Taylor, 1981).

GEOGRAPHY

Norfolk Island is the oldest of Australia's external territories. It is situated 1676 km east-northeast of Sydney at latitude 29 degrees 02 minutes south and longitude 167 degrees 57 minutes east (Fig. 1). The Island is about 8 km long, 5 km wide and has a total area of 3455 ha. It is of volcanic origin and the coastline of some 32 km consists of precipitous cliffs except for a small section on the south side at Kingston where there is a jetty. There is a second landing place at Cascade on the northeast coast and a few other accessible foreshores. An airport has been built on the southwest portion of the island, and aircraft now provide the main means of passenger transport to and from the island. The average elevation is about 110 m; two peaks rise slightly over 305 m.

The climate on Norfolk Island is mild and subtropical. Mean maximum and minimum temperatures recorded between 1939-74 are 21.3^{o}C and 16.1^{o}C. The annual mean rainfall is approximately 1335 mm which is well distributed through the year with some decrease in summer months. Prevailing winds blow mainly from the east and southeast.

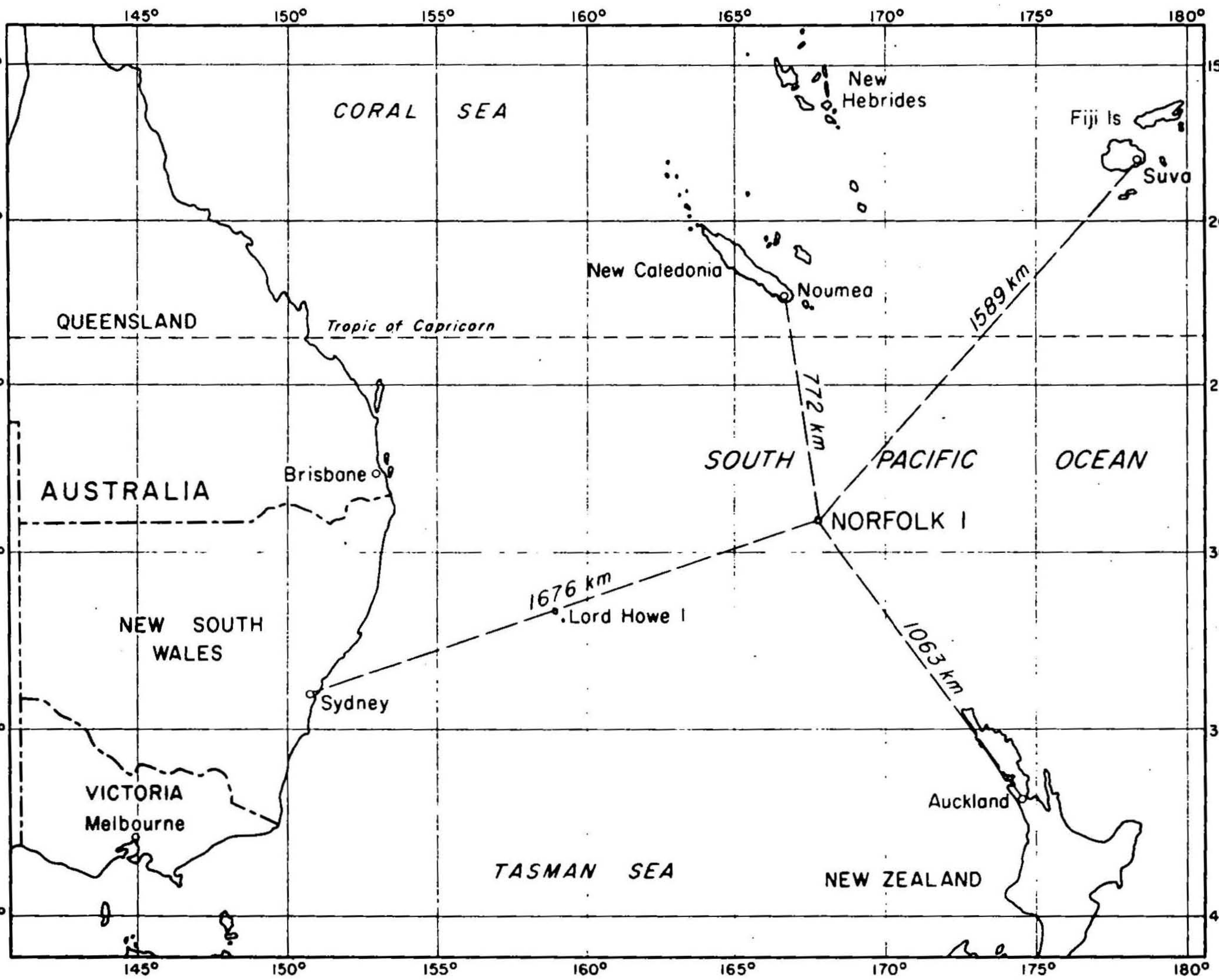

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Fig. 1 Location of Norfolk Island

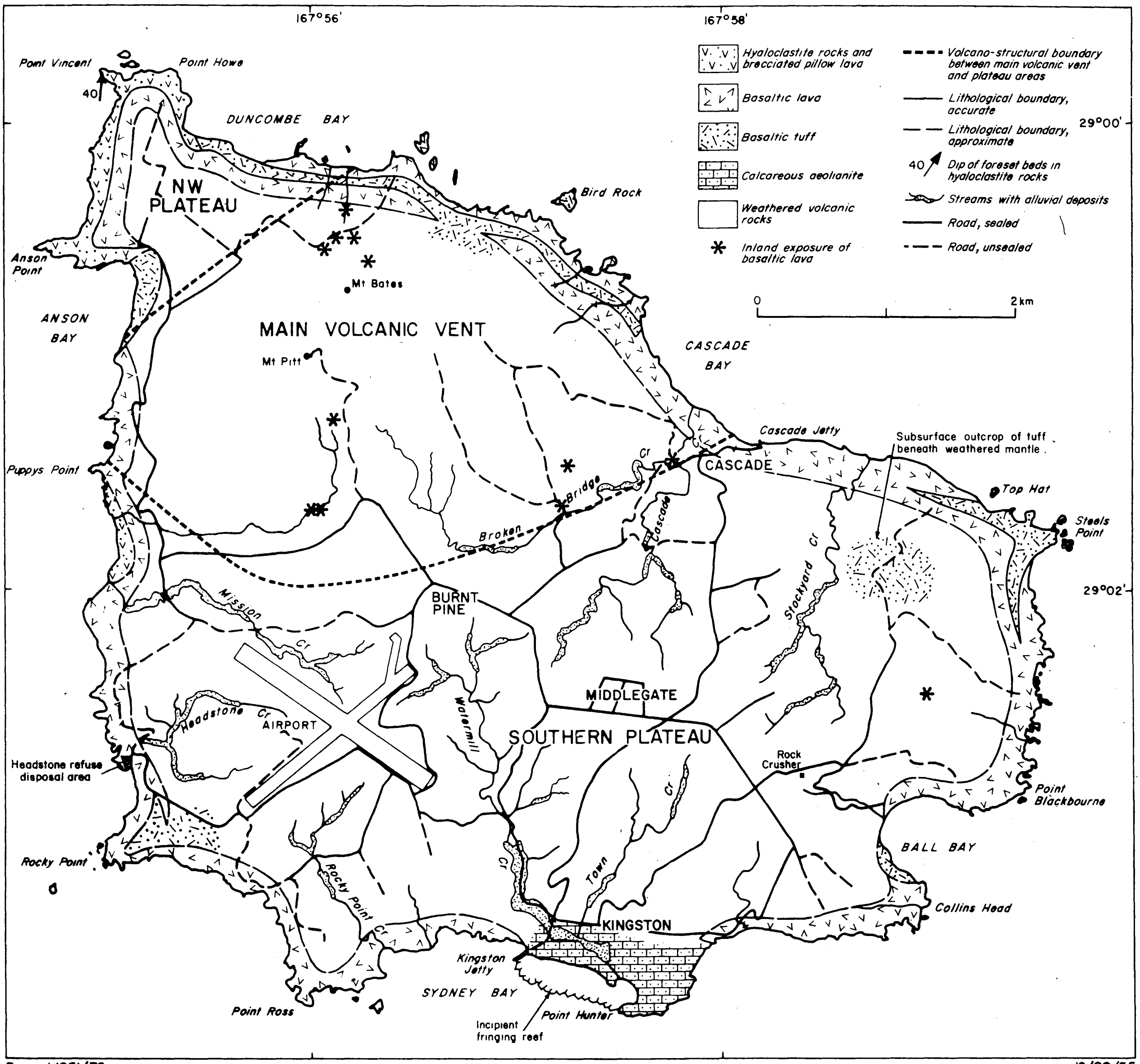

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Fig. 2 Simplified geology

GEOLOGY

Norfolk Island lies towards the eastern edge of the Australian lithospheric plate and rises as a small landmass from the Norfolk Rise, a pronounced north-trending continental ridge between New Zealand and New Caledonia. A review of the plate tectonic, oceanographic and biogeomorphic development in the southwest Pacific over the last 100 million years is contained in a collection of papers given at the 1979 ANZAAS conference in Auckland, NZ (Ballance, 1980). Norfolk Island is an erosional remnant of probably a number of local volcanic centres that erupted several times between 3.05 and 2.3 m.y. ago. The stratigraphy, eruptive history, petrology and geochronology of the island has been studied by Jones & McDougall (1973) and Green (1973).

The cliffs surrounding Norfolk Island provide a nearly continuous horizontal section of the geology (Fig. 2). Inland, outcrop is obscured by deep weathering and in places by thick vegetation. The unweathered part of the volcanic sequence consists mainly of basaltic lavas and tuffs. The lavas are generally flat-lying or have a dip of a few degrees. Individual flows range from 1 m to 30 m thick and commonly show well developed columnar jointing. The tuffs are interbedded with and rest unconformably on the basalts; they range in thickness from a few metres up to 40 m; palagonite (an alteration product of sideromelane) imparts a deep yellow colour to these rocks in coastal exposures. Bedding in the tuffs is generally horizontal but sedimentary structures such as current bedding, occasional scour and fill structures and impact distortion structures (volcanic bomb sag) suggest that water and wind have been active agencies in the formation of these rocks. The irregular vertical and lateral distribution of the volcanic rock sequence suggests a series of complex and spasmodic eruptive events in which lava and tuff units were deposited on a series of weathered or eroded topographic surfaces. Intrusive basaltic dykes and sills have been described from Phillip Island (Jones and McDougall, 1973). Similar rocks are expected to occur on Norfolk Island but have yet to be described in coastal sections; inland their existence is obscured by deep weathering.

Along the northwest coast between Anson Bay and Duncombe Bay, exposures of hyaloclastite deposits occur at the base of cliffs a few metres above sea level. These deposits contain subrounded clasts of scoriaceous basalt (disrupted pillows) in a yellow, tuffaceous matrix which grades up into hackly (irregular) jointed lava. At Point Vincent these brecias are crudely stratified at angles of up to 40° and lava tongues contained within them dip approximately northwards (Plate 1). The lower contact with pillow lavas is below present day sea level. According to Jones & McDougall (1973) this autoclastic lithofacies has been interpreted as the product of fragmentation of lava by a process of friction and quenching as lava flows from a subaerial environment to seawater. The gradational contact between lava and breccia approximates to sea level at the time of eruption. This interpretation is confirmed by the presence near the top of the quench zone of current-bedded tuffs and boulder deposits which represent a local reworking of the breccias in a littoral or beach environment (Plate 2). A shallow marine volcanic delta has been the interpretation given to similar rock relationships studied by Furnes and Fridleifson (1974) in Iceland. The continuous distribution of the quench zone a few metres above sea level round the northern half of the island is taken to indicate slight post-volcanic tilting southwards (Jones & McDougall, 1973).

Along the shore of the Kingston Lowland is a sequence of cross-bedded and massive calcareous aeolianites with thin carbonaceous clay of Holocene (Recent) age. The aeolianite forms a wave-cut platform supporting an incipient fringing coral reef. These rocks were probably deposited during periods of lower sea level in the Quaternary when a series of bevelled platforms around the island exposed to wind and current action acted as a source of calcareous and sandy material. The palynology of the carbonaceous clay is described in Appendix 1.

Under a humid and subtropical environment a deep weathering profile up to 50 m thick has developed without interruption in the volcanic succession. The main residual products are lateritic soils (krasnozems), unweathered and spheroidally weathered basalt boulders and decomposed volcanic rock. The weathered profile is well exposed in numerous road cuttings and cliff sections around the island. There is no evidence of marine erosion and deposition in the weathering profile that might suggest that the island has been submerged since its formation.

In active creek catchments surface water run off has been sufficient to aid in the deposition of narrow, localised strips of alluvial clay and silt (Fig. 2). Perched alluvium occuring in the higher reaches of Watermill, Cascade, Stockyard, Rocky Point and Town Creek probably represent local base levels of deposition. More continuous tracts of alluvium occur in Mission, Broken Bridge and Headstone creeks. Along the coastal lowland at Kingston

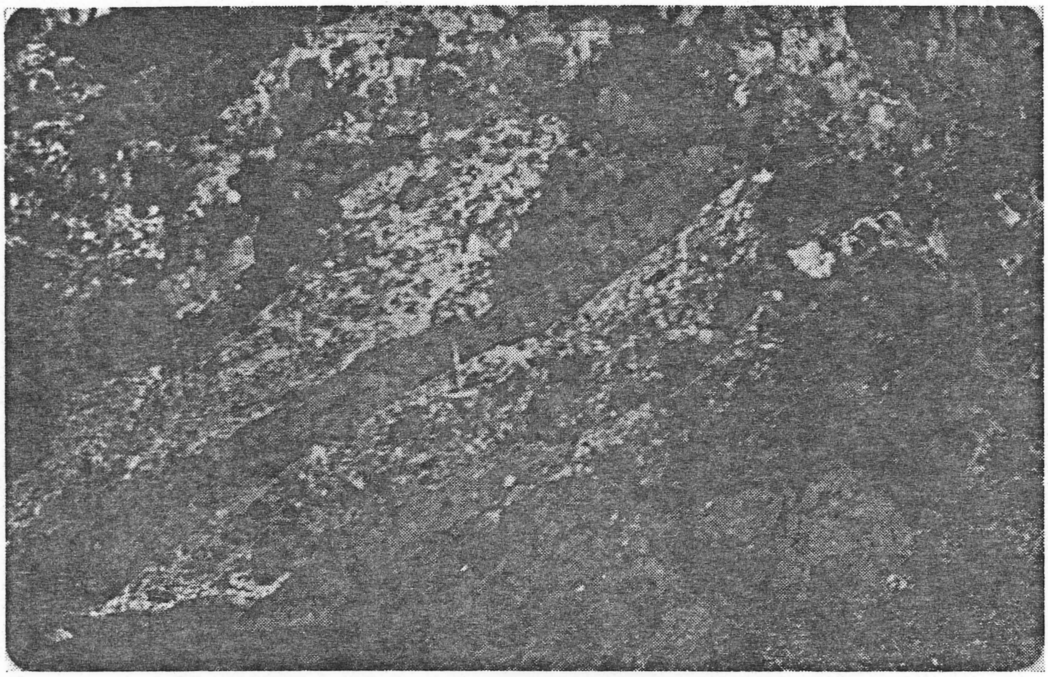


Plate 1. Dipping lava tongue in hyaloclastite deposit, Point Vincent

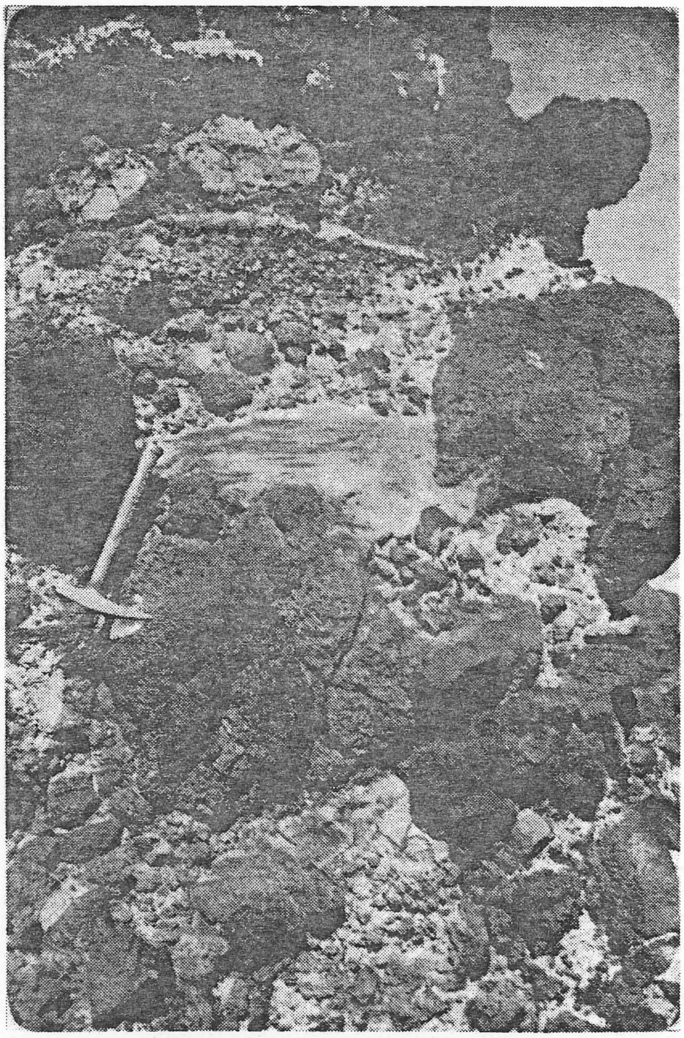


Plate 2. Reworked hyaloclastite deposit, Point Vincent. Note the channel infilling of tuff and graded boúlder deposits

an open channel has been constructed to drain a wider strip of alluvium deposited in the lower reaches of Watermill creek.

Norfolk Island comprises two main volcano-structural elements: an eruptive centre and a constructional lava apron (Figs. 2 & 5). The main eruptive centre corresponds to elevated terrain centred on Mt Pitt and Mt Bates and is thought to be composed mainly of volcaniclastic rock, thin basalt lava flows and intrusive dykes and sills. The constructional lava apron corresponds to a deeply dissected plateau making up the southern half of the island and a small part of the northwest. This feature has built up around the main eruptive centre and comprises basalt lava flows and local basaltic tuff. The complex boundary between the two volcano-structural elements is probably a lithofacies change marked by the interdigitation of lava flows and volcaniclastic rocks. It is expressed topographically by the deeply dissected valley of Broken Bridge Creek which trends northeast between Cascade and Burnt Pine. The upper valley development of Mission Creek may be a further continuation of this zone. Aerial photographs show that the island is crossed by numerous lineaments or fracture traces which are probably an expression of joints, zones of closely spaced joints or faults. Polar graphs (Abell 1976), show that fracture trace directions are predominantly NNW but with a significant percentage trending ENE. It is probable that these fracture directions are a complex response to stress relief resulting from a post eruptive history of submergance and subsidence of the island since volcanism ceased in the late Pliocene.

Although the post-eruptive evolution of Norfolk Island is poorly known, an examination of the bathymetry shows that the island is surrounded by a plateau-like submarine bench coincident with the 250 m bathymetric contour (Van der Linden, 1969). The submerged pedestal appears to have developed as an extensive wave cut platform (Fig. 3) and may approximate to the greatest aereal extent of the "Norfolk land mass" at the end of the Pliocene. Global cycles of sea level changes documented by Vail and others (1977) indicate that there was a global lowstand in sea level in the late Pliocene-early Pleistocene. Since that time there has been a progressive reduction in size of the "Norfolk land mass" by post-eruptive submergence and relative changes of sea level during the Quaternary.

GEOMORPHOLOGY

Norfolk Island is roughly pear-shaped in plan with its long axis trending northwest. In the northwest the terrain is dominated by an elevated semi-circular ridge rising to more than 300 m which reflects the remains of a volcanic vent in part responsible for the formation of the island. The remainder of the island consists of a deeply dissected southern plateau averaging about 100 m in height; a small remnant of the plateau occurs in the far northwest. Cliffs up to 100 m high supporting rugged coastal scenery along the northwest side of the island slope to the southeast where they reach 50 m. At Kingston an ancient coastline modified by subaerial denudation marks the boundary between the southern plateau and coastal lowland. The coastal lowland about 1.5 km long and 0.5 km wide is less than 20 m above sea level. Mass movement in form of soil creep and landslips occur along the coastline and in catchments that have been cleared. Some control is being attempted by planting Norfolk Pine (*Arucaria* sp.) in the lower valleys of Watermill Creek.

The geomorphology of the coastline has evolved from the interaction of geology, marine and subaerial processes and sea level changes associated with climatic change during and since the end of the Pliocene. Marine processes appear to be active as shown by erosional features such as wave-cut platforms, sea stacks, arches and caves. Clearly the present cycle of marine erosion is causing cliffs to recede quicker than streams can incise their courses. This truncation of the drainage by cliff recession is suggested by hanging valleys that are dry or carry streams that cascade over cliffs as rapids or small waterfalls.

The drainage system on Norfolk Island consists of a network of dry valleys leading into perennial and intermittent streams. Streams are fed in their higher reaches from spring seepages and to a large degree are maintained by baseflow. Some structural control of drainage by joints and fractures is suggested by the local development of straight reaches e.g. Watermill Creek, and where tributaries join the main streams at right angles. Stream profiles locally have swampy reaches and alluvial tracts (Fig. 2) which has led to the development of meanders typical of underfit streams that are too small to have eroded the valleys in which they flow. Streams are gradually losing their erosive power and in most cases only reach solid rock at the perimeter of the island.

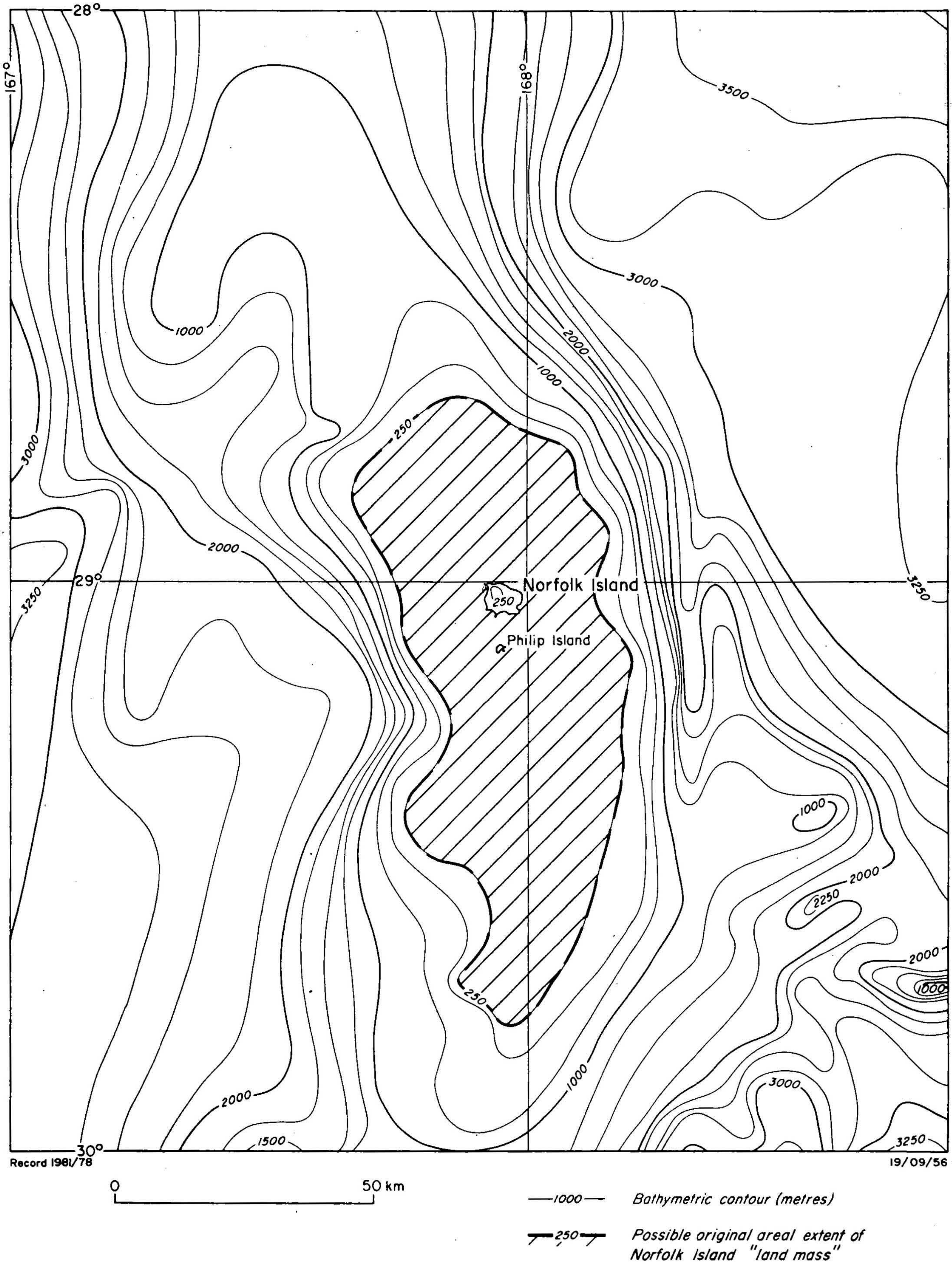
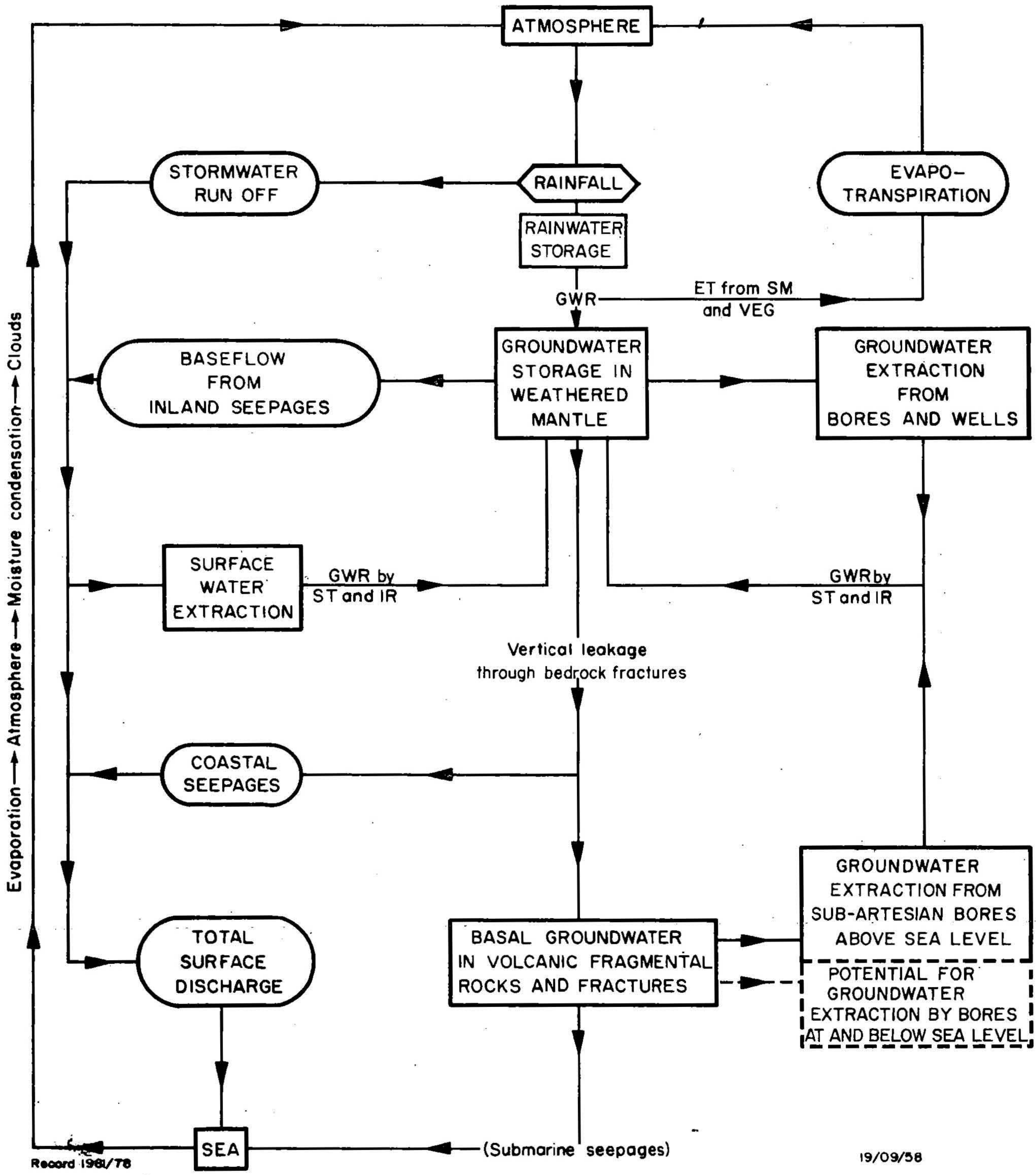


Fig. 3 Bathymetry



ET	*EVAPO-TRANSPIRATION*	GWR	*GROUNDWATER DISCHARGE*
SM	*SOIL MOISTURE*	IR	*IRRIGATION*
VEG	*VEGETATION*	ST	*SEPTIC TANKS*

INPUT OUTPUT

Fig.4 Hydrological cycle

It is evident that during the late Pliocene and at intervals during the Pleistocene many of the stremas had much greater erosive power than at present. Dry valleys were cut originally by active streams which have now been reduced in size owing to changing climatic conditions, vegetation patterns, a lowering of the water table and the development of a porous weathered profile indicative of a now decreasing permeability regime in the volcanic succession.

GROUNDWATER OCCURRENCE

Groundwater on Norfolk Island functions as a dynamic system within the framework of the hydrological cycle (Fig. 4). Rainfall reaching the ground either returns to the atmosphere by evapotranspiration, runs off the ground surface into streams and thence to the sea, or because of the high porosity of the soil, infiltrates and moves downwards under gravity past the root zone of plants to the saturated zone. The top of the saturated zone is marked by a water table in the weathered mantle. Groundwater moving laterally in the direction of the water table gradient may discharge as coastal seepages near the top of the cliff line or in the floor of valleys where the groundsurface intersects the water table. If the water table descends below the base of the valleys during dry periods, streams are reduced in flow or dry up. At the base of the weathered mantle it is likely that there is vertical leakage of groundwater through bedrock fractures. Some groundwater moving through these fractures is either discharged as coastal seepages close to sea level or will recharge thin tuff and agglomerate beds between lava flows to form local confined groundwater; the remainder continues to deeper levels where it accumulates as a basal groundwater body in volcanic breccias (Fig. 5). The cycle is completed with groundwater discharge as submarine seepages at and beyond the margin of the island.

Weathered mantle

Current development of groundwater on the island is from numerous bores and wells tapping a high level leaky unconfined aquifer in the weathered mantle (Abell, 1976). The upper boundary of the aquifer is defined best on the southern plateau by a water table which in some places exceeds 100 m ASL (above sea level). The base of the aquifer is a gradational boundary with fresh volcanic rock; its lateral extent is truncated by marine erosion at the margin of the island (Fig. 5). The porous nature of the aquifer suggests it has considerable groundwater storage capacity but the elevated watertable indicates only moderate permeability. In the Burnt Pine - Middlegate area which supports the greatest concentration of people there is entry and movement of sanitary waste into the ground from septic tanks. Chemical and bacterial pollution of this aquifer has not yet reached disastrous levels, largly because porous clay in the unsaturated portion of the weathered mantle acts as a filtering agent and an adsorption medium to remove bacteria, undissolved solids and some chemicals. However continued dependance on shallow groundwater will tend to aggravate this problem and in the long term it is desirable to develop a deeper source of groundwater free of this form of pollution.

Basaltic tuff and agglomerate

These rocks are accessible in exposures along the northern coastline at Anson Bay and from Duncombe Bay to Cascade, Steels Point and between Rocky Point and Headstone. Although the lateral extent and thickness of these rocks inland is conjectural it is likely that they thicken towards the summit area of the island (the main volcanic focus) but occur as thin lenticular beds underlying the southern plateau (Fig. 5). Unlike the lava flows with which they are interbedded, tuffs have poorly developed fracture permeability. Intergranular or primary porosity in these rocks was originally high (50%) at the time of deposition but has since been reduced by the formation of palagonite (a weathering product of basaltic glass). Samples subjected to porosity and permeability tests (Abell, 1976) showed good storage capacity (20-40% porosity) and good hydraulic conductivity (up to 7.3 m/day). In most samples hydraulic conductivity in the horizontal direction exceeds that in the vertical owing to grain size changes associated with bedding.

Further evidence of significant permeability associated with these rocks is afforded by the presence of coastal spring seepages. The largest and most important is a seepage close to Cascade Jetty (Fig. 6, Plate 3). At this locality groundwater seeps from a tuff bed 2 m thick over a strike length of about 30 m A rough estimate of groundwater loss at this site can be made by applying D'Arcy's law from the formula Q = K.I.A.

where Q = Seepage discharge in M^3/day

K = Average hydraulic conductivity value of tuff in m/day

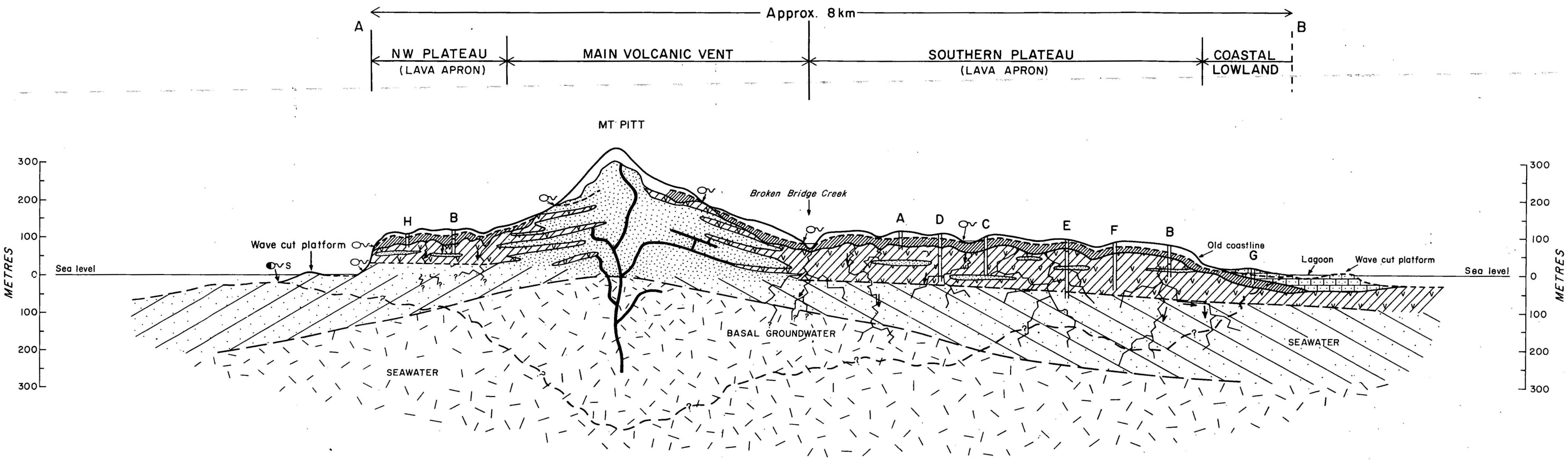
I = Hydraulic gradient

A = Area of seepage loss in m^2

Applying the formula

$$Q = 4.8 \times .412 \times 60$$

$$= 119 \ m^3/day$$



GROUNDWATER DEVELOPMENT

A Bore or well taps the water table in the weathered zone, water supplies obtained are subject to periodic drought conditions, bacteriological and chemical pollution

B Bore taps saturated tuff bed recharged by a wet fracture system, and confined by impermeable basalt; gives sub-artesian water supply

C Bore tapping dry tuff bed intersected by a dry fracture system. No recharge to aquifer; no water supply and lost circulation expected during drilling

D Bore intersects wet fracture system in basalt recharged from a creek; gives sub-artesian supply

E Bore intersects dry fracture system and tuff bed in basalt; lost circulation during drilling; if bore deepened will provide sub-artesian supply from basal groundwater in hyaloclastite rocks at base of island

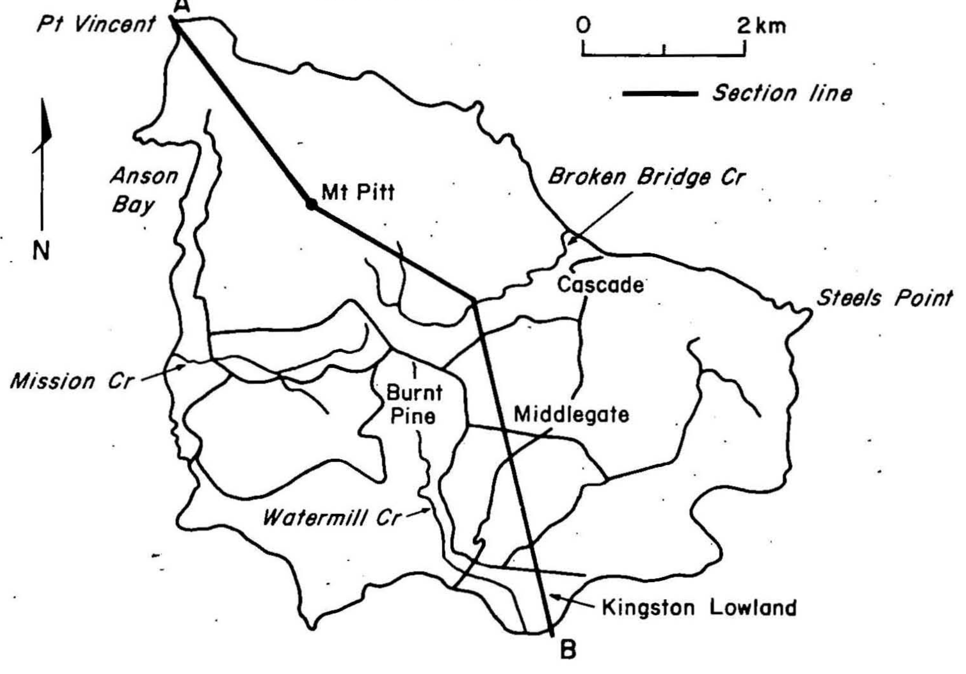
F Bore penetrates impermeable and poorly fractured basalt; no water supply

G Shallow well taps water table in calcareous aeolianite; water supplies subject to saline intrusion if overpumped

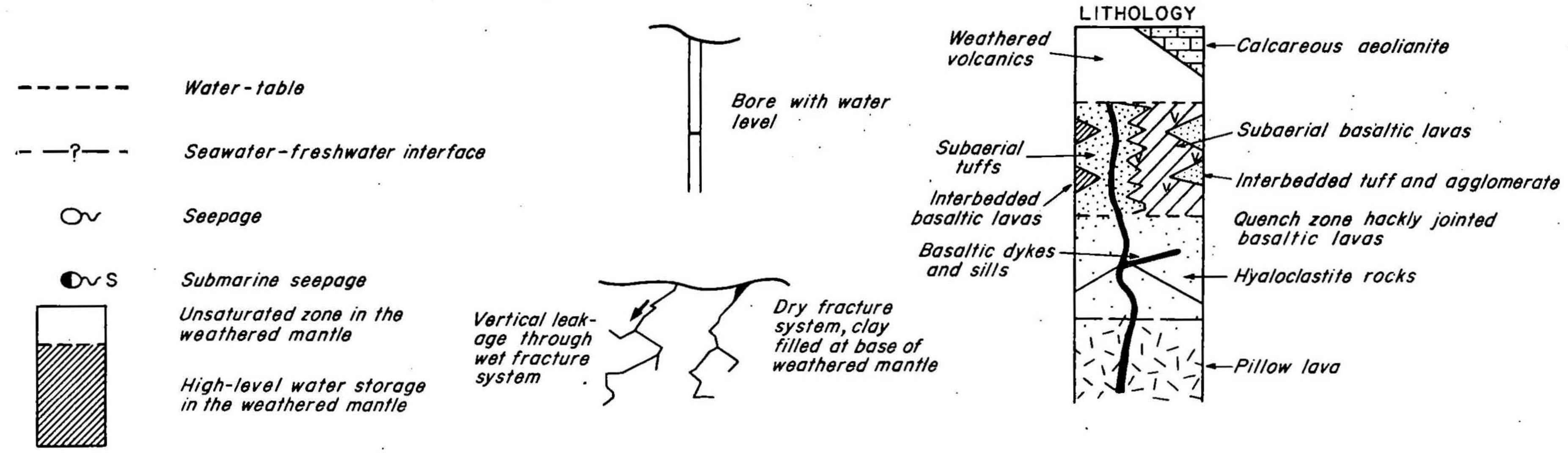
H Shallow well taps high level saline groundwater at the base of weathered mantle. Groundwater polluted by initial high concentration of chloride salts dissolved in recharging groundwater; stagnant zone, no vertical groundwater leakage to bedrock aquifers

Fig.5 Simplified schematic hydrogeological section across Norfolk Island showing current groundwater development

LOCALITY MAP



LEGEND



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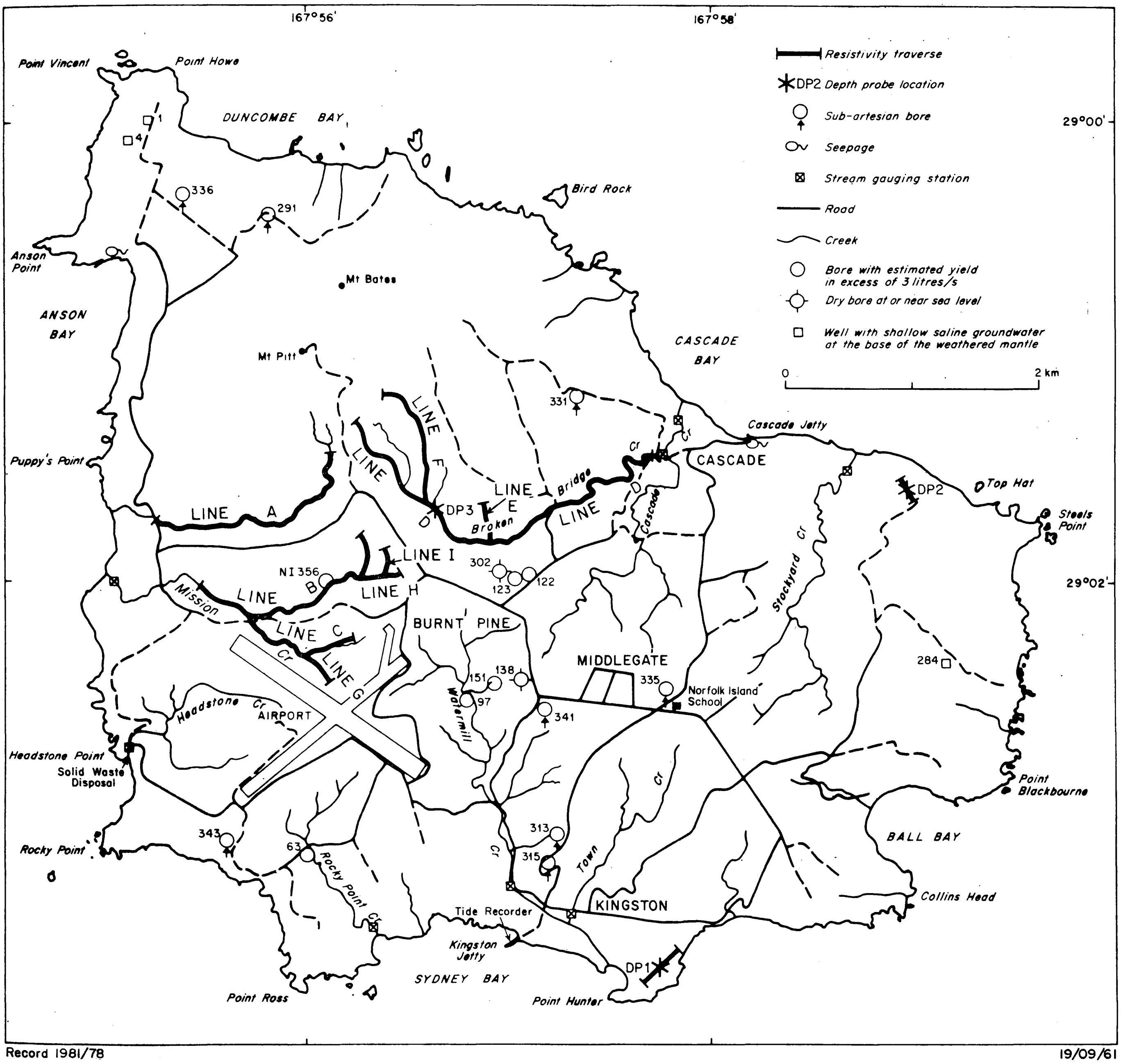


Fig.6 Location map of resistivity traverses, distribution of bores and stream gauging stations

Over the last few years drilling on Norfolk Island has penetrated more frequently below the weathered mantle and has now provided evidence of subartesian groundwater supplies. The locations (Fig. 6) and details of the bores are given in Table 1. The lithological logs for these bores supplied by G. Duvall (Unpubl. Rept. 1980) suggests that they are tapping beds of tuff and or agglomerate between lava flows; the layers of hard, dense impermeable basalt capping the tuff act as confining layers or permeability barriers for groundwater contained in the aquifer. When a confined aquifer of this type is intercepted by a bore, water will rise in the hole to a static level which approximates to atmospheric pressure. The head of water measured in the bore reflects the pressure of the water in the aquifer. The data provided in Table 1 indicates that where pump tests have been undertaken these bores have given good yields with negligible drawdowns.

From laboratory measurement of porosity and permeability values, an estimate of groundwater loss at a coastal seepage at Cascade and evidence of subartesian groundwater it is concluded that basaltic tuff and agglomerate layers between basaltic lavas are capable of storing and transmitting significant quantities of groundwater provided that they are accessible to recharge from the fracture system in surrounding basalt flows. Futher investigation of these aquifers as part of a deep drilling program will lead to a better understanding of their subsurface distribution and ultimately the long term development of groundwater supplies beneath the weathered mantle.

Hyaloclastite rocks

Along the northwest coast between Anson Bay and Duncombe Bay and also locally south of Puppys Point exposures of hyaloclastite breccia can be examined at the base of cliffs a few metres above sea level (Fig. 2).

The nature of the primary porosity and permeability of these rocks observed in coastal section at Point Vincent can be explained in terms of the model for a marine basaltic volcano proposed by Moore and Fiske (1969) and Jones (1970). Thin sections of these rocks show spheroidal and channel-like void spaces in palagonitized basaltic glass containing corroded crystals of pyroxene and euhedral laths of plagioclase. The void space originates from the entrapment of gas/liquid in the glass when subaerial basalt lava was quenched and brecciated as it flowed into seawater. The brecciation process was aided by the release under pressure of the entrapped gases and liquids which ruptured

Table 1 INVENTORY OF SUBARTESIAN BORES ON NORFOLK ISLAND

Number	Date Completed	Owner	Land Division	Elevation (m)	Depth (m)	Water level (m) (below surface)	Depth (m) water entry into bore (below surface)	Lithological log	Comments
NI 291	28-2-75	J. Hayes	100f	105	79	26	79(?)	No	Bore completed and reported to yield 4,500 litres/hour.
NI 313	26-10-77	M. Bailey	80a	43	45	14	37 - 45	No	Bore completed 2m BSL; yielded 1125 litres/hour without drawdown after 4hrs pumping.
NI 315	29-6-78	L. Hutchinson	81j	77	64.5	24	64	Yes	Bore uncompleted; hole blocked by drillpipe.
NI 331	2-7-80	N. Tavener	106b-1	91.5	49	26.5	33.5 - 46	Yes	Bore completed and capable of yielding 1080 (+) litres/hr; no drawdown after ½hr pumping.
NI 335	19-10-80	G.B. Gray	34	134	64.5	33	56 - 64	Yes	Bore completed and yields 2025 litres/hr; 2m drawdown after 4hrs pumping.
NI 336	16-10-80	C.L. Evans	99b	97.5	39.5	26	37 - 39.5	Yes	Bore completed and yields 6480 litres/hr; no drawdown.
NI 341	21-12-81	Hillcrest Hotel	53a	119	98.0	45	88.5(?)	Yes	Bore completed. Continuous 48 hr pump test yielded 900 litres/hr over the first 12 hrs and 600 litres/hr over last 36 hrs. Drawdown details unknown.

Table 1 con't

Number	Date Completed	Owner	Land Division	Elevation (m)	Depth (m)	Water level (m) (below surface)	Depth (m) water entry into bore (below surface)	Lithological log	Comments
NI 343	27-7-81	C.M. McCullough	93k	87	103.5	32	71(?) and 85 - 97	Yes	Bore completed 17m BSL Bore cased to 85m. Yield and drawdown details unknown.
NI 356	26-1-82	R. Barnett	15oe	76.2	106.7	35.4	105.8	Yes	Bore completed to 27.43m below sea level currently the deepest bore on the island. Bore yield 2160 litres/hr over a 5 hr pump test with a draw-down of 4.3 m.

and fragmented the glass to cause the interconnected void space on their escape to the sea. It now appears that the original void space in the breccia has been reduced by a lining of pale yellow clay. The clay has been identified as belonging to the montmorillonite and illite clay mineral group (J. Fitzsimmons, pers. comm. 1981 and P.A. Duff, Appendix 2). The origin of this clay maybe as a decomposition product of palagonite or possibly clay fines from the weathered mantle washed into and deposited in the void space by groundwater circulation. Porosity and permeability values have been determined by laboratory techniques on samples of these rocks submitted to P.G. Duff, Petroleum Technology Laboratory (Appendix 2).

Evidence that these rocks have potential as an aquifer is afforded by the occurrence of seepage zones. A seepage at the base of sheer cliffs on the north side of Anson Bay (access only at low tide levels) is the largest known coastal seepage on the island. At this locality groundwater discharges from hyaloclastite rocks and hackley jointed lava over an area about twice that of the seepage at Cascade. In addition other smaller seepages are present just above the wave cut platform east of Point Vincent (Plate 4).

Field observation, petrographic examination and laboratory analysis of these rocks suggest they have a porosity and permeability framework capable of retaining basal groundwater. It is evident that if this aquifer is to be developed as a groundwater supply, the subsurface distribution and thickness of these breccias below sealevel and under-lying Norfolk Island, must be proved in more detail by an exploration drilling program.

GEOPHYSICS

Geophysical work was carried out as a major investigatory method to aid in the selection of drill sites for the development of basal ground water on the island. The work involved Wenner resistivity depth probes and resistivity profiling, and was carried out by the Engineering Geophysics group of the Bureau of Mineral Resources. Personnel involved were F.J. Taylor and P. Swan of the BMR as well as field assistants provided by the Norfolk Island Administration.

Apart from three Wenner depth probes the work included 12.5 km of Wenner profiling along selected creek courses, the locations of which are shown in Fig. 6. This profiling was carried out to locate possible areas of deep weathering and fracture zones which could contribute to the recharge of underground aquifers. Several drilling targets were selected from the results of this profiling.

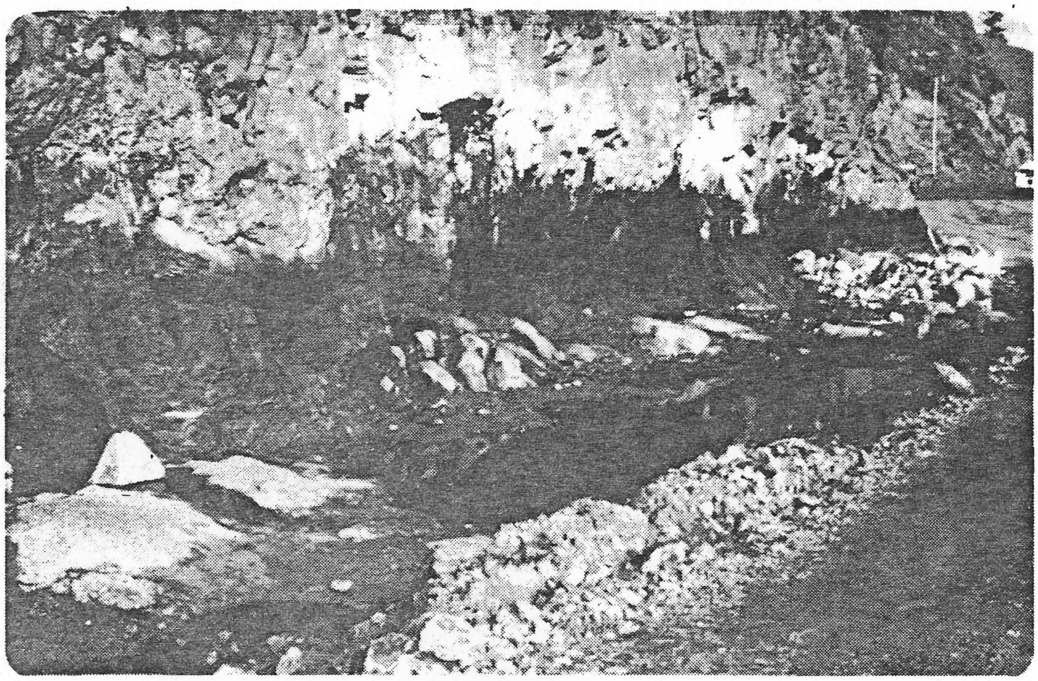


Plate.3 Seepage from basaltic tuff and agglomerate exposed behind Cascade Jetty

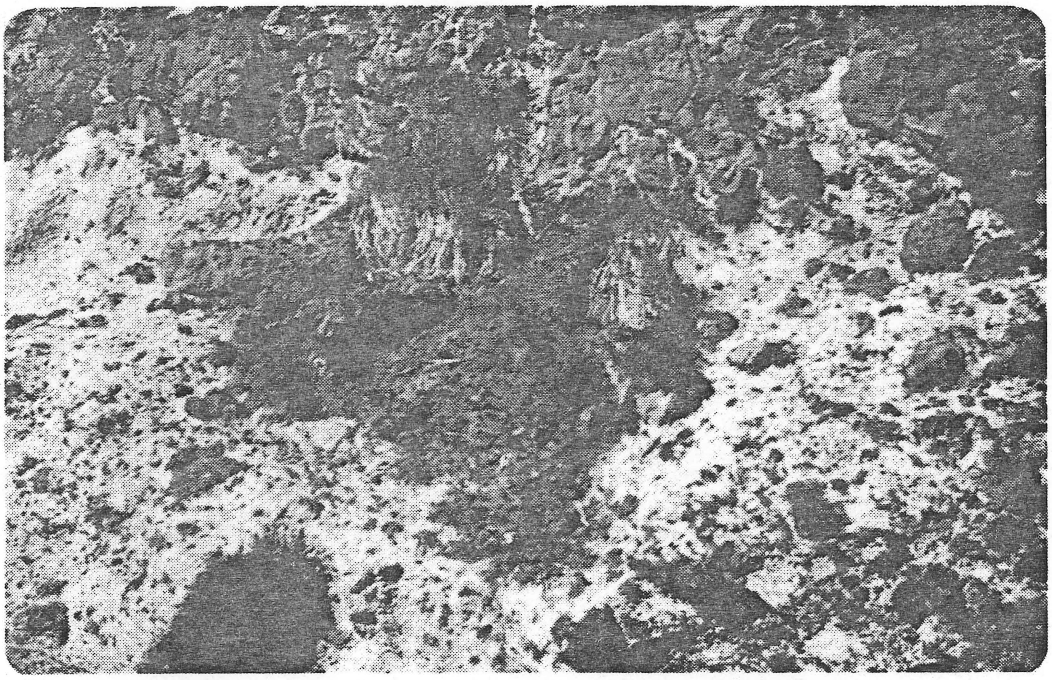


Plate.4 Small seepage from hyaloclastite rocks Point Vincent

Resistivity Methods and Equipment

The resistivity method measures the electrical resistance of the earth by applying a current into the ground using two current electrodes and measuring the resultant induced potential using potential electrodes. The electrical resistance of the earth depends on both the geology and the water content of the earth. Clay and salt water have low resistivities and fresh water in a highly porous medium and fresh unweathered rock have high resistivities.

Two systems of resistivity prospecting are commonly used; depth-probing and profiling. With depth-probing a group of electrodes are spaced in specified geometrical patterns in order to obtain a plot of apparent resistivity versus electrode separation. In general the larger the electrode separation the deeper the current penetration and the deeper the zone being investigated. The resulting plot is interpreted using computer programs to devise plausible models which agree with the field data. The output of these programs is a vertical earth section defined in terms of resistivity and depth. These sub-divisions are then given a geological interpretation. Resistivity depth-probing requires long straight lines and fairly uniform earth conditions in order to achieve deep current penetration and interpretable results. These are severe limitations for this method in areas such as Norfolk Island.

Wenner probes were carried out initially to obtain a representative vertical profile and hence to select a suitable spacing for the Wenner profiling. A good description of the resistivity method together with computer programs for interpretation can be found in Mooney (1980). In resistivity profiling the electode spacing is fixed, depending on the depth of investigation. The electrode configuration is moved from one station to the next in order to build up a profile of resistivity versus station number. In this manner changes in the near-surface resistivity, the depth to unweathered rock, or variations in the resistivity of sub-surface layers can be measured over a long distance.

The resistivity work on Norfolk Island was carried out using an Atlas Copco SAS 300 Terrameter. This particular instrument uses a low current with stacking and cross-correlation. It avoids common sources of error such as electrode polarisation and earth currents. Three Wenner depth probes to a maximum spacing of 100 m were completed, and a total of 12.5 km of Wenner profiling was carried out along lines designated A to I (Fig. 6). The Wenner spacing used in profiling was 16.5 m and the station interval was 50 m.

The objective of the Wenner profiling was to find possible areas of deep weathering and fracture zones which could contribute to recharge of underground aquifers. The profiling was carried out along creek courses in order to avoid the blanketing effect of up to 30 m of fairly unifrom material existing on the plateau. The area investigated was in the Broken Bridge and the Mission Creek catchments.

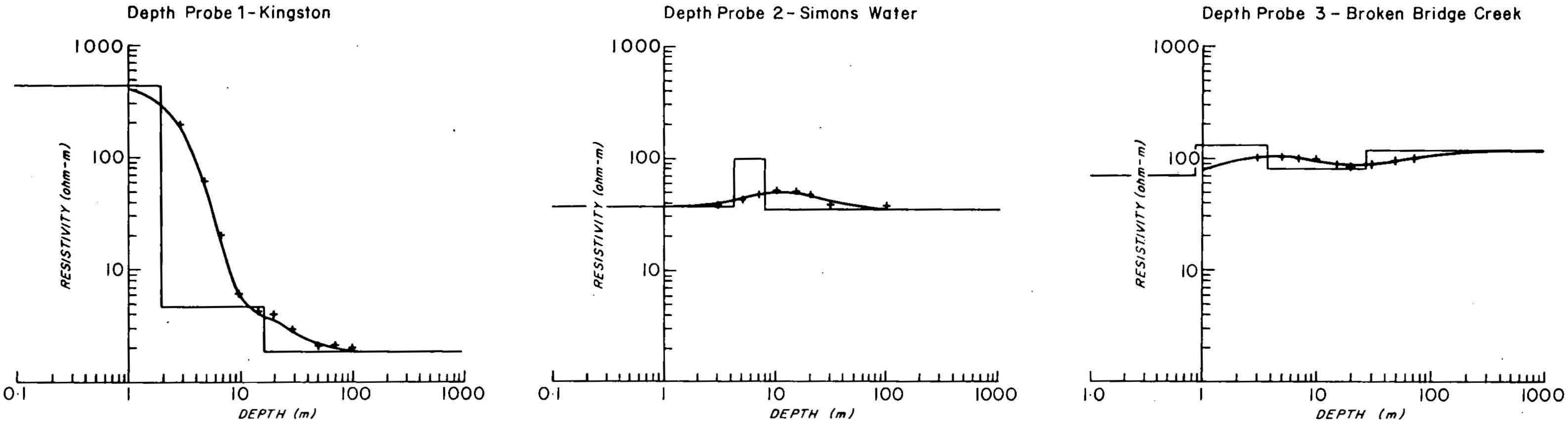
Results

Field curves, together with computer interpretation of the three Wenner depth probes, are presented in Fig. 7. Resistivity probe 1 at Kingston is the only one which shows the deepest electrical subdivision on the Island. This probe shows fresh water overlying saline sediments (1.9 m) with an appreciable transition zone. Resistivity probe 2 at Simons Water illustrates the low resistivity contrasts which are present at higher elevations on the Island. The section is interpreted as 4 m of weathered basalt overlying relatively fresh basalt 4 m thick which in turn, overlies more weathered material. Information on deeper material is not available because of the limited electrode spacing available. Resistivity depth probe 3 in Broken Bridge Creek is located at station 63 on line D. Although there is limited contrast a resistivity layer of 115 ohm-m at a depth of 27 m may represent the total thickness of alluvium and weathered material in this valley.

The resistivity profiles are shown in Figs. 8, 9, and 10. In general the resistivity decreases from high to low altitudes. This reflects an increase in the deposition of finer sediments as well as an increase in water content downstream. In an environment such as Norfolk Island resistivity lows can be caused by:

(a) an increase in the water content of otherwise dry, weathered basalt
(b) an increase in the depth of weathering, i.e. fresh basalt is at a greater depth
(c) an increase in the thickness of alluvium (clay and silt). Finer sediments tend to hold moisture and hence are more conductive.

Examples of alluvial deposits producing resistivity lows are Line D Station 63 and Line A Station 20. In these places the resistivity lows indicate a relatively high concentration of shallow water, and these areas may be significant sources of recharge to deeper aquifers. Two examples of fresh basalt at shallow depth causing resistivity highs are Line A Station 30 and Line D Station 0.



Depth Probe 1 - Kingston

Layer No.	Resistivity	Thickness	
1	447·0	2·0	Fresh water
2	4·7	15·1	Transition zone
3	1·9		Saline sediments

Depth Probe 2 - Simons Water

Layer No.	Resistivity	Thickness	
1	36·7	4·2	Weathered basalt
2	100·9	3·7	Fresh basalt
3	35·3		Weathered basalt

Depth Probe 3 - Broken Bridge Creek

Layer No.	Resistivity	Thickness	
1	67·5	0·9	Saturated alluvium
2	120·2	2·9	
3	78·8	23·7	
4	114·9		

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Fig.7 Resistivity depth probes at Kingstone, Simons Water and Broken Bridge Creek

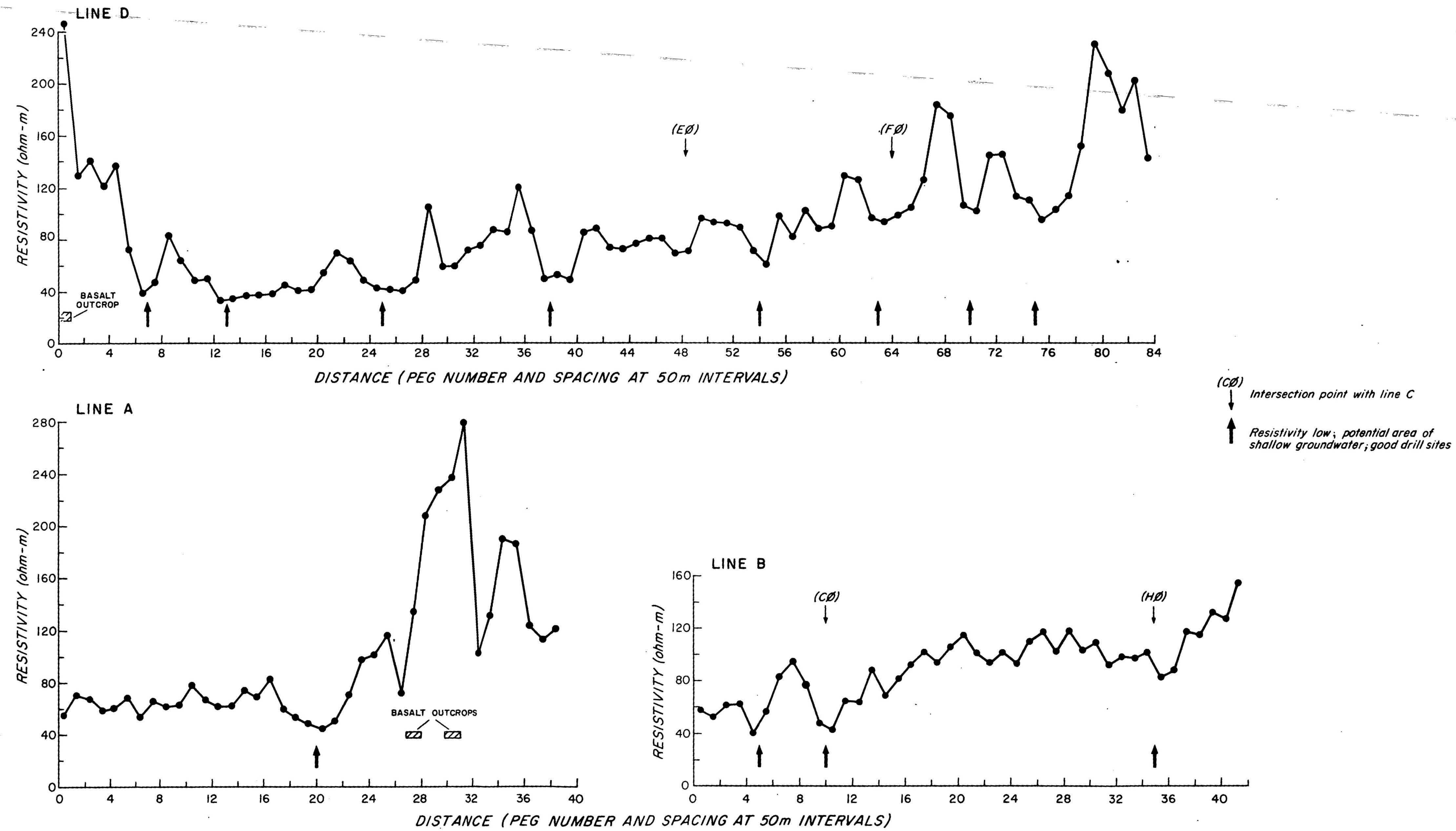

Fig.8 Resistivity profiles , lines A,B and D

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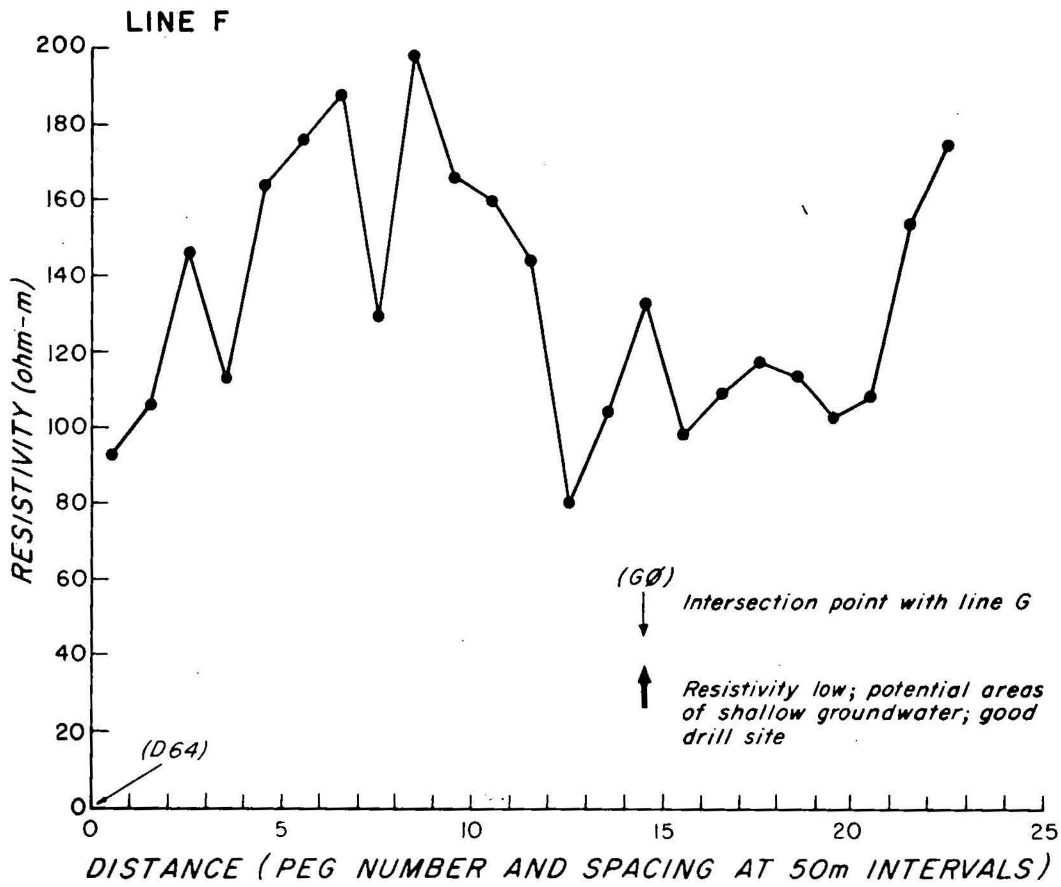

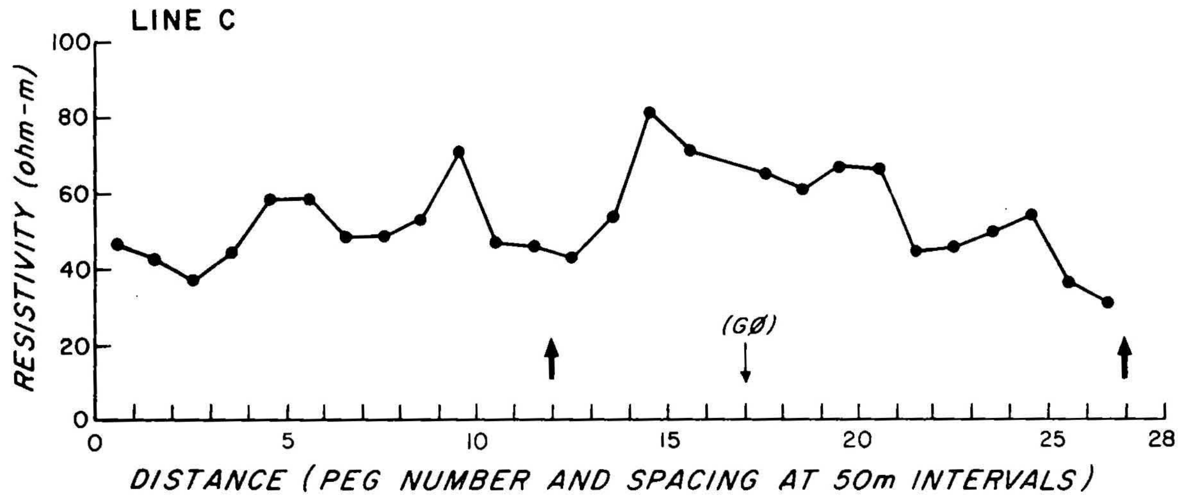

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Fig.9 Resistivity profiles, lines C and F

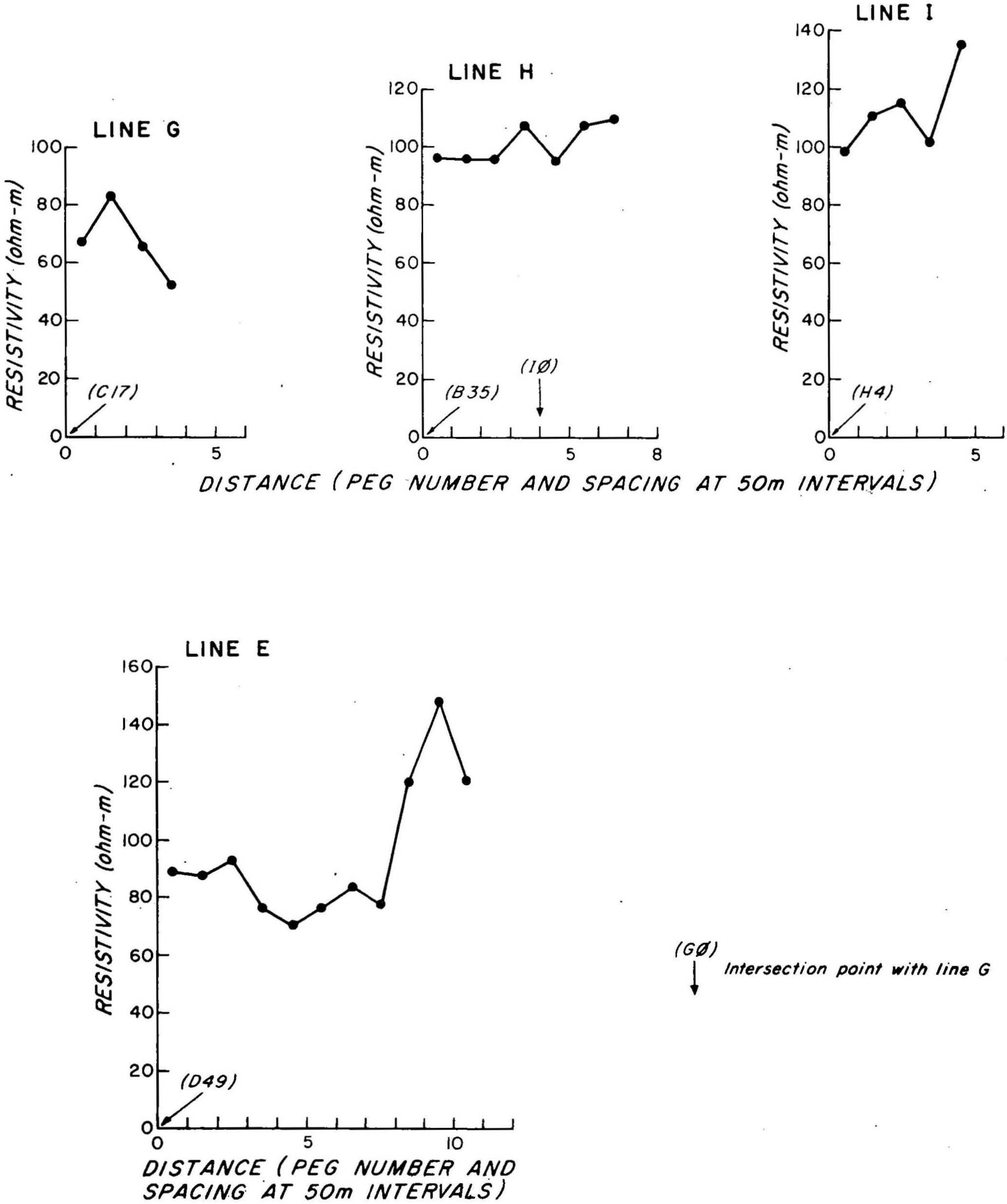

Fig.10 Resistivity profiles, lines E,G,H and I

TABLE 2

SUMMARY OF RESISTIVITY AND PHOTOLINEAMENT DATA IN THE

BROKEN BRIDGE - MISSION CREEK AREA

	Station Numbers	
Line	Resistivity Lows	Photo Lineaments
A	20, 33	33
B	5, 10, 35	35
C	12, 27	
D	7, 13, 25, 38, 54, 63, 70, 75	7, 13, 26, 38, 63 70, 75
E	-	
F	-	
G	-	
H	-	
I	-	

Table 2 lists station numbers associated with resistivity lows. These locations are potential areas of shallow groundwater as well as being good sites for deep drill holes. Where the resistivity lows coincide with aerial photo lineaments these are also shown in Table 2. The location of the resistivity lines, principal photo lineaments and existing water bores are shown in Figure 11. It is not advocated that shallow groundwater cannot exist in areas outside the resistivity lows indicated in Table 2 but rather that these are the more prospective areas. In September 1981 a shallow bore 30 m deep was drilled on plot 146c-2 (owner Daisy Buffett) which yielded approximately 8,000 liters/hr without drawdown over a 4 hr pump test. The drill site is located near survey pegs B9 and B10 where resistivity traverse Lines B and C intersect (Figs. 8 & 11 and Table 2). This successful water bore affords early evidence in support of the views expressed above that drill holes sited on resistivity lows are likely to produce good yields of shallow groundwater in the weathered mantle.

Magnetic Methods and Equipment

The total magnetic field of rocks measured at any point on the Earth's surface is the resultant of two vectors: an induced magnetic intensity vector in the direction of the present Earth's magnetic field; and a remanent magnetic intensity vector imposed on rocks at the time of their formation, which may lie in directions different to the present Earth's field. Most magnetic anomalies are caused by the presence of magnetite. Unlike the resistivity method, magnetic contrasts do not offer direct information on the availability of groundwater, but the method may locate structural boundaries such as faults and fractures, the extent of basic intrusive bodies, and the limits basaltic flows, which will provide useful hydrological information when combined with known geological data.

Magnetic measurements were taken using a proton precession magnetometer Geometrics (816) manufactured in Palo Alto, California, USA. The instrument, which measures total magnetic field intensity in nanotessla units (nT), is portable with the sensing head mounted on a 3 m aluminium pole. Values of magnetic intensity were taken at 25 m-intervals along the same survey lines used for the resistivity measurements (Fig. 12). Some data were also collected at Anson Bay (northwest plateau), Steels Point and Kingston, where readings were taken at 30 m-intervals along straight lines. The magnetic data collected during the survey are listed in an unpublished report by Duvall (1981) and are here presented as a series of magnetic intensity profiles (Figs. 13, 14, and 15). Trend curves added to some profile lines were deduced by eye.

The total magnetic intensity data measured on Norfolk Island are consistent with the concentration of magnetite in the basaltic lava and tuff sequence. The intense amplitude fluctuations in the magnetic profiles broadly range from 51,000 - 54,000 nT. The high amplitude 'noise level' in the magnetic profiles, coupled with the relatively large station spacing, allow only a tentative interpretation of the magnetic data.

<u>Factors affecting the interpretation of magnetic data</u>

(a) A spectrum of normal and reverse polarity magnetism in the unweathered volcanic sequence reflects a complex history of remanent magnetism on Norfolk Island. Palaeomagnetic studies by McDougall and Aziz-ur-Rahman (1972), and Aziz-ur-Rahman and McDougall (1973), show that the basalts span the boundary between the Gauss normal and Matuyama reversed polarity epochs. According to Jones and McDougall (1973) basaltic lavas with normal polarity underlie the summit area of Norfolk Island and lavas with reversed polarity are distributed beneath most of the southern plateau; a small area where reverse polarity lavas overlie normal polarity lavas occur on the western side of the plateau (Fig. 12). The investigation area straddles the boundaries between these three polarity zones. Where the severely dissected topography in Broken Bridge and Mission Creek catchments intersects volcanic rocks containing multiple polarity reversals it will enhance 'noise levels' in the magnetic field. According to D.C. Stuart (pers. comm. 1981) slow-moving partly congealed basaltic lavas may persist at a

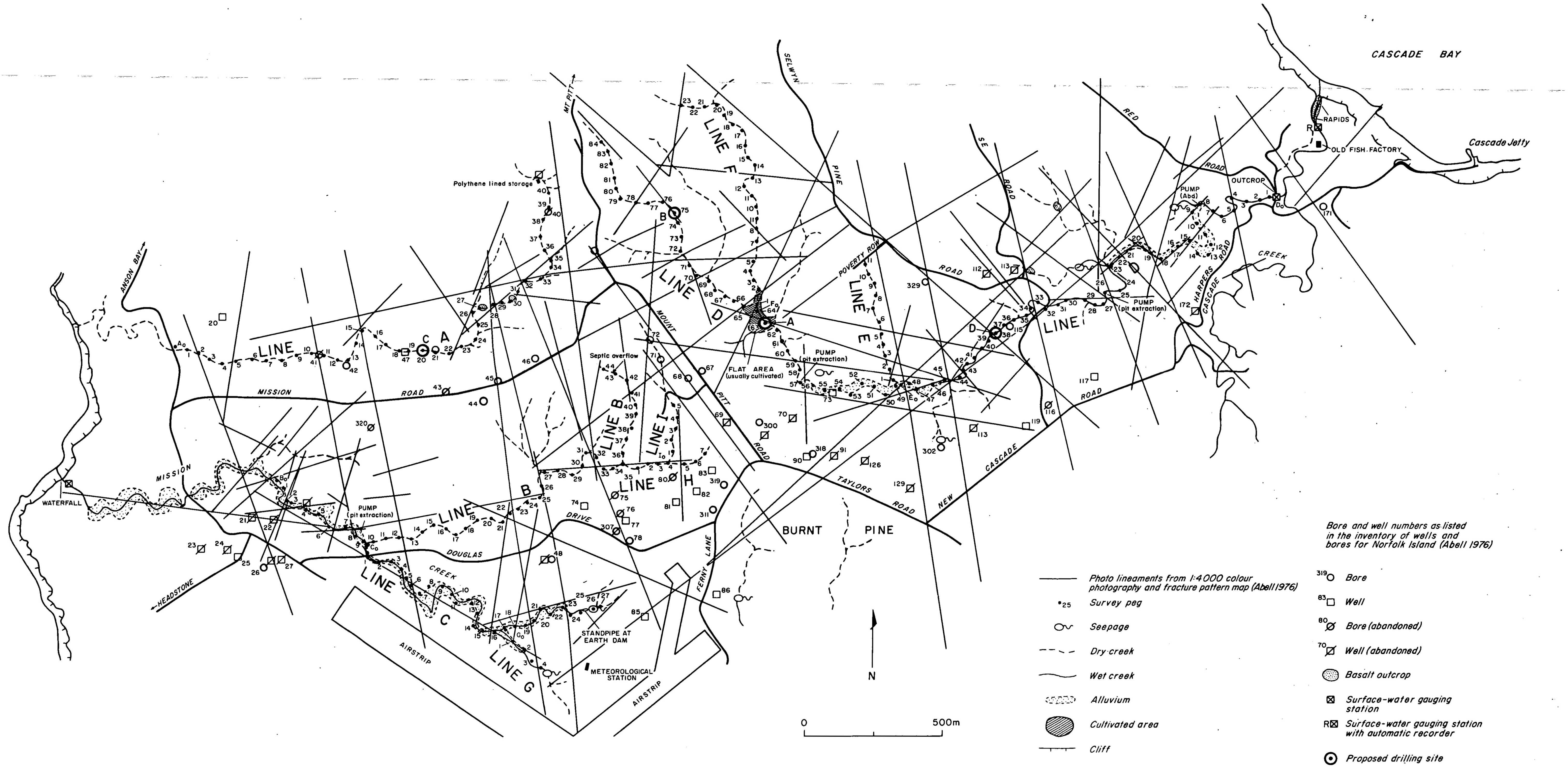

Fig. 11 Hydrogeological sketchmap of the Mission Creek - Broken Bridge Creek area

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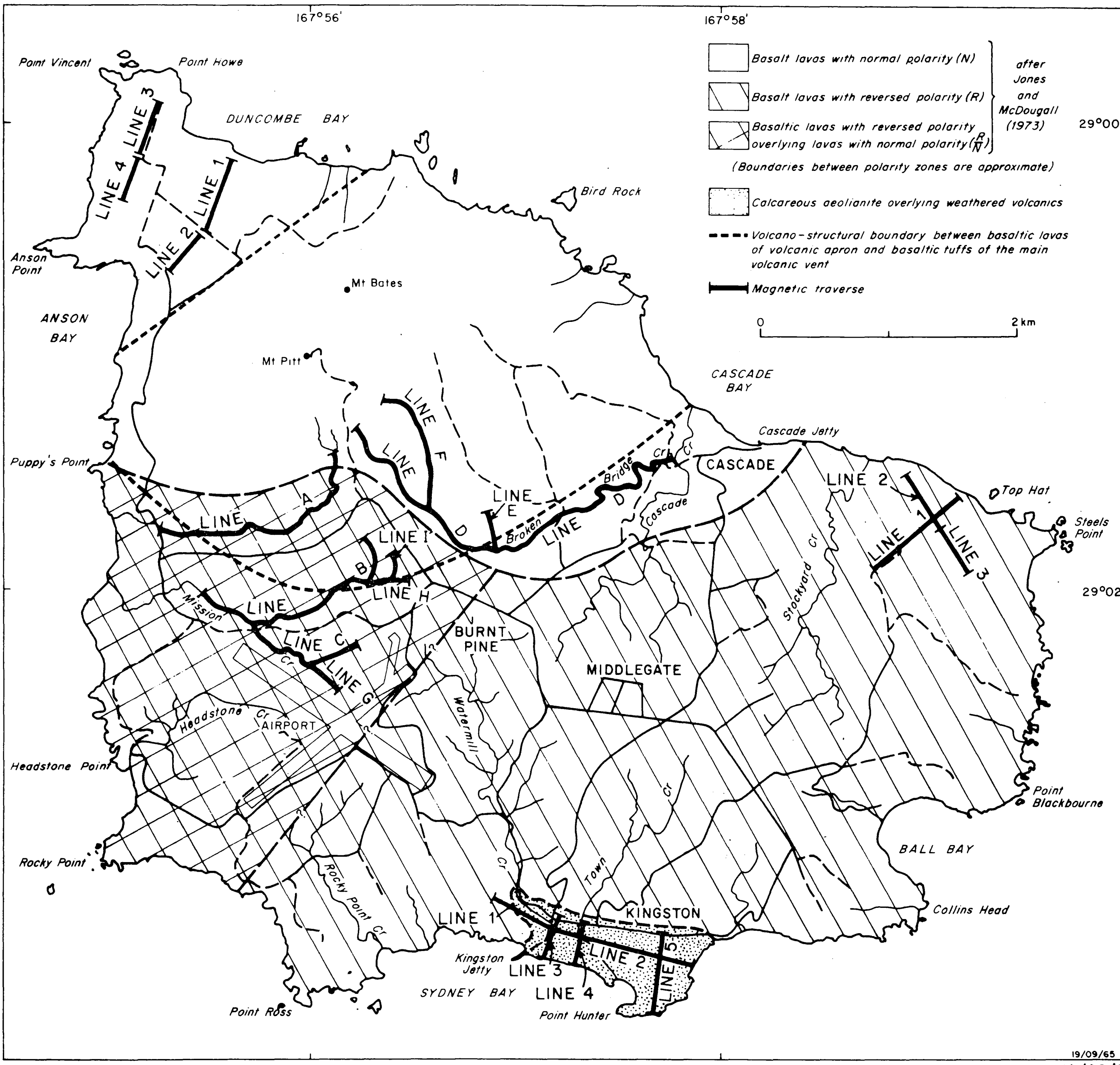

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Fig.12 Location of magnetic traverses and distribution of remanent magnetism temperature below the Curie point for magnetite (585°C). Such movement could cause the formation of randomly oriented blocks of lava to give local reversals of remanent magnetisation.

(b) In the fresh basaltic lava black opaque titano-magnetite is a common constituent. Magnetite concentrates as numerous euhedral grains in the finer-grained varieties of basalt suggesting that it has crystallised out relatively early in the ground mass. In the vesicular basalt magnetite forms thin lath-like growths in the groundmass indicating a variety more typical of late magmatic crystallisation. Green (1973) reports a normal titanium content for Norfolk Island basalts of 1.8 - 2.2%, which compares favourably with other adjacent basaltic provinces. According to McIntyre (1980) the amount of titanium in magnetite may affect its magnetic properties by reducing the Curie temperature below 585°C and the magnetic susceptibility of the mineral. Many of the petrological and mineralogical factors which attribute to the magnetic inhomogeneity and intensity of magnetisation of pillow basalts discussed in Marshall and Cox (1971) may also apply to the variation in magnetic properties of Norfolk Island basalts.

(c) Volcanic fragmental rocks are composed largely of clasts of basaltic glass, containing microlites of plagioclase and broken crystals of clinopyroxene and olivine interspersed with weakly magnetic secondary red-brown haematite. The apparent absence of magnetite in thin sections of these rocks supports the work of Buddington & others (1955) and Peck & others (1966), that magnetite does not separate out until after a substantial portion of the basaltic magma has crystallised. The lack of magnetite in tuffs and breccias suggests that, if these rocks obtain sufficient thickness and lateral extent in the volcanic sequence, they may assist in attenuating the magnetic anomaly.

(d) The heterogeneity of the weathered volcanic rocks is apparent in many roadside exposures on Norfolk Island. Generally the weathered profile consists of reddish brown ferruginous clays containing haematite and limonite (hydrated iron exides), and basalt shows varying degrees of spheroidal weathering. In many places unweathered cores of basalt are surrounded by concentric layers of decomposed basalt. Rounded unweathered corestones of basalt are commonly present at the surface and on valley slopes bounding active creek sections. The close juxtaposition of strongly magnetic basalt core stones and weakly magnetic haematitic clay may contribute to local variations in magnetic intensity over short distances.

(e) On Christmas Island (Indian Ocean) Polak (1976) considered that magnetisation induced by susceptibility differences (a measure of the degree to which rocks are magnetised by the Earth's magnetic field) may amount only to 'several hundred gammas at most'. In a later geophysical survey, Pettifer and Polak (1979) considered that induced magnetic intensity could be up to 20 times lower than remanent intensity. Until susceptibility values for Norfolk Island volcanic rocks have been obtained it is assumed that induced magnetisation contributes only in a minor way to the magnetic intensity profiles.

(f) In addition to the contrasts in magnetic properties of the basaltic sequence the magnetometer is influenced by metal of various kinds. Within Broken Bridge and Mission Creek catchments power lines, fence lines (some electrified), galvanised iron, water pumps and other forms of agricultural and domestic waste metal were noted during the survey. However, it is only in a few instances that interference from these sources is known to affect the total magnetic field. Along Line A (Station A2), a sudden rise of about 2,200 nT in the magnetic profile was due to an overhead 6,600 V power line. At Anson Bay no readings were possible at some stations owing to power and telephone lines and radio-station masts. Tests with a similar make of portable magnetometer (Taylor, 1975) have shown that there is little effect from a long wheel-base Land Rover at distances greater than 10 m. Since the magnetometer sensor is about 3 m above ground level it is considered that the effects of scrap metal are only minor contributions to the overall 'noise level' in the magnetic profile.

(g) The possibility of small dispersions of the direction of rock magnetisation due to the effect of lightning strikes is possible, but it is thought that the thick weathering cover will tend to minimise this effect.

Summary interpretation

A summary interpretation of the magnetic data is given in Table 3. Whilst it is emphasised that the collection of the data was only at reconnaissance level some interpretative leads may be given on (a) the distribution of lithologies, (b) the relative thickness of the weathered profile and depth to magnetic basement, and (c) the possible existence of volcano-structural boundaries. Only in some instances is there a broad correlation with the resistivity profiles. Although the magnetic data on this occasion have not been used for the selection of drill sites it is possible that the decrease of the magnetic intensity at Station 30A Line B (Fig. 13) and Stations 52 and 80 on Line D (Fig. 14) may reflect volcano-structural boundaries such as faults or fractures.

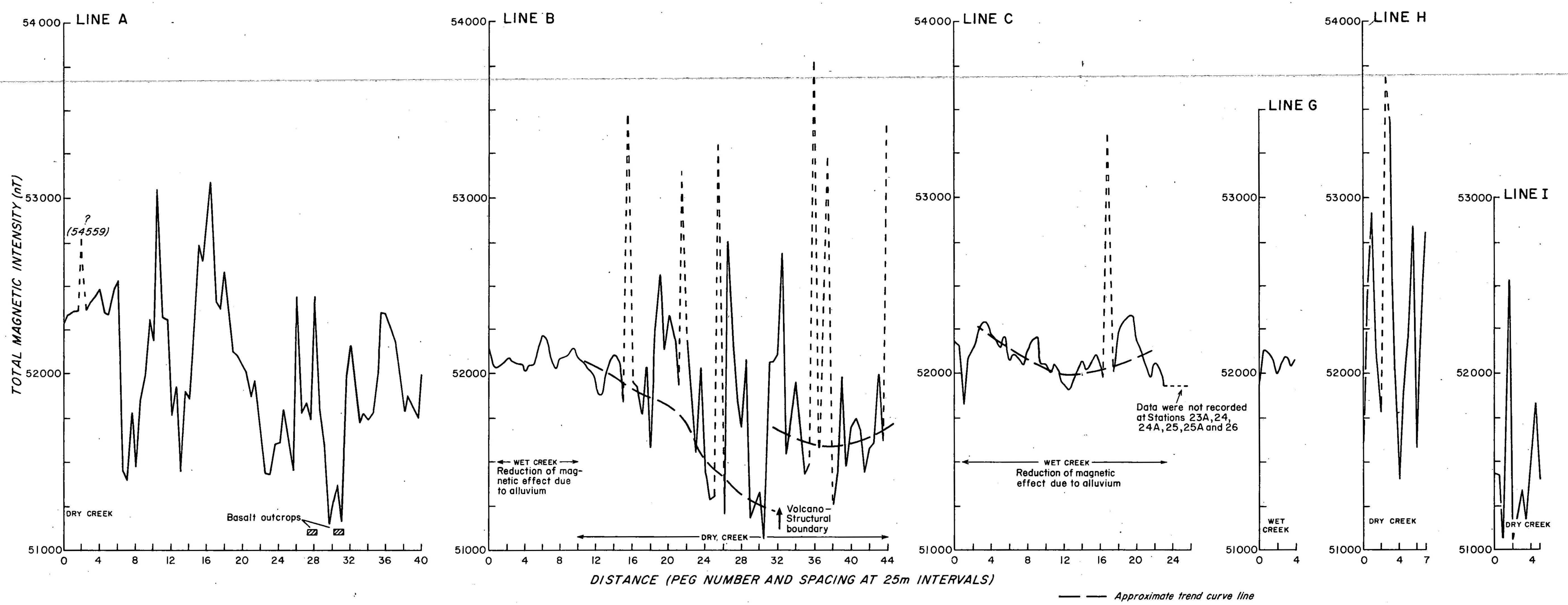

Fig.13 Magnetic profiles - Mission Creek catchment

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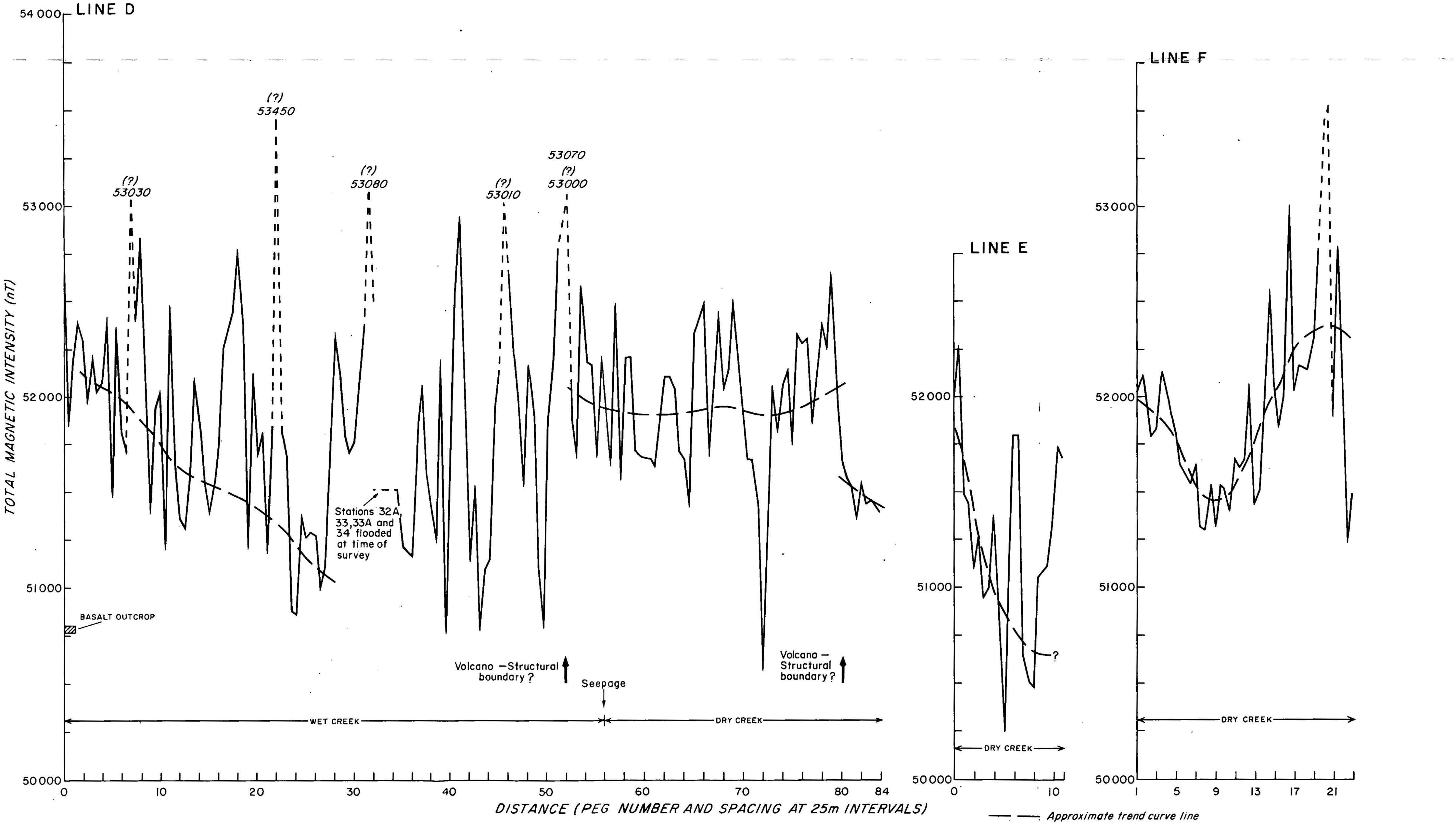

Fig. 14 Magnetic profiles – Broken Bridge Creek catchment

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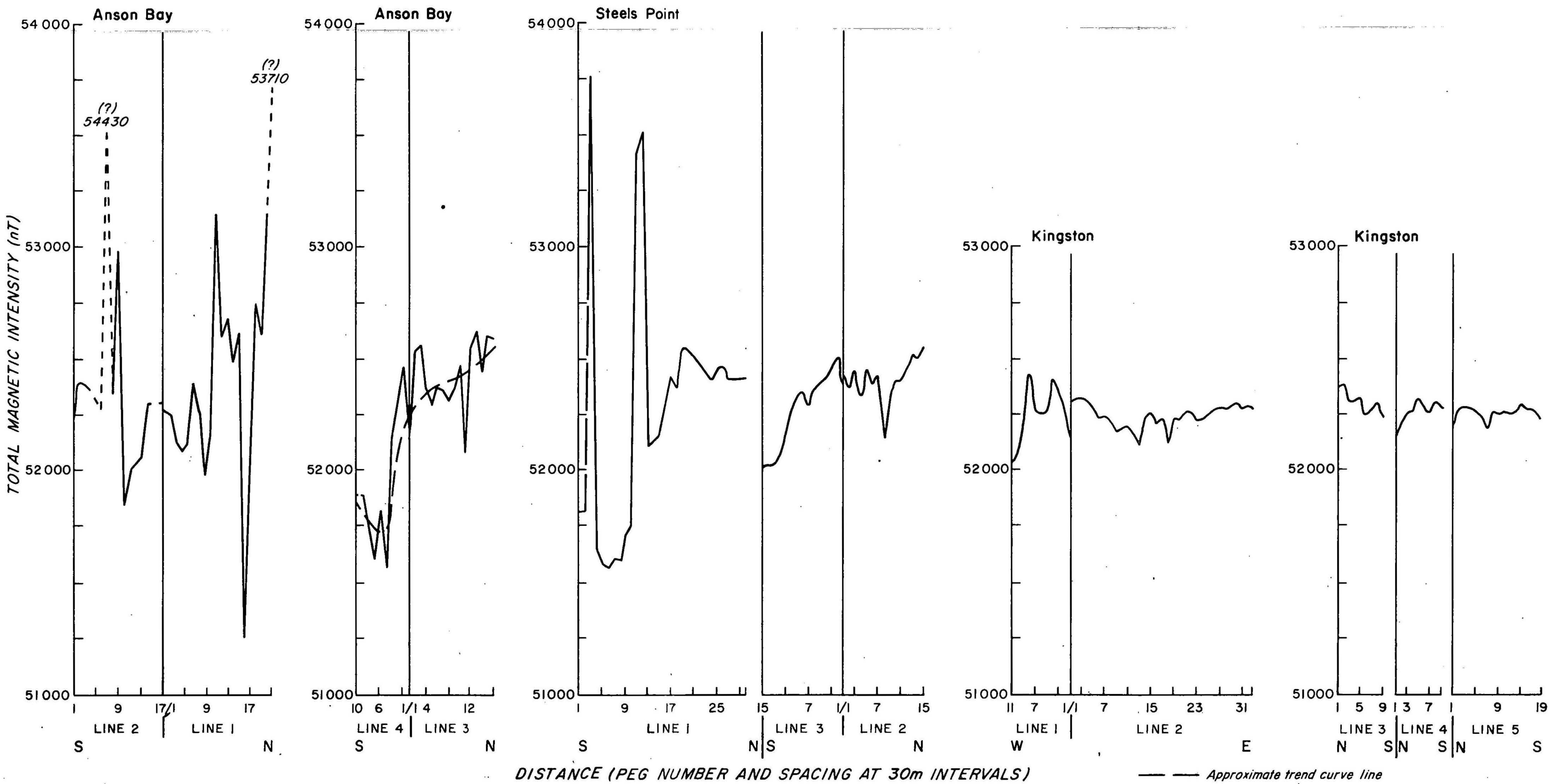

Fig.15 Magnetic profiles - Anson Bay, Steels Point and Kingston

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TABLE 3 SUMMARY INTERPRETATION OF MAGNETIC DATA

LOCALITY	LINE AND STATION NUMBERS	NATURE AND APPROX. RANGE OF MAGNETIC INTENSITY VARIATION (nT)	LITHOLOGY	COMMENT
MISSION CREEK CATCHMENT	LINE A (0-40)	Intense (51,00-52,000)	Weathered basaltic lava (apron)	Drycreek; basalt outcrops at Stns 27/28 and 30/31 causes resistivity 'high' (200+ohm metres) but no magnetic effect. Continuous low resistivity values (40-80 ohm-metres) over stns. 0-22.
	LINE B (0-10)	Low amplitude (52,000-52,200)	Alluvium overlying weathered volcanics	Wet creek to stn 10; magnetic effect strongly attenuated at stn 10 by thin layer of alluvium overlying local thickening of weathered volcanics; low resistivity values (40-80ohm-metres) over stns 0-10.
	LINE B (10-44)	Intense (51,500-53,000)	Weathered basaltic lava (apron)	Dry creek stns 10-44; decreasing magnetic intensity stns 10-30; possible volcano-structural boundary at stns 30-32 where trend curves are displaced; increasing resistivity intensity to +80ohm-metres over stns 10-44.
	LINE C	Low amplitude	Alluvium overlying weathered volcanics	Wet creek; magnetic effect strongly attenuated by thin layer of alluvium overlying local thickening of weathered volcanics; stn 17 possible interf-erence by metal; low resistivity values (40-80 ohm-metres).
BROKEN BRIDGE CATCHMENT	LINE D (0-52)	Intense (51,000-53,000)	Weathered basaltic lavas (apron)	Wet creek stns 0-56; seepage at stn 56; dry creek stns 56-84; basalt outcrop at stn 1; decreasing magnetic intensity over stns 0-26; attenuation of magnetic effect over stns 52-80 due to increased depth to magnetic basement and/or thickening weathered volcanics; possible volcano-structural boundary at stns 52 and 80 where trend curves are displaced; decreasing resistivity intensity (200+ to 60 ohm-metres) over stns 0-5; low values with increasing resistivity intensity to 80+ohm-metres over stns 28-84.
	LINE D (52-80)	Low amplitude (51,500-52,500)	Weathered basaltic tuffs and lavas (eruptive centre)	

TABLE 3 con't

LOCALITY	LINE AND STATION NUMBERS	NATURE AND APPROX. RANGE OF MAGNETIC INTENSITY VARIATION (nT)	LITHOLOGY	COMMENT
BROKEN BRIDGE CATCHMENT	LINE E (0-11)	Intense (50,500-51,750	Weathered basaltic tuffs and lavas (eruptive centre)	Dry creek; decreasing magnetic intensity stns 0-8; abrupt increase in resistivity values at stn 8 (80 to 120+ohm-metres).
	LINE F (0-23)	Intense (51,300-53,000)	Weathered basaltic tuffs and lavas (eruptive centre)	Dry creek; magnetic 'low' over stns 7-11 corresponding with resistivity 'high' (120 +ohm-metres) maybe due to weathered basaltic intrusion or poorly magnetic tuff/breccia.
	LINE G (0-4	Low amplitude (52,000-52,100)	Alluvium overlying weathered volcanics	Wet creek; refer to comments at Line C (Stns 0-26) and Line B (Stns 0-10).
	LINE H (0-7)	Intense (51,500-53,500)	Weathered basaltic lavas (apron)	Dry creek; insufficient data for interpretation.
	LINE I (0-5)	Intense (51,000-52-500)	Weathered basaltic lavas (apron)	Dry creek; insufficient data for interpretation.
ANSON BAY	LINES 1, 2, 3, and 4	Intense (51,800-53,200)	Weathered basaltic lavas overlying hyaloclestite rocks (apron)	Data interpretation hampered by power line and radio mast interference on lines 1 and 2; decreasing magnetic intensity from north to south on lines 3 and 4.
STEELS POINT	LINE 1 (1-17)	Intense (51,600-53,500)	Weathered basaltic lavas with local tuff development	Line 1 attenuation from stns 17-30 and on lines 2 and 3 due to increased depth to magnetic basement and effects of poorly magnetic basaltic tuff in the weathered profile.
	LINE 1 (17-30)	Low amplitude (52,400-52,500)		
	LINES 2 and 3	Low amplitude (52,000-52,500)		
KINGSTON	LINES 1,2,3 &4	Low amplitude (52,100-52,400)	Calcareous aeolin-ite overlying weathered volcanics	Magnetic effect strongly attenuated by layer of aeolianite overlying a local thickening of weathered volcanics and increasing depth to magnetic basement.

TABLE 3 con't

LOCALITY	LINE AND STATION NUMBERS	NATURE AND APPROX. RANGE OF MAGNETIC INTENSITY VARIATION (nT)	LITHOLOGY	COMMENT
KINGSTON	LINES 1, 2, 3 and 4	Low amplitude (52,100-52,400)	Calcareous aeolianite overlying weathered volcanics	Magnetic effect strongly attenuated by layer of aeolianite overlying a local thickening of weathered volcanics and increasing depth to magnetic basement.

Further magnetometer surveys in these areas using more closely spaced traverses could provide more detail on the geological structure which may help in the selection of drill sites for basal groundwater.

EXISTING WATER SUPPLIES

Water supply development from 1788 to 1974 is summarised by Abell (1976). An average yearly rainfall of 1335 mm is sufficient to provide rainfall runoff from roof catchments which is presently the commonest method of obtaining good quality water. In the older homes rainwater is stored in corrugated galvanised iron tanks at the side of the house and in the newer homes may be stored in large concrete tanks sunk into the ground. Surface water development has only been exploited on a small scale by either pumping directly from streams or from small surface storages and is likely to retain only subsidiary importance to rain and groundwater development. Ground water development in the early years of settlement began with wells of which there are now about 175 on the island. Wells were excavated to either solid rock or more usually to a few metres below the water table. Groundwater development from bores began on a large scale in the early 1970's when a modified Failing rotary drilling rig mounted on a truck arrived on the Island from New Zealand. This rig can drill easily through weathered volcanic rock but has had only sporadic success in penetrating sufficient thickness of hard volcanic bedrock to obtain deeper supplies of ground water. At present, there are about 165 bores in use which range in yield from 500-1000 litres per hour; most bores tap groundwater from weathered volcanic rock and a few derive useful supplies from basaltic tuff beds in lavas below the weathered mantle. Most groundwater is used for domestic and garden purposes and some for stock watering, irrigation and light industry.

The overall demand for water has increased considerably over the last 20 years largely through the demand caused by the expansion of the tourist industry (Fig. 16). Tourist activity has meant the erection of more hotels boarding houses and an expansion of the business sector (shops, restaurants, clubs, etc.) in the Burnt Pine - Middlegate area. Based on a population of 2000 (including tourists) and a daily water demand of 450 litres per capita per day, Goldfinch and Cross (1980) estimated that the water requirement for Norfolk Island is 3.3×10^5 m^3 per annum; confirmation of a similar estimate proposed by Abell (1976) who calculated that projected domestic water demand by 1983 would be 2.9×10^5 m^3 per annum.

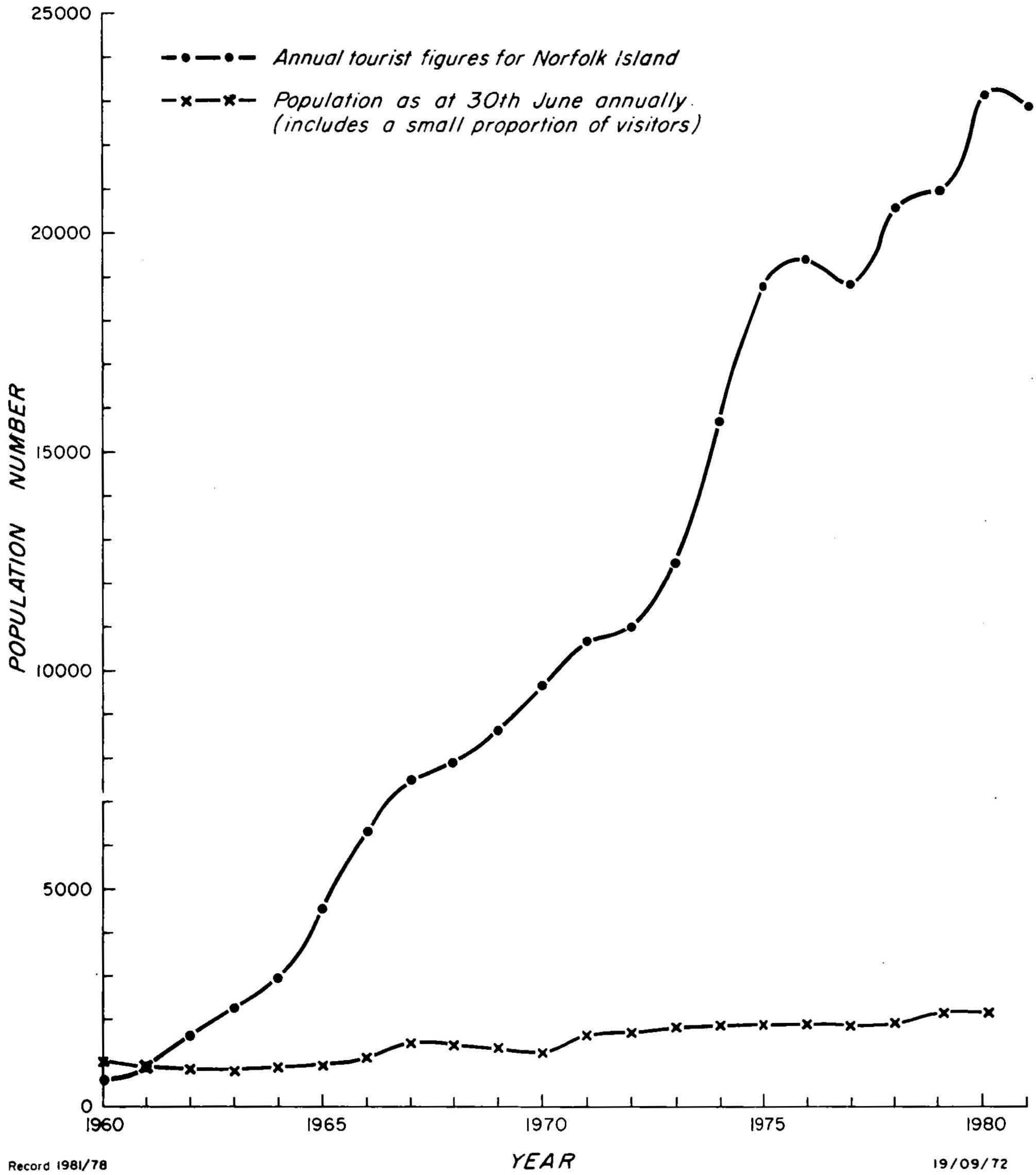
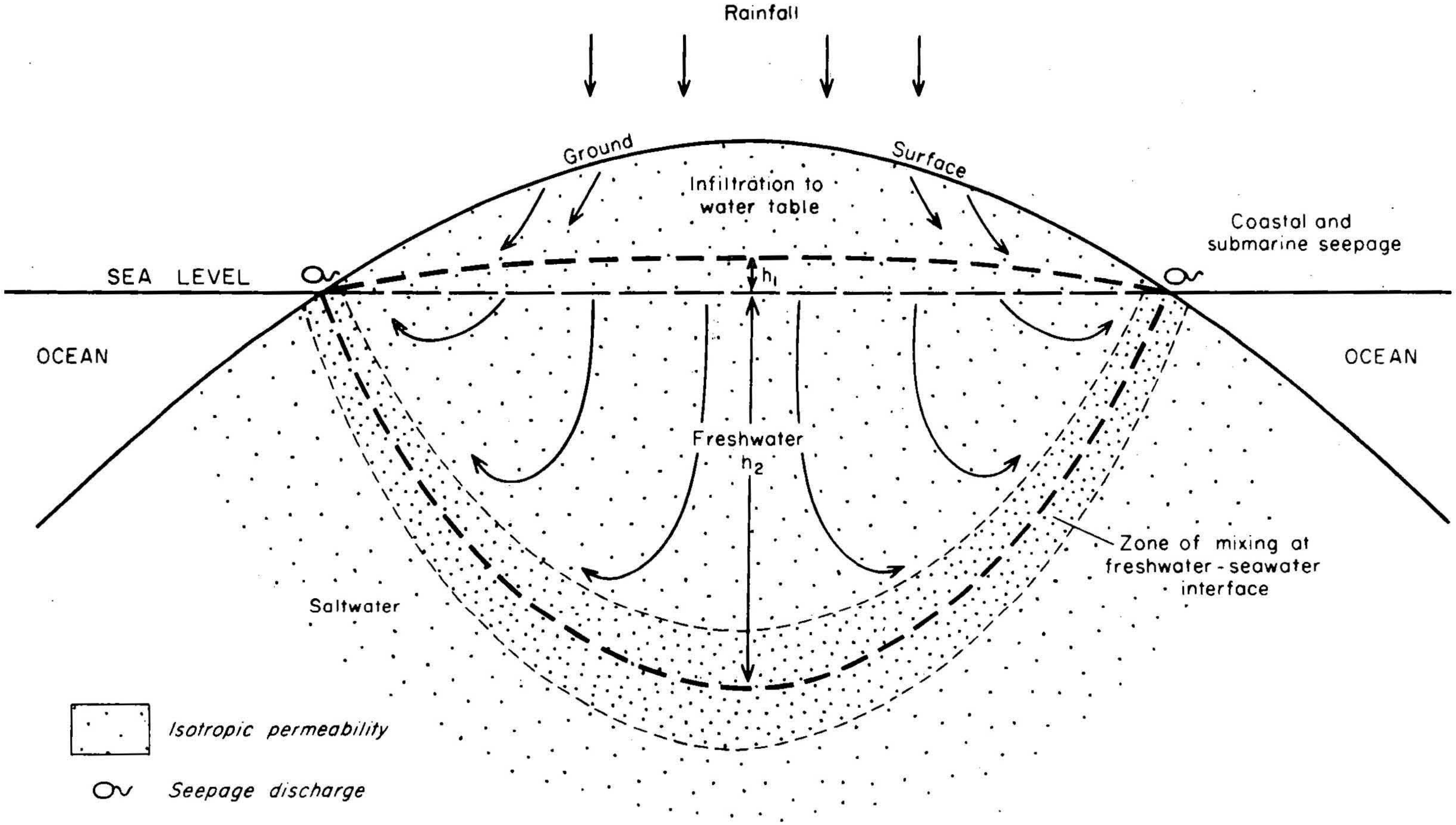


Fig.16 Population and tourist trends 1960-81



Using the Ghyben – Herzberg relation, the approximate thickness of the basal water lens $(h_2) = 40h_1$,
where h_1 = elevation of water table above mean sea level

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Fig. 17 Ghyben - Herzberg model of a freshwater lens in an oceanic island

At present the most concentrated groundwater development is on the southern plateau in the Burnt Pine - Middlegate area where most people live and work and where there is the greatest concentration of bores and wells. Prior to 1970, concern regarding contamination of ground water from septic tank waste and over-development was expressed by Eden (1965) and Wood (1968). Water quality data collected and interpreted for this area by Abell (1976) suggested that locally high levels of NaCl content in the ground water were caused in part by saline septic tank water moving to the water table. The hydrological cycle proposed in this report shows that groundwater in the weathered mantle not lost as base flow or passing to deeper levels on the Island has the capacity to circulate in a closed system. During summer or in drought conditions when water demand is high, the constant re-use of shallow groundwater causes salinity levels to rise with a consequent reduction in water quality. Salinity concentrations will only remain at reasonable levels if there is sufficient rainfall to dilute and stabilise salt concentrations in the weathered mantle. In a report by Goldfinch and Cross (1980) it was noted that medical authorities had considered that domestic use of groundwater by Norfolk Island residents was subject to the possibility of bacteriological contamination from sewerage of human origin.

BASAL GROUNDWATER

In classical schemes proposed for the accumulation of groundwater in small islands fresh groundwater derived from rainfall reaching hydraulic base level near sea level will float because of its slightly lower density on the surrounding saline ground water to form a basal fresh water lens or 'Ghyben-Herzberg lens' (Figure 17). Depending on the hydraulic properties of the aquifer, the water table will remain under dynamic balance some height above sea level. Since sea water is denser than the fresh water the latter forms a lens-shaped body, floating upon and displacing the sea water beneath the island to a depth about 40 times the fresh water head above sea level. The total difference in head between the lens upper surface and sea level is maintained by the hydrological properties of the rock formation and by the rate of replenishment. An extremely permeable aquifer at the island's base with high hydraulic conductivity exceeding periodical replenishment, will not maintain a stable freshwater lens beneath the island. Likewise, if the freshwater lens is not recharged regularly by rainfall there will be a loss of hydraulic head and salt water will up-well and dissipate the freshwater lens. Groundwater enters the lens by intermittent recharge from rainfall and moves through it to the sea where continuous but fluctuating discharge occurs at springs and seeps in coastal zones. The interface between the groundwater lens and sea water does not occur as a sharp well-determined area, but as a transition zone which varies in position according to hydraulic factors such as tidal and re-charge fluctuations. Mixing and thickening of the transition zone is also assisted by molecular dispersion between fresh and saline water.

This classical case is ideal and assumes uniform isotropic permeability throughout the rock sequence as for example in sand dunes and some limestones. In practice the lens is a dynamic system as it is recharged from above and discharges downwards and outwards to the sea, permeability distribution is usually anisotropic and salt water and fresh water mix at the base of the lens. Under natural conditions, the quality and quantity of ground water in a basal fresh water lens depends mainly on:

(a) the rate and distribution of recharge
(b) the distribution of permeability
(c) the effect of mixing of the fresh water and the sea water due to tidal changes.

Volcanic islands

The literature on the hydrogeology of volcanic islands is sparse, but in recent years a few case studies have been published which include the Hawaiian Islands, (Visher and Mink, 1964), Guam (Ward and others, 1965) Che Ju Do Island, Korea (Eckestein, 1969) and Tenerife, Canary Islands (Ecker, 1976). Brief summary articles given at an international symposium on the hydrology of volcanic rocks at Lanzarote in the Canary Islands under the auspices of the Government of Spain and UNESCO have been reported in Geotimes (1974) and Nature and Resources (1975).

For the Hawaiian Islands, Guam and Che Ju De Island the accumulation of groundwater at or below sea level appears to follow the orthodox Ghyben-Herzberg model with some modification proposed for perched aquifers above sea level. However, Ecker (1976) has departed from the classical scheme to propose a model of groundwater compartments connected by permeable rocks or secondary leakage paths in the rough shape of a lens to explain groundwater occurrence on Tenerife, the largest volcanic island in the Canary group. The model for Tenerife suggests that groundwater occurs in pockets or cells which are controlled by variations of permeability and porosity. If a pocket is very permeable, it can act as 'a drain' leaving masses of dry rock between wet pockets. In other places, where less permeable pockets are bounded by less permeable rocks which resist groundwater recharge dry rock pockets will also form.

BASAL GROUNDWATER ON NORFOLK ISLAND

The classical Ghyben-Herzberg model already outlined is not considered to apply in toto to Norfolk Island although elements of this model will have application. The existence of basal groundwater on Norfolk Island is favoured by fractures and joints in the volcanic sequence which provides the means for shallow groundwater to leak vertically towards sea level. If the degree of anisotropic permeability evident in the hyaloclastite rocks underlying the island is not excessive then the prevailing recharge rate of groundwater from higher levels has the potential to form a basal groundwater body provided that the landward effects of tidal fluctuations are not too great to cause mixing of salt and freshwater. The predominantly vertical groundwater movement pattern on Norfolk Island is also supported by poor surface water run off conditions, few major coastal seepages and the reported existence of submarine seepages off Point Vincent.

An extension of Ecker's model to hydrogeological conditions on Norfolk Island seems appropriate, especially as the bore data suggests that dry zones exist in the volcanic rocks in close juxtaposition with saturated zones. Whether a zone is wet or dry will depend on whether vertical movement of groundwater can take place through fractures to recharge permeable zones in the volcanic bedrock sequence. To date, of the few bores that have been drilled and presumably have at least partially penetrated hyaloclastite rocks at or near sea level the hydrogeological data (see Table 1) shows that only bores NI 313 and NI 343 & NI 356 either yield or have the potential to yield groundwater from this aquifer at sea level. In a hole (NI 302) drilled to sea level a number of permeable zones indicated by the geological log of the bore were encountered, all of which were dry. There appears little doubt that the disposal of sewage effluent down a bore at the South Pacific Hotel (NI 138) can be explained by dispersal into a dry but permeable compartment in the volcanic sequence not actively being recharged by groundwater; a fact supported by lost circulation reported when the hole was originally drilled. This model might also explain pockets of high-level saline groundwater which occur at the base of the weathered mantle. If groundwater flow patterns change permeable zones become isolated and are no longer recharged.

Groundwater in such zones will become stagnant when removed from the hydrological cycle, e.g. bore Nos. NI 1, 4 and 284 (see Figure 6). Clearly the explanation given for the existence of dry permeable zones at deeper levels and localised pockets of saline groundwater at the base of the weathered mantle give some credence to Ecker's groundwater model. However, overall acceptance of this model as applied to Norfolk Island needs further evaluation and must await future results of deep drilling.

Fractures

Fracture traces appear on aerial photographs as linear ground features defined by vegetation, topography and soil tonal alignments. Fractures influence the shape of the island but also reflect the structure and aid in the development of drainage patterns. If fractures provide the means for a strong vertical component to groundwater movement in the unweathered part of the volcanic sequence they should in theory reflect zones of increased permeability and weathering at the top of this sequence and assist in providing recharge zones for entry of shallow groundwater to deeper levels on the island. Fractures interpreted from photo lineaments are shown on the hydrogeological map of the Broken Bridge - Mission Creek area (Fig. 11).

A fracture trace analysis (Abell, 1976) showed an inconclusive correlation between fracture zones and bore yield since most bores are sited between fractures and generally away from the drainage network which is partly fracture-controlled. The analysis suggests that fractures trending NNW are the longest and most numerous and according to local information offshore springs close to Point Vincent lining up with this fracture direction tend to confirm their importance as conduits for groundwater movement. Lost circulation reported at drilling indicates that at some sites permeability does increase at or near to fractures; in these cases yields could have been obtained or improved by deeper drilling. Over what length a fracture zone will behave as an active conduit for groundwater still remains uncertain, but permeability variation will relate to the degree of fracture closure with depth or locally by the amount of clay formed by increased penetration of weathering in the fracture zones. Nevertheless the apparent lack of large scale coastal seepages near sea level and lost circulation during drilling point to fractures adding to the overall permeability of the rock succession and therefore a consideration in the selection of deep drilling sites.

Permeability

Models for the substructure of oceanic volcanic islands that have application to Norfolk Island have been proposed by Moore and Fiske (1969) and Jones (1970). These models suggest that hyaloclastite deposits will form when subaerial lavas erupted from a volcanic vent flow almost immediately into water. Although the available hydrogeological data on the extent and capability of hyaloclastite deposits to act as suitable aquifers is not documented in the literature it would appear from field observations of these rocks on Norfolk Island and examination of thin sections that they appear to have the permeability framework to support a basal groundwater body. The permeability distribution of the hyaloclastite deposits and pillow lavas underlying Norfolk Island is poorly known but if Eckers model (1976) is followed basal groundwater is depicted as occurring in large permeable pockets sealed by relatively impermeable rock or in fractures (Fig. 18). This anisotropic permeability distribution suggests that the classical geometrical lens shape of a fresh water body is likely to be distorted into a complex interfingering shape. The zone of mixing between freshwater and seawater will be greater along fracture zones and permeable pockets rather than intervening impermeable pockets. While it is evident that groundwater from the weathered mantle gravity feeds and recharges basal groundwater in bedrock aquifers through fractures, recharge may be cut off locally and dry permeable pockets in bedrock form where deep weathering has penetrated sufficiently to clay-seal the fractures.

Permeability distribution may also be affected by clay minerals lining cavities in hyaloclastite rocks (See p. 16). Fresh groundwater moving through these breccias will make clay minerals swell as they take up water molecules. Swelling will cause some reduction in the hydraulic conductivity of the aquifer which will assist in the maintenance of basal groundwater.

The ability of the hydrogeological system on Norfolk Island to support a basal groundwater body depends largely on the magnitude of permeability variations of the volcanic rocks. If K_h (horizontal permeability) is greater then K_v (vertical permeability) of the volcanic rocks it is unlikely that a basal groundwater body will form since groundwater flow patterns are directed horizontally to the margin of the island. On the other hand if K_v exceeds or is equal to K_h, then the prospects for basal groundwater retention are substantially better. On Norfolk Island field investigations indicate a permeability distribution which is anisotropic ($K_v \gg K_h$) which supports the contention that volcanic rocks at and below sea level have the potential to support a basal groundwater aquifer.

Groundwater model

Three main hydrogeologic units comprise a simplified groundwater model provisionally proposed for Norfolk Island (Figure 18). The groundwater system is a two-component storage system consisting of an upper and a lower groundwater storage connected by a plumbing arrangement which is analagous to the fracture system. The upper storage is high level groundwater occurring in the weathered mantle; permeability distribution is generally isotropic. The lower storage is basal groundwater occurring in hyaloclastite rocks and possibly pillow lavas at and below sea level; permeability is strongly anisotropic. An intermediate groundwater storage occurs in fractures and tuff beds between basalt flows in the bedrock sequence above sea level; permeability is generally anisotropic and aquifers may be semi-confined.

Groundwater in the upper storage gravity feeds the lower storage and provided the upper storage remains saturated then a lower or basal groundwater storage will be maintained. To all intents and purposes on Norfolk Island this system remains in equilibrium with natural recharge balancing coastal and submarine discharge. It needs to be emphasised that at the present time only the upper storage is being utilised by bores and wells. The quantity of groundwater per annum passing to deeper levels has been estimated by a study of the components of the water balance equation. Abell (1976) estimated that about 14 per cent of average annual rainfall is available for groundwater recharge to bedrock aquifers. In the near future it will be possible to calculate a more precise value for groundwater recharge as evapotranspiration can now be estimated with more certainty by an evaporimeter now installed at the meteorological station and surface water discharge is currently measured at gauging stations recently installed by the Department of Housing and Construction (Fitzgerald and Falkland, 1981). Although drought conditions may affect the capacity of the upper storage to maintain a basal groundwater body it will need severe conditions to cause a depletion of the basal water body. If there is sufficient groundwater in the upper storage to move to lower levels then basal water will be maintained. Falling water levels in the upper storage do not necessarily imply a reduction in the lower storage although the rate of gravity feed will be reduced.

The pollution threat to groundwater from the disposal of human and livestock waste should be minimised if a basal groundwater body is developed.*

*According to G.C. Duvall (pers. comm. Jan 1982), a bore re-drilled at the Hillcrest Hotel (NI 341) to a depth of 98 m sampled polluted groundwater during a continuous 48 hour pumping test (Table 1). The source of pollution is attributed to sewage effluent disposal down a dry bore at the South Pacific Hotel. Detailed investigations are currently planned to prove the validity of this suggestion (R. Cross pers comm. 1972)

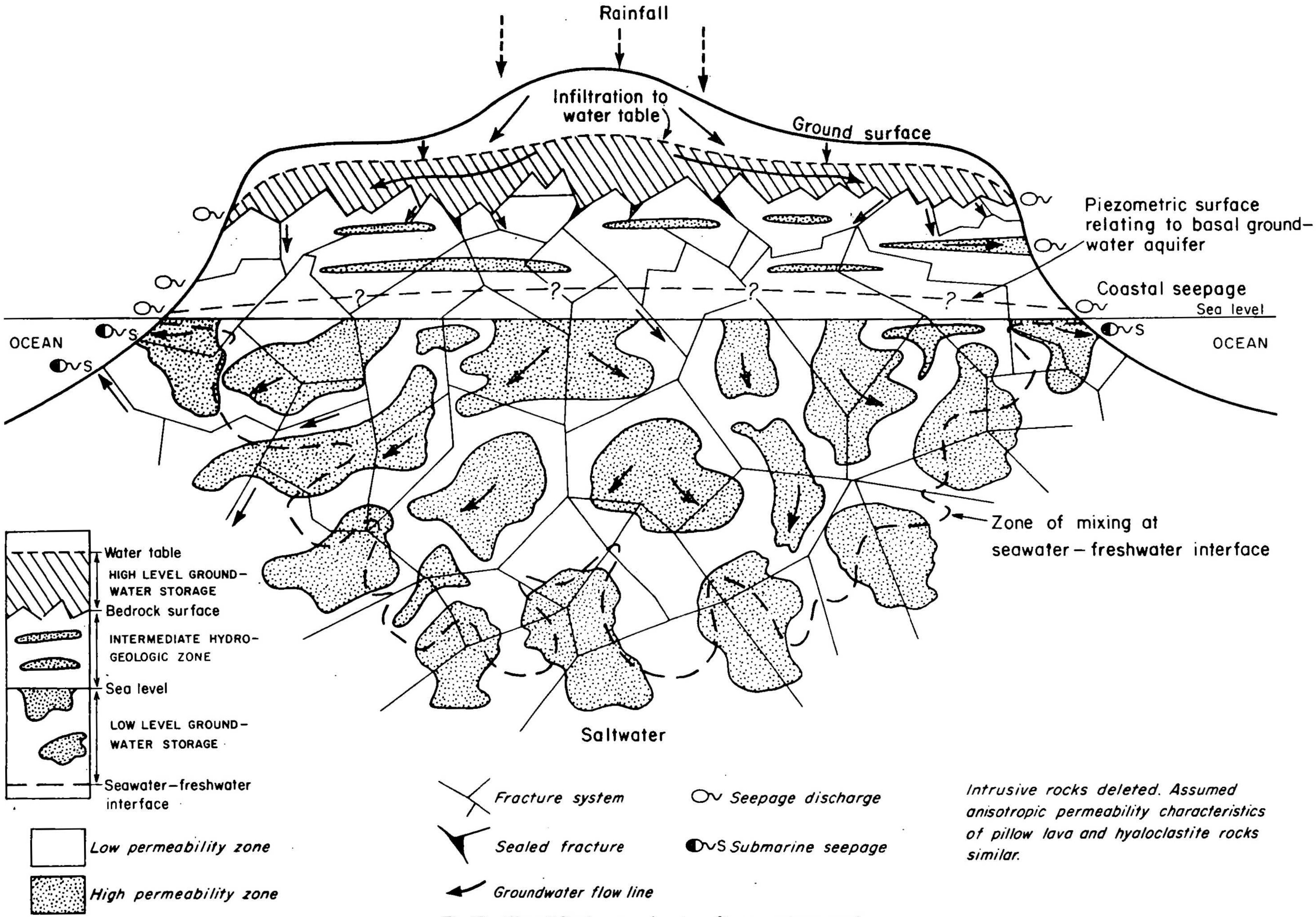

Fig.18 Simplified groundwater flow system and permeability model for Norfolk Island

Although the time for groundwater to move between the upper and lower storages is presently unknown, it is possible to estimate the rate of groundwater movement using isotopic dating techniques e.g. tritium, by sampling bores developed in upper and lower groundwater storages and also groundwater from coastal seepages near sea level. Apart from this, the complex vertical distribution of flow directions of groundwater are such that some natural purification of any polluted groundwater in the weathered mantle sould be achieved by the time it accumulates as basal groundwater. The other main cause for concern in the development of a basal groundwater body is the amount of natural mixing that may take place at the saline/fresh water interface below sea level. The mixing is largely dependant on the permeability distribution of the hyaloclastite rocks below sea level, the landward effect of tidal fluctions and the size of the Island. Tidal fluctuations on Norfolk Island are measured by an automatic tidal recorder situated at Kingston Jetty. Tidal data is forwarded to the CSIRO Division of Oceanography at Cronulla. The mean annual tidal range based on data for 1973 is about 1.7 m. Graphs of adjusted mean sea levels at Norfolk Island for 1970-73 are given in Hamon (1979). Tidal fluctuations remain fairly constant through the year but are probably large enough to cause mixing of fresh water and sea water under the Kingston Lowland and perhaps elsewhere at the perimeter of the Island. As there are no observation bores drilled to sea level at inland localities the influence of tidal fluctuations on the water levels and quality of groundwater beneath Norfolk Island is so far unknown. However it is expected that the extent of tidal fluctuations decrease with distance from the sea shore. Tidal influences on groundwater and water quality levels are known to extend at least 1 km from the coast on the volcanic island of Tenerife which has an area of 2058 km^2 (Ecker, 1976), and to extend throughout Niue, a limestone island with an area of 259 km^2 (Jacobson and Hill, 1980). Providing there is sufficient permeability, tidal fluctuations will tend to thicken the mixing zone at the base of the fresh water layer. On Norfolk Island, which only has an area of 35 km^2, tidal fluctuations must be expected to have some influence on salinity levels in basal groundwater particularly where there is a strong hydraulic connection along permeable zones and open fractures.

FUTURE GROUNDWATER DEVELOPMENT

Hydrogeological factors and water balance data already discussed in this and an earlier report (Abell, 1976) suggest that sufficient reserves of groundwater on Norfolk Island probably exist for future exploitation. A basal groundwater body outlined in Figure 5 appears to offer the best potential for development using bores drilled to depths in excess of 100 m. The resistivity survey outlined four sites to be drilled to confirm the existence of deep groundwater and to provide production bores for the needs of the Burnt Pine - Middlegate area (Table 4). In addition, there appears to be some prospects for the development of shallow groundwater as a second class water supply using shallow bores or possibly collector wells in alluvium along Mission Creek.

Over the last two decades the acquisition of data on the existence of bedrock aquifers has been supported at some considerable cost by the efforts of Norfolk Island residents drilling bores on their own properties. The responsibility for advising and developing deeper sources of groundwater using sound and well maintained equipment must be undertaken through the Administration in conjunction with other appropriate Government authorities. The Administration needs to come to some agreement with landowners regarding ownership of groundwater if it is to be used for communal use. Since there is no water legislation on the Island, drilling bores on other than Crown land has the potential for disputes as to access rights and ownership of production bore installations. Whilst it is expected that in the short term these problems can be overcome it is in the interests of the Administration that such piecemeal agreements should be replaced by the introduction of water legislation covering both ground and surface water resources. These problems have already been treated briefly by Abell (1976) but to assist further the Administration is referred to an AWRC (Australian Water Resources Council) technical document which reports in detail on water legislation matters in Australian States (Clark, 1979).

To overcome the pollution threat to groundwater in the long term, the possibility of the existence of a potable water supply utilising groundwater was the subject of an investigation by Abell (1976). In that report it was concluded that although hydrogeological conditions favoured the accumulation of basal groundwater, the nature and extent of the aquifers below the weathered mantle needed further hydrogeological studies supplemented by geophysics. Recommendations in that report were taken up by Goldfinch and Cross (1980) who formulated proposals for the development of a safe poteable water supply based on groundwater from the

Table 4 DRILLING SITES IN THE BROKEN BRIDGE - MISSION CREEK AREAS

Site Number	Line and Station number	Land Subdivision	Land Classification	Approx. elevation above sea level (m)	Approx. drilling depths (m)	Comments on selection of sites
A	Line D; Station 63	23	Freehold	80	80 - 200	Deep exploration hole sited on resistivity 'low'; at fracture intersections; centrally situated to tap maximum thickness of basal fresh water layer; near the confluence of three drainage lines; good access
B	Line D; Station 75	155g	Crown	100	100 - 125	Sited on resistivity 'low' close to fracture intersection; access difficult.
C	Line A; Station 20	149	Crown	70	70 - 100	Sited on resistivity 'low' adjacent to strong resistivity 'high' Nearby bore has good yield from shallow groundwater in weathered volcanic rock; good access.
D	Line D; Station 38	25	Freehold	60	60 - 100	Sited on resistivity 'low' close to fracture intersection; access difficult.

Broken Bridge - Mission Creek areas and a sewerage scheme for the removal of contaminated liquid waste from the more densely populated areas of Burnt Pine and Middlegate. Following on from that report Fitzgerald and Falkland (1981) have set up an operating network of stream-gauging stations to measure surface water run-off; the data is sent monthly to the Department of Housing and Construction (ACT region). Further recommendations were also made concerning water supply and sewerage systems.

Planning a drilling program for production bores presents a number of problems centred around drilling logistics, availability of funds and the type of water supply best suited for the needs of Norfolk Island. Initially a drilling program must be planned to prove the availability of deep groundwater resources. If such a resource is found to be adequate then its exploitation can be phased in with proposals for water reticulation and sewerage disposal schemes.

EXPLOITATION OF DEEP GROUNDWATER

Exploitation of basal groundwater in the Broken Bridge - Mission Creek area will be based on a water bore drilling program using the drilling sites selected by the resistivity survey (Table 4 and Fig. 11). There are three available drilling options that need consideration in the planning of a production bore drilling program that is to develop basal groundwater in bedrock aquifers. Which option is favoured depends on funding but more importantly on the strategies to be adopted for future water resource development schemes on Norfolk Island. The options are:

(a) update and use the drilling rig already operational on the Island.
(b) tender for a reputable water well drilling company for a contract of say 8 or more fully operational water bores.
(c) purchase a light drilling rig for the Administration which can be used initially to train personnel and drill production bores.

Island Rig

Brief background information on this rig, drilling methods and procedures with recommendations is given in Abell, (1976). During the 1981 visit discussions were held with the owner concerning a proposed water bore drilling program. Some comments on drilling methods, condition of the rig and suggestions for overhaul program involving drilling depths of 100 m or more is briefly outlined in Appendix 3.

Contract Drilling

An advantage of this option is that providing a suitable water well drilling company can be approached to undertake the drilling program the job should be completed quickly and efficiently. The tender specifications will ensure that the correct drilling equipment is used and the task capable of completion without prolonged break-downs and heavy standby costs. The tendering company will need to ensure that suitable accessories such as plain casing and pump test equipment accompany a truck mounted rig. The contract driller can expect that a water tanker, concreting facilities, crushed stone for gravel packing, extra labour and vehicles will be available on the Island. A side benefit of contract drilling is that it would provide a demonstration and give first-hand experience on water bore drilling techniques to interested parties on Norfolk Island.

To maximise as far as possible the cost effectiveness of contract drilling on Norfolk Island a program of 8 or more drill holes needs to be given serious consideration to prove the existence and nature of basal groundwater aquifers at and below sea level. Until deep holes have been drilled at widely separated sites across the island to prove the existence of basal groundwater it will not be possible to effectively plan water resource schemes for Norfolk Island.

Some disadvantages for this option are problems in shipping the drilling equipment to Norfolk Island. The crane equipment on the Island has o nly freight handling capacity of 5 metric tonnes which means that the drilling rig will need to be partly dismantled and reassembled at Sydney and on Norfolk Island. Ships call at Norfolk Island every five to six weeks so that a charge for stand-by time needs to be added to the budget for completion of the work between ship arrivals. Transport costs by ship are estimated at about $10,000* for a return journey to Norfolk Island. An alternative method of transport is the use of RAAF Hercules. The main problem in this method of transport are the constraints imposed by weight and size of the drilling rig. A typical truck-mounted drilling unit for use on Norfolk Island might weigh about 10 metric tonnes with the weight of ancillary equipment being about 5 metric tonnes (drilling rods, pumps and other ancillary equipment). A typical size would be about 7 m x 4 m x 3 m. Enquiries made to the RAAF base at Richmond, Sydney indicate that the capacity of an RAAF Hercules to carry a drilling rig of that weight and size to Norfolk Island is marginal. The rig would have to be dismantled and in good condition to satisfy the safety needs of the aircraft. Transport costs are estimated at about $20 000* for a return journey to Norfolk Island.

Purchase of Drilling Rig

Some consideration needs to be given to the purchase of a light drilling rig for Norfolk Island that can be used and maintained as the property of the Administration. Recently a tractor-mounted drilling rig was designed and built in Brisbane for ADAB (Australian Development Assistance Bureau) as part of an Australian bi-lateral aid project with the Niue Island Government. The rig with accessories was a Bourne 1000R drill mounted on a Ford tractor costing just under $140 000* and capable of drilling to 300 m. Another rig that might be suitable is the Gardner-Denver portable Mayhew 500 air-water drill. Either type of rig would be suitable for Norfolk Island. Purchase of a reconditioned drilling rig is not recommended.

An advantage of purchasing a rig is that expenditure on a deep drilling program is unlikely to be any more costly than one undertaken by a mainland contractor or by contract negotiated with the owner of the present rig on the Island. An Administration-owned rig could give priority to Government initated drilling projects and be hired out for private use at competitive drilling rates. A drilling program to prove basal groundwater could be supervised by an experienced drilling supervisor who would be expected to train two or three local personnel in drilling techniques, equipping and completion procedures for production bores. The operation and maintenance of the rig to be responsibility of the Public Works Department on Norfolk Island.

Equipment and drilling procedures

In the Broken Bridge - Mission Creek area water bores should be drilled at the sites marked on Figure 11 and in the order set out in Table 4. To achieve the capacity requirements of 10.4 litres per second and stand-by needs it maybe necessary to drill all four sites. Typical specifications required for a deep production bore tapping bedrock aquifers is shown in Fig. 19. Budget estimates for drilling and equipping production bores are given in Appendix 4

* These estimates are given only as a guide to costs. They are based on transport rates and equipment costs current in 1981.

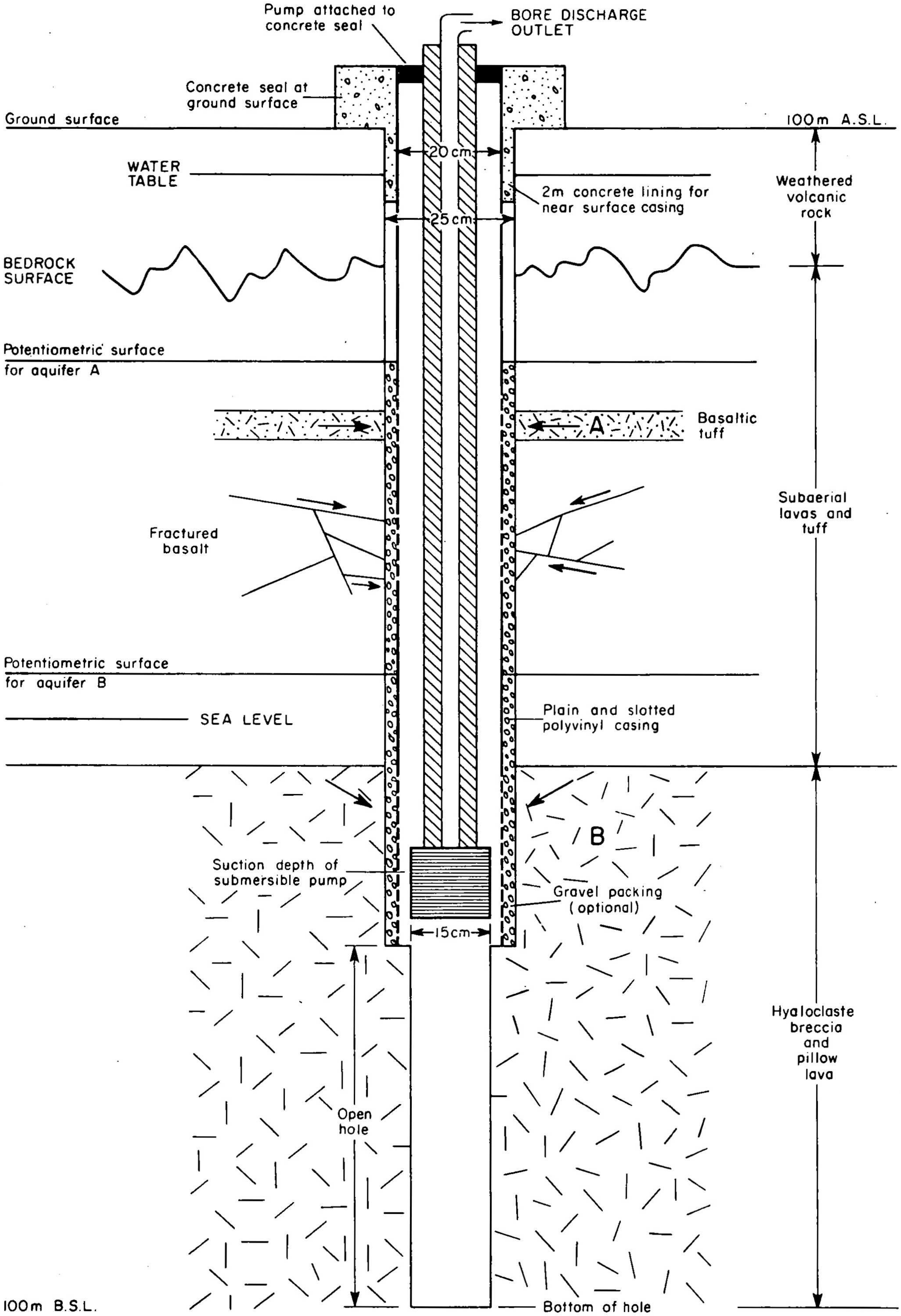

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Fig. 19 Typical specifications required for a deep production bore tapping bedrock aquifers on Norfolk Island

19/09/73

Air-water rotary drilling is favoured over the percussion method because continuous core can be obtained, penetration is quicker through hard massive lavas and drilling is less commonly deflected from the vertical through the hard and soft layers and fracturing typical of volcanic rocks.

Drill holes must have proper vertial alignment to facilitate pump installation and maintenance when operating as production bores. Rotary drilling in volcanic rocks may cause drilling fluids to escape into highly permeable zones which in turn, removes its support of the upper portion of the hole. Casing must be advanced down the hole during drilling to prevent a cave-in but also to seal off shallow groundwater in the weathered mantle which may be polluted and a potential contaminant of water supplies at deeper levels.

The use of submersible pumps is recommended for aquifer testing and for long-term production bores providing the pump setting is at or above sea level to minimise the risk of up-coning of sea water. Suction pumps can be used for testing shallow groundwater in the weathered mantle.

PVC casing is recommended as groundwater on Norfolk Island is known to be corrosive with pH values commonly less than 7 (Abell, 1976). Lengths of PVC casing must be properly connected and sealed.

All holes to be fully cored and logged. All water intersections to be noted and associated water level changes noted using a downhole water level recording device. Yield can be measured using a bailer or by a 'V' notch weir plate erected on the bore discharge channel.

Completion procedures

(a) Drill a 15cm diameter hole through the weathered mantle to bedrock. Advance casing to the water table leaving the remainder of the hole open and test for water yield in the upper groundwater storage using a suction pump; monitor groundwater salinity using a portable 5 range Dionic conductivity tester.

(b) Plain case the weathered mantle and drill hole to required depth, e.g. 100 m. The hole can remain open but if caving insert screened PVC casing. If substantial water intersections are encountered during drilling measure the yield by bailing for 1 hour. Estimate the drawdown and the amount of water bailed.

(c) If the hole is likely to yield a significant supply (more than 3 litres per second) below the weathered mantle then ream out to 25 cm, insert submersible pump and carry out a multistage test followed by a 24-hour single rate test after the bore has recovered measuring water levels and discharge rates. Monitor salinity levels and take water samples. When undertaking aquifer tests on a bore tapping water intersections in bedrock make sure the groundwater in the weathered mantle is cased off. From the known water intersections run screened casing and gravel pack if necessary.*

(d) Insert submersible pump at correct suction depth, concrete seal and cap the bore.

EXPLOITATION OF SHALLOW GROUNDWATER

Development of shallow groundwater from alluvium and the weathered mantle along Mission Creek is worthy of further investigation. At other localities on Norfolk Island (Fig. 6) significant yields in excess of 3 litres/sec. are already known from shallow bores drilled into alluvium in upper tributaries of Watermill Creek (NI 97 and 151) and Rocky Point Creek (NI 63). Annual stream flow in these catchments in maintained largely by baseflow which if properly developed has the capacity to provide useful reserves of shallow groundwater.

During the survey a brief examination of a narrow but continuous tract of alluvium along Mission Creek (Fig. 2) showed that streamflow begins at two spring seepages in its upper tributaries located on land belonging to Norfolk Island Airport. Some exploitation of shallow groundwater in this creek has already been attempted by direct pumping of water from a shallow pit in alluvium close to survey peg <u>Bq</u> (Fig. 11). Recently a bore drilled nearby (see GEOPHYSICS Section p. 19) encountered alluvium and weathered volcanics to a depth of 30 m and gave a yield of 8,000 litre/hr. In the past earth dam storages have been built but many have been breached; currently a water storage structure is near completion at peg C31. At peg C24 a standpipe has been erected at a small earth dam storage a few hundred metres below the seepage on Line C (Fig. 11). Attempts to exploit

* A rock crushing plant on Stockyard road owned by Mr G. Aafjes uses basalt quarried at Cascade. The standard sizes of crushed basalt available are:

Nominal	19 mm	The smallest size is 3 mm
	9.5 mm	
	6.3 mm	

this water resource indicates that baseflow is maintained at or near the surface along Mission Creek during dry spells.

The probable existence of shallow groundwater reserves along Mission Creek provides an opportunity to develop the resource predominately as a second class water supply. Uses for this supply include small scale irrigation watering, construction projects, road watering, fire fighting, carwashing and stock watering. If domestic and livestock pollution can be controlled and production bore or well installations are properly constructed, sealed and maintained, the quality of this water maybe good enough for domestic use. Development of shallow groundwater can be undertaken by a truck-mounted rotary drilling rig already operational on the island which has the capability for tackling soft rock and drilling bores 50 m deep. An alternative is large diameter collector wells which can be constructed by lowering a concrete caisson into the margin of the alluvium and sealing it with a concrete plug. Polyvinyl slotted pipe laterals connected to port holes near the bottom of the caisson can be driven into the saturated alluvium using hydraulic jacks. Groundwater flow is induced into the laterals by a lowering of the water table and collected in the main well whereupon it is pumped to storage. Yields to collector wells are generally increased during high stages of stream flow, but reduced over time if excessive clay in the alluvium silts up the laterals.

Before considering this proposal further more hydrogeological data is required for an estimate of shallow groundwater reserves along Mission Creek. The areal extent of the alluvium can be accurately mapped with the aid of aerial colour photographs at a scale of 1: 4000. The nature and thickness of the alluvium can be investigated cheaply and quickly using a small truck-mounted augering tool capable of drilling up to 50 m to bedrock. This data will provide information on the geometry and lithology of the alluvial deposit and if the hydraulic gradient of the creek is known the groundwater reserves can be estimated. For development of this resource the seasonal behaviour of stream flow conditions along Mission Creek needs monitoring. Currently stream flow data is collected at a stream gauging station installed by the Department of Housing and Construction (Fitzgerald and Falkland, 1981) close to the western extremity of the alluvium where the creek flows over the cliff line (Fig. 11).

The short term advantages in developing this water resource along Mission Creek exists in terms of cheap and easy exploitation at sites removed from the principle pollution sources in the Burnt Pine - Middlegate area. However, shallow groundwater reserves will always be subject to depletion during summer and in droughts by falling water levels and there is always the threat that long term domestic and livestock pollution will cause a deterioration in water quality standards. If this scheme can be shown as a viable proposition then other alluvial areas on Norfolk Island can be similarly investigated for development as second class water supplies.

RAIN WATER QUALITY

Under recommendations for pollution control made by Abell (1976), ten rainwater and two seawater samples were collected for analysis during 1977-80 to assess their quality and cyclic salt concentration. The chemical analyses are listed in Table 5. A rainwater sample from Tarawa Atoll has been added for comparison. The first sample of rainwater collected on 17.11.77 has been deleted as this analysis was incomplete.

Rainwater samples were collected by Mr G. Duvall on his property (Plot No. 43S). The site is situated at an elevation of 128 m above sea level on the southern plateau towards the eastern side of the Island. The samples were collected in a stainless steel tray measuring 430 x 303 x 63 mm deep. The container was placed in the open away from sources of contamination such as trees, buildings, animal life and industrial plant. The stainless steel container was placed on a 1.2 m high wooden stand of sufficiently heavy construction to prevent it being overturned by wind gusts which might accompany rain-storms. Enough sample was collected to fill at least a 500 ml polyethelyene bottle. The sample was poured into the sample bottle using a plastic funnel. The stainless steel tray and plastic funnel were carefully cleaned before and after use. Sample bottles were labelled and dispatched by air freight to Canberra and then on to AMDEL laboratories at Adelaide for chemical analysis.

Interpretation

Cyclic salt concentrations of rainwater samples as determined by the SO_4: Cl ratio shows that rainwater salinity is due to atmospheric salt spray from the ocean dissolved in rainfall. This interpretation is confirmed from Figure 20 which shows that sulphate and chloride concentrations for rainwater on Norfolk Island plot close to the line representing the average SO_4: Cl ratio for seawater of 0.14.

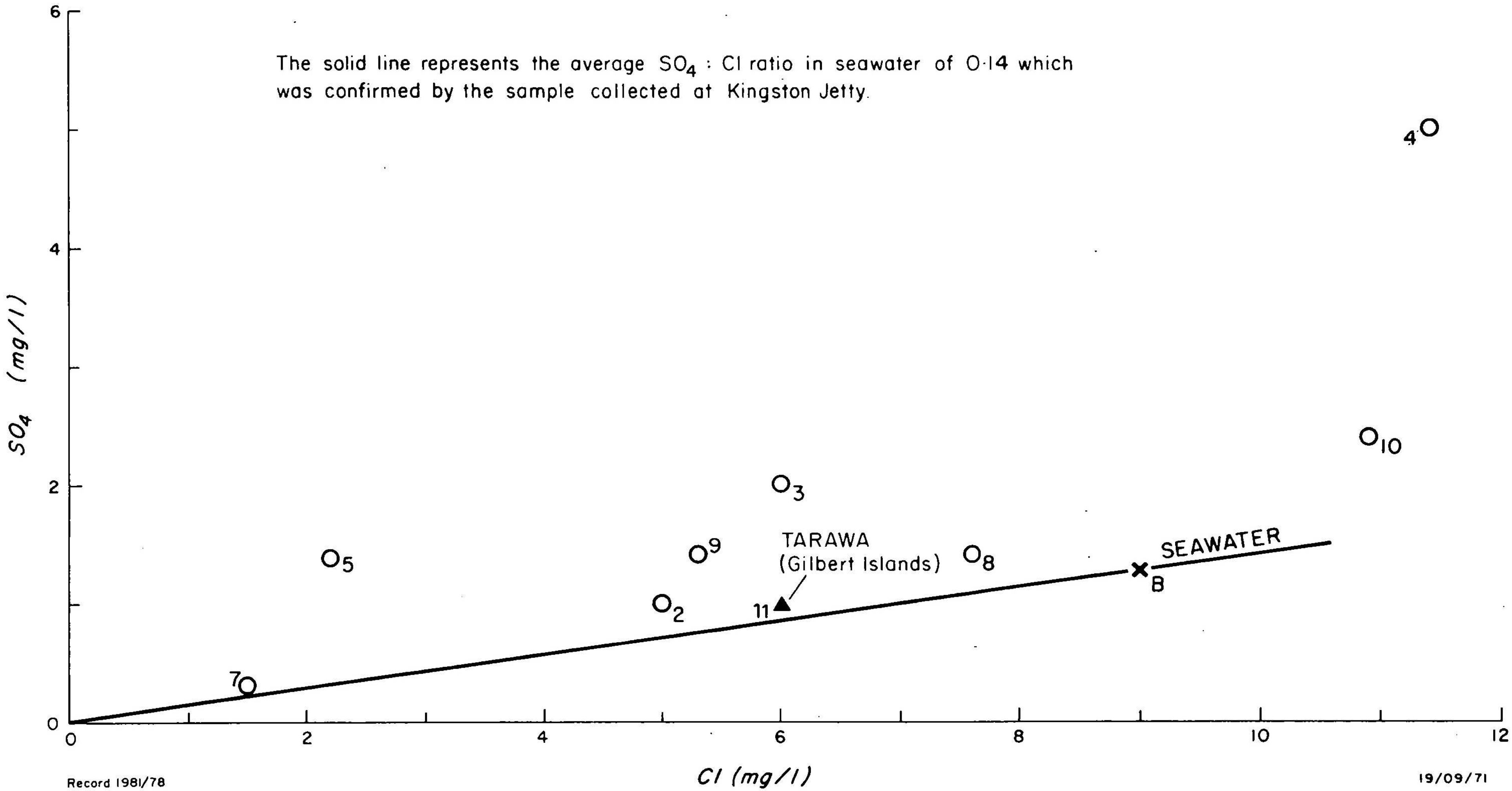

Fig.20 Concentration of dissolved sulphate versus dissolved chloride in rainwater

TABLE 5 CHEMICAL ANALYSES OF RAINWATER (expressed in mg/litre)

No	Time (hrs)	Date	Ca	Mg	Na	K	HCO_3	SO_4	Cl	NO_3	PH	Total Hardness (as $CaCo_3$)	TDS	Specific Conductivity (micromhos/cm)	WIND Direction	WIND Intensity (knots)	RAINFALL(mm) Over 24hr period covering sample collection time	Comment
2	15.00	7-2-78	.05	.03	3.20	.06	1.00	<1.0	5.00	<.10	6.3	1.0	9	26.0	050	15 & gusting to 25	28* (19.2)	
3	02.00	11-5-78	1.00	.20	3.90	.10	2.02	2.00	6.04	0.50	5.8	3.32	14.13	55.0	040	8	40* (40.6)	
4	02.00	14-8-78	1.00	.80	7.60	.60	5.80	5.00	11.4	1.00	5.7	5.79	26.28	63.0	270	20 & gusting to 40	6.2	
5	06.30	9-11-78	.62	.10	1.30	.40	1.40	1.40	2.20	.19	5.2	1.96	6.79	19.0	035	13 (Ave intensity	Heavy rain for about 30 mins. (25mm from 0.400 to 07.00 hrs)*	No rain for previous 14 days
6	15.00	17-2-79	.16	.06	0.26	.80	-	1.50	(0.50)	<.04	(4.8)	.65	2.61	17.0	NNW	Calm	69.8	
7	21.00	8-5-79	.10	.10	1.07	.04	-	0.30	1.50	<.04	5.9	.66	3.10	15.0	060	10	121.4* (96.8)	Heavy rain
8	15.45	11-8-79	1.20	.50	4.20	.30	2.50	1.40	7.60	<.04	5.6	5.05	16.47	41.0	260	8	1.4	Short but heavy rainfall
9	18.00	18-11-78	.31	.26	2.67	.10	1.10	1.40	5.30	.30	5.6	1.84	10.87	25.0	140	2	2.6	Rainfall 1-11-79 to 18-11-79 only 13.9 mms
10	09.00	13-2-80	.88	.65	5.89	.16	2.50	2.40	10.90	<.04	5.8	4.87	22.22	47.0	060	2	22.0	Light fine rain with occasional heavier falls for short periods.
11	-	20-9-80	1.30	.44	2.50	.76	5.00	1.00	6.00	<1.0	6.2	5.00	15.00	55.0	-	-	-	Tarawa atoll, Gilbert Islands.
A	11.30	22-1-79	432	1350	11,600	382	142	(2135)	20815	<1.0	7.8	6634	36,784	40,466	-	-	-	Seawater sample from Duncombe Bay
B	09.15	14-2-80	387	1337	11,280	393	141	2756	20057	<1.0	7.3	6468	36,280	45,933	-	-	-	Seawater sample from Kingston Jetty

* Rainfall as measured in rain gauge on the Duvall property; values in brackets are comparative rainfall measurements at the Metrological station

There appears to be little correlation between rainwater salinity and climatic data. Salinity levels in rainwater do not appear to correlate with strong wind intensity. According to Nagourney and others (1978) the salinity levels of precipitation taken at Mauna Loa observatory station, Hawaii, at an elevation of 3 400 m is 1000 times lower than at their comparative sampling site at Samoa where collectors were situated at sea level. While there is no guide for comparison on Norfolk Island the position and height of the sampling point about 2 km inland from the coastal perimeter suggests that the diminished concentration of salt spray in the atmosphere accounts for the low salinity levels ($<$63 micromhos/cm) in the rainwater. In other respects the variations in rain chemistry will also depend on time elapsed between rainstorms, the amount of rain, surf conditions and perhaps the build up of cyclonic weather patterns.

Variations in rainwater chemistry may result from chemical changes set up by the prolonged 2-3 week storage period of the sample prior to laboratory analysis. This may explain the low chloride value in sample 6, the low sulphate value in seawater sample A and low pH values in sample 6 and in both seawater samples. These discrepancies may be accounted for partly by hydrogen ion changes (pH) in storage and the laboratory techniques used for the detection of low concentrations of ions. The accuracy of pH and conductivity values could be improved by field measurement of these parameters at the time of sampling. Chemical fractionation has been suggested as a main cause for variations in the chemical constituents of rainwater (Kroopnick, 1977).

The low concentrations of ions in Norfolk Island rainwater compares favourably with a similar range of low chloride and sulphate values obtained from the Marshall Islands, Hawaii, and Tarawa Atoll. The rainwater analyses for Norfolk Island provide a good example of uncontaminated rainwater collected in an oceanic environment far removed from continental influences and other pollution sources. The data may also find comparative use with other island environments in the southwest Pacific.

The chloride concentration of rainfall (Cl^-_R) can be used to estimate groundwater recharge (Playford and Leech, 1977; Vacher and Ayers, 1980). The chloride ion in rainfall is stable and becomes concentrated by evapotranspiration as rainfall infiltrates through the unsaturated zone to recharge the water table. This evapotranspiration related concentrative process can be used to estimate recharge to perched groundwater occurring in the weathered mantle on Norfolk Island. If values of the chloride concentration of recharged groundwater (Cl^-_r) in the weathered mantle are known then the percentage groundwater recharge maybe estimated from the ratio

$$\frac{Cl^-_R}{Cl^-_r} \times 100\%$$

For Norfolk Island this method of estimating recharge can only be applied over the main watershed crossing the southern plateau which is also coincident with the Burnt Pine - Middlegate area. The high hydraulic potential in this area indicated by the water table contours which in places reach 110 m A.S.L. and low groundwater salinities ($<$ 500 micromhos/cm) designate the watershed as a recharge area. Examination of water quality records for the Burnt Pine - Middlegate area (Abell, 1976) indicate that only 7 bores and wells tapping the weathered mantle have chloride concentrations $<$ 100 mg/l. On the premise that the lowest chloride value is the best indicator of natural recharge a value of 35 mg/l has been assigned for Cl^-_r (measured in two wells in the recharge area). The mean chloride content of rainwater is 6.2 mg/l. Substituting in the ratio $\frac{Cl^-_R}{Cl^-_r} = \frac{6.2}{35} = .177$ or 17.7%

is the estimate of groundwater recharge. This technique can be used to approximately calculate the magnitude of recharge from the chloride content of rainfall relatively quickly and cheaply.

This estimate is subject to a number of constraints:

(i) Recharge to the water table aquifer in the weathered mantle is totally dependent upon winter rainfall (Abell, 1976). Chloride estimates for groundwater used in the calculation must be from samples taken between May and September. Lack of recharge and increased demand during summer months will degrade the quality of water in the aquifer to give anomalously high chloride values.

(ii) A time lag exists between the groundwater samples collected in 1974 and the rainwater sampling under taken in 1978-80. However, the chloride concentrations of rain fall were from samples taken in the recharge area and these values are not expected to vary much over the time lag interval.

(iii) Accuracy of the recharge estimate is increased by direct sampling and analysis of rainwater rather than by collection from rainwater tanks. Chloride concentrations taken from rainwater storage are higher due to rainfall runoff intercepting salt spray on house roofs and gutters and evaporative losses in house tanks.

(iv) Drawbacks to the use of the Cl^-_R/Cl^-_r ratios for estimating recharge relate to the identification of the correct low value for groundwater. Chloride concentrations may be locally increased by permeability variations in the weathered mantle and the disposal of sewage effluent. It is emphasised that the recharge value of 17.7% does not represent the available recharge of groundwater to the basal aquifers; losses of groundwater from the weathered mantle occur as baseflow along creeks, coastal seepages at the perimeter of the island.

CONCLUSIONS

(1) The current hydrogeological model proposed for Norfolk Island is a two component groundwater storage system connected by fractures.

The upper storage is a perched water table aquifer in the porous weathered mantle having considerable groundwater storage capacity. This is the main aquifer presently exploited but is currently threatened in the short term by pollution arising out of effluent from septic tanks and other domestic and livestock waste.

The lower storage is thought to be a basal groundwater aquifer in hyaloclastite rocks at and below sea level and as yet unexploited. Evidence that these rocks may have potential as an aquifer is afforded by (a) the occurrence of seepage zones near sea level particularly in coastal exposures around the northwest plateau and (b) field observations, petrographic examination and laboratory analyses which show these rocks to have a porosity and permeability framework apparently capable of retaining basal groundwater. It is evident that if this aquifer is to be developed as a groundwater supply the lateral extent, thickness and anisotropic permeability distribution of these breccias below sea level must be investigated in more detail by an exploratory drilling program.

An intermediate hydrogeologic zone connects the upper groundwater storage in the weathered mantle and the lower groundwater storage in breccia. Recharge to the basal aquifer is accomplished through this zone by vertical groundwater leakage from the weathered mantle into a complex of fractures in unweathered basaltic lava. Where vertically migrating groundwater occurs in basaltic tuff beds in this zone recently drilled water bores indicate the system behaves as a semi-confined aquifer with the potential to yield groundwater supplies between the weathered mantle and basal aquifer.

The quality of the groundwater in the bedrock aquifer is expected to be suitable for domestic use and substantially better than the groundwater currently extracted from the weathered mantle.

(2) The resistivity survey in the Broken Bridge - Mission Creek area was successful in providing information on prospects for the occurrence of shallow groundwater. Low resistivity values indicate zones of saturated, deeply weathered rock which may provide sources of shallow groundwater and, if co-incident with fractures, contribute to the recharge of deeper aquifers. Measurement of the hydrogeophysical response of bedrock was hampered in the investigation area by the dissected terrain which restricted the electrode spacing that could be used for Wenner profiling and depth probes. The interpretation of resistivity results was limited by the low resistivity contrasts that characterise the volcanic sequence; however, on the Kingston lowland a depth probe confirmed the existence of salt water at a depth of 17 m with an overlying zone of brackish water 15 m thick.

The limited areal coverage of the magnetic data means that only a broadly based interpretation of the results can be attempted. The recorded total magnetic field is typical of a basaltic lava and tuff sequence; the high noise level is due to variations in remanant magnetism rather than man-made interference (metal, powerlines, etc). The attenuation of the magnetic intensity profiles along Mission Creek and at Kingston maybe due to poorly magnetic alluvium and calcareous aeolianite overlying a local thickening of the weathered volcanic profile and increasing depth to magnetic basement. The data are unsuitable for the selection of drill sites, but more detailed surveys could outline information on the thickness of the weathered volcanics, distribution of bedrock types, and the existence of volcano-structural boundaries.

(3) To meet the water demand of 10.4 litres/sec from the Broken Bridge - Mission Creek area and also assist in the overall evaluation of groundwater resources, four drill sites in order of priority are selected (Table 4).

Water balance estimates (Abell, 1976; Fitzgerald and Falkland, 1981) indicate not less that 10% of average annual rainfall is available for groundwater recharge and therefore exploitation if it can be retained and has widespread occurrence in a basal aquifer. It is emphasised that within the complex hydrogeological environment of Norfolk Island it will be necessary to drill all the sites to at least the recommended depths to prove or disprove the existence of a basal aquifer. Any drilling program to probe the existence of groundwater at deeper levels needs to be formulated in the context of a long-term water resource development and pollution control program for Norfolk Island.

(4) The Administration must be alerted to the possibility that development of a basal aquifer does not automatically imply the assurance of a safe potable water supply independent of groundwater in the weathered mantle. Nevertheless it is predicted that the pollution threat to basal water will be diminished by natural purification processes operating longer as shallow groundwater moves to recharge aquifers at deeper levels. The discharge of sewage effluent into a borehole at the South Pacific Hotel presents a direct pollution hazard locally to the development of deeper aquifers on Norfolk Island. The loss of effluent appears to be in a permeable zone in bedrock only 11 metres above sea level (see p. 32).

The thickness of a freshwater layer underlying the island is still unknown, but taking into consideration the anisotropic permeability distribution through the hyaloclastite rocks, the landward effect of tidal fluctuation and the size of the island it is expected that the transition zone between fresh and saline water may be substantial where a strong hydraulic connection exists along permeable zones and fractures.

(5) Shallow groundwater in alluvium along Mission Creek and to a lesser extent in Broken Bridge Creek could be developed only as a second class water supply. While short term advantages appear to exist in terms of cheap and easy exploitation, it is emphasised that shallow groundwater reserves are subject to depletion during summer and in droughts by falling water levels; domestic and livestock pollution will also cause a deterioration in water quality standards. The potential of this resource cannot be assessed properly until at least 5 years stream gauging data have been collected.

(6) Interpretation of the chemical analyses of rainwater samples collected during 1978-80 indicate:

(a) rainwater is a very weak solution of NaCl having a similar SO_4 : Cl ratio to seawater

(b) there appears to be little correlation between rainwater salinity and climatic data; the range of chloride in the rainwater samples probably depends on the time elapsed between rainstorms, the amount of rain, wind, surf conditions and the elevation and position of the smapling site relative to sea level.

(c) the chemistry and low salinity values (not exceeding 63 micromhos/cm) is typical of rainwater collected in an oceanic environment far removed from continental influences and pollution sources. The analyses provide a useful set of data that may find comparative use with other island environments in the southwest Pacific.

(d) in the Burnt Pine - Middlegate area groundwater recharge to the weathered mantle is estimated at 17.7% of annual rainfall based on an evapotranspiration related concentrative process using the ratio of the chloride ion in rainwater and shallow groundwater. This does not represent a direct recharge value to basal aquifers since groundwater losses from the weathered mantle occur as baseflow along creeks and coastal seepage at the perimeter of the island.

RECOMMENDATIONS

It is recommended that:

(1) The Department of Housing and Construction, Bureau of Mineral Resources and the Norfolk Island Administration jointly plan a deep drilling program to prove the existence and nature of basal groundwater aquifers at and below sea level. Until deep holes have been drilled as recommended in Table 4 to prove the existence of basal groundwater it will not be possible to effectively plan water resource schemes for Norfolk Island. This drilling is also an urgent priority to overcome the present short-term pollution threat to currently exploited shallow groundwater supplies in the weathered mantle.

(2) As a first stage in the implementation of this drilling program, four sites be drilled in the Broken Bridge - Mission Creek area (as listed in Table 4). All sites to be test drilled as exploratory holes to provide in the first instance lithological, water level and water quality data on weathered mantle and bedrock aquifers. In all holes the extent, thickness and hydraulic behaviour of bedrock aquifers to be examined under properly controlled aquifer test pumping programs. The drilling and aquifer testing to be implemented under contract through an experienced water well drilling company and supervised by appropriate professional and technical staff. At the completion of test drilling, bores to be equipped as appropriate for production.

(3) With the assistance of the Department of Housing and Construction and Bureau of Mineral Resources, the Norfolk Island Administration consider schemes for communal point watering supplies using groundwater from bedrock aquifers as the basis for their future expansion into an island-wide water supply system. It is recognised that many island residents have their own bores and wells and for this scheme to succeed it will require a survey of consumer water use on the island as suggested by Fitzgerald and Falkland (1981).

(4) To assist in the investigation of pollution control measures groundwater samples should be collected for tritium analysis. Tritium is a naturally occurring hydrogen isotope which has a half-life period of 12.4 years which can be used to date and trace groundwater. The tritium content of groundwater samples taken from bores and wells and seepages in the weathered mantle when compared with samples taken from bedrock aquifers and coastal seepages should provide a good estimate of rates of groundwater movement in the hydrogeological system. More specifically this method should be able to assist in predicting whether polluted groundwater in the weathered mantle can affect the quality of groundwater in basal aquifers.

(5) To overcome the shallow groundwater pollution hazards in the Burnt Pine - Middlegate area an appropriately scaled sewage reticulation scheme be established as outlined in the proposals of Fitzgerald and Falkland (1981). This scheme will terminate the practice of sewage effluent-disposal down a bore at the South Pacific Hotel.

(6) A minimum of 5 years streamflow data is collected from the 8 recently installed gauging stations (Fitzgerald and Falkland, 1981). Early data returns show that a provisional percentage estimate of runoff to rainfall is about 4-6% which suggests that baseflow is a significant

quantitative component of the water balance. Processing of the streamflow data will allow for refinements of the water balance, more accurate determination of groundwater recharge, appraisal of the baseflow characteristics of the gauged catchments and assessment of schemes for the conjunctive use of ground and surface water. At the end of the 5 year period the data collected needs to be revieved with regard to the continued operation of the stream gauging network over a further time period.

(7) To develop a second class water supply system for Norfolk Island, investigate and attempt initially to estimate shallow groundwater reserves in alluvium along Mission Creek and possibilities for its exploitation by shallow bores or collecter wells. If such a scheme is viable other alluvial occurrences in Broken Bridge, Watermill, Cascade, Stockyard, Town, Headstone and Rocky Point Creeks can be similarly investigated.

(8) The Administration draw up a preliminary draft for a simple water Ordinance that will best serve the needs of Norfolk Island. Ownership of water to be vested in the Crown with individual and riparian owners rights being covered by statute. The ordinance will protect individuals from the depletion, pollution and other misuse of water resources by irresponsible people and organisations. Some of the factors governing groundwater legislation are briefly discussed in Abell (1976).

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APPENDIX 1

PALYNOLOGY OF A CARBONACEOUS CLAY FROM NORFOLK ISLAND

by

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A single sample of balck carbonaceous clay collected by R.S. Abell in the course of hydrological investigations on Norfolk Island was macerated and examined for its spore and pollen content. The organic-rich clay crops out on the beach in front of the cemetery at Kingston, and forms part of a sequence of coastal sedimentary rocks described by Veevers (in Abell, 1976). According to Veevers' account, the black clay is at least 2.5 m thick, rests on basalt, and may lap on to a cross-bedded calcareous aeolianite unit. The clay contains, according to Veevers description, excellently preserved logs, fruits, and leaves of *Araucaria heterophylla*, the Norfolk Pine. The wood has yielded a radiocarbon date of 6870 ± 230 years B.P. (as determined by K. Kigoshi; Gakashuin University, Tokyo); it is not clear, however, from where in the clay sequence the wood comes. Pumice fragments in the clay suggest that it was deposited in a coastal lagoon that was periodically open to the sea. Veevers suggested that palynological work should be undertaken on the clay in order to provide some kind of climatological history.

The clay yielded abundant spores and pollen showing outstanding preservation. Identifications of pollen and spore types observed in preparations from the clay were made iwth some difficulty; in the absence of a reference collection of pollen from plants now growing on Norfolk, most taxa have been identified to genus only; a few only to family, and some are still tentative. The generous assistance of Mr John Grindrod, of the Department of Biogeography and Geomorphology, ANU, in making identification, is acknowledged. In checking identifications against the flora of the island, the floral lists presented by Maiden (1903) and by Turner, Smithers and Hoogland (1968) for Norfolk Island have been of considerable assistance.

Palynological Content - Sample 7722 - Cemetery Beach

Ferns	:	Cyathaeaceae	*Cyathea* sp
		polypodiaceae	? *Polypodium* spp.
			Microsorium sp.
		Pteridaceae	*Pteris* sp.
		Dennstaediaceae	*Histiopteris* sp.

Gymnosperms :	Araucariaceae	Araucaria
Monocotyledons :	Palmae	Rhopalostylis sp.
	Cyperaceae	? Carex sp.
Dicotyledons :	Malvaceae	Hibiscus sp.
		Unknown Malvaceae
	Euphorbiaceae	Excoecaria sp.
	Ulmaceae	Celtis sp.
	Rubiaceae	? Coprosma sp.
	Gunneraceae	Gunnera sp.
	Chenopodiaceae/Amaranthaceae	
	Leguminoseae	
	Unknown dicotyledons	

A count of 300 specimens showed that fern spores, chiefly Cyathea types, are overwhelmingly dominant. The only other element of numerical significance are the Cyperaceae or sedges. The very low representation of Araucaria pollen, which occurs in the sample but was not observed in the count, is surprising in view of the reported occurrence of Araucaria macrofossils in the clay. Major elements apparent from the percentage figures are listed below:

Ferns	(Cyathea spp.	78.0
	(Polypodiaceae	12.0
	(Pteris sp.	1.0
	Cyperaceae	4.5
	Tricolporates	2.0
	Others	2.5

Depositional environment

A coastal lagoon depositional environment has been suggested for the black clay on the basis of its sedimentological character and stratigraphic setting. The palynological content of the clay is broadly in accord with such a setting, although many of the spores may have been transported to the depositional site from growth sites further away. The dominant Cyathea spores, for instance, probably came from tree ferns of which two species, Cyathea brownii Domin and C. australis (R.Br.) Domin presently grow on the island. Today, these species form thickets in the valleys, and it is likely that these moist areas have always been the preferred habitat. The high concentration of spores in the clay probably reflects drainage into the lagoon via tree-fern gullies similar to those now present on Norfolk (Turner et al., 1968)

The endemic palm, Rhopalostylis baueri (Hook.f.) is also concentrated in such habitats, and the rare pollen grains identified as Rhopalostylis sp. in the clay may have come from palms in the gullies or on steep volcanic slopes.

The significant content of sedge (Cyperaceae) pollen possibly derives from vegetation on the lagoon margin, but this is uncertain as some species are also reported as growing within the forests on Norfolk (Turner et al., 1968). Identification of the habitat of the Quaternary types is complicated by the lack of a modern reference collection, and by the fact that no coastal lagoon habitats which could provide analogs for the Quaternary pollen flora are now present on the island.

The presence of Excoecaria pollen in the clay is of interest. Excoecaria agallocha l. grows on Norfolk today, according to Turner et al. (1968, p.35) 'Near the coast from Ball Bay to Bumbora, e.g. near Bloody Bridge, near the cemetery, and along Watermill Creek near Flagstaff Hill '. In Australia, the same species is always part of mangrove communities (J. Grindrod, personal communication); its entry into the Norfolk Island vegetation may have been as part of communities that grew in coastal lagoon habitats in the Quaternary.

The record of Gunnera pollen presents a problem, as Gunnera does not grow on Norfolk Island today; its present range in the western Pacific includes New Guinea, New Zealand and Tasmania (see Jarzen, 1980 for a summary). The presence of Gunnera species on Hawaii suggests that it is capable of long-distance dispersal, so it is possible that a species may have become established on Norfolk in the past. The other possibility, that these extremely rare grains have been wind-blown into the Norfolk deposit, also presents problems; there are no sources closer than 500 km away, and there is no evidence for any other wind-blown elements in the pollen spectrum.

Recommendations

On the inadequate basis of the single sample examined, there is no reason to believe that the Late Quaternary climate of Norfolk Island was any different from that of the present. However, in order to assess Late Quaternary environments and vegetation more clearly, and to discern any fluctuations in climate, a closely sampled sequence is needed. It may be possible to obtain such a sequence through the clay by a program of shallow drilling in the Kingston Lowland area, but development of the clay is likely to be patchy and confined to pockets on the bedrock surface. A first step might be to use a hand-corer to try and obtain a sequence through the clay where it crops out near Cemetery Beach.

There is much interest currently in island biogeography and in processes and patterns of colonization of remote islands. The Norfolk site, which contains datable material and well-preserved pollen, appears to offer a potentially valuable record in this regard, a record that could be obtained for relatively low cost and effort.

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APPENDIX 2

POROSITY AND PERMEABILITY OF ROCK SAMPLES FROM PT. VINCENT, NORFOLK ISLAND

by

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Laboratory preparation and procedures

Six samples of volcanic breccia were submitted for porosity and permeability tests from a possible basal aquifer on Norfolk Island. Sample plugs 2.8 cm in diameter and approximately the same length were drilled from 3 outcrop samples using a diamond core bit. Plugs were dried at 100^{o}C overnight before determining their porosity and permeability characteristics.

Permeability

Initially, the permeability to nitrogen of each plug was determined in a rubber sleeved Hassler cell and calculated according to the following formula:

$$K - \frac{Q}{T} \times \frac{L}{A} \times \frac{1}{P} \times \quad \times 1000$$

K = absolute permeability, millidarcies
Q = volume of nitrogen passing through the plug in time T, ccs
T = time for volume Q to flow through plug, secs.
L = length of plug, cms.
A = cross sectional area of plug, sq. cms.
P = pressure differential across plug, atmospheres
u - viscosity of fluid flowing, centipoise

At a later stage the 6 plugs being investigated were 100% saturated with fresh water and the permeability of fresh water flow determined.

Porosity

This value was determined using the laboratory porosimeter which incorporates an accurate pycnometer utilising mercury. The bulk or total volume of each plug was determined as was the grain volume and from these values porosity and densities were calculated using the following formula.

$$P.V. = B.V. - G.V. \qquad O = \frac{P.V.}{B.V.} \times 100\%$$

$$B.D. = \frac{\text{Sample Weight (gms)}}{B.V.} \qquad G.D. + \frac{\text{Sample Weight (gms)}}{G.V.}$$

P.V. = Pore volume (cc)
B.V. = Buld " "
G.V. = Grain " "

O = Porosity, % of B.V.

Benzidine Test

This test consists of crushing the rock sample and placing it in a test tube to which is added a similar amount of powdered benzidine.

The two powders are intimately mixed before adding water to half fill the test tube. The mixture is shaken vigorously and allowed to stand.

Production of a blue colour in the mix indicated that a smectitic clay was present.

DISCUSSION OF RESULTS (Table 1)

As shown in the table the porosity of most of the samples was high. Note that the porosity tabulated in "Effective Porosity" which consists of all void space that is interconnected. There maybe a percentage of isolated pores present within these samples that cannot be reached or measured by laboratory apparatus.

If such isolated pore space exists then the grain density given will be low due to isolated pores being included in the grain volume measurement.

Some samples exhibited small vugs, the volume of which would not be included in the measurement of bulk volume and, as porosity is calculated as $\frac{P.V.}{B.V.}$ %, then the effective porosity values given may be fractionally high.

Shrinkage cracks, due to oven drying, were observed in some plugs and this would lead to higher, measured permeabilities. This is verified in Table 1, where, on saturation with fresh water, there was a marked reduction in permeability. This reduction is attributed to clay swelling or particle movement both activated by fresh water.

The results of the tests shown in Table 1 indicate that the breccias have good water storage capacity (20-40% porosity). The permeability values vary greatly but suggests (as in sample 1) that these rocks have potential as a basal aquifer. A more realistic assessment of the permeability variations in these rocks could be made on fresh core samples obtained from exploration drilling.

TABLE 1: POROSITY AND PREMEABILITY DETERMINATIONS ON HYALOCLASTITE BRECCIAS FROM NORFOLK ISLAND

Sample Number	Porosity (% bulk volume)	Permeability to Nitrogen (md)	Permeability to freshwater (md)	Dry bulk density (gms/cc)	Apparent grain density (gms/cc)	Remarks
1	44.3	1,736	1,180	1.71	3.07	Large pores;
2	30.6	0.49	0.1	2.58	3.71	Large pores; some vugs; shrinkage
3	39.9	630	16.2	1.83	3.04	Small vugs; shrinkage
4	5.7	0.1	0.1	2.63	2.79	Dense; few large pores
5	24.4	31.8	0.98	2.23	2.94	Few large vugs
6	25.1	7.7	0.24	2.22	2.97	Relatively dense; some fissures

APPENDIX 3

DRILLING EQUIPMENT ON NORFOLK ISLAND

The rig currently in use on Norfolk Island is a modified Failing rotary drill mounted on a truck. The drilling rig is presently owned by Mr. R. Barrett and is currently operational. He took over ownership of the rig from Mr. G. Quintall in 1979. Since that time new and reconditioned equipment has been purchased and the rig is now better maintained and has on occassions drilled in bedrock conditions to depths in excess of 90 m.

During the 1981 visit the rig was inspected and appeared to be reasonably well maintained and overall looked in better condition than in 1974. The rig had been painted and working parts were lubricated. The current drilled practice uses water circulation. The owner hopes to add compressed air and make the rig operational for down-hole hammer drilling. The rig is designed to take a modification for a dual circulation system using fluids or air. The circulation of bentonite mud is not recommended practice; mud will expand in contact with fresh water to reduce the porosity and permeability of aquifers.

The gearbox serving the hoist mechanism and rotary table needs replacement bearings. The pump used for circulating fluids is beginning to wear out and is unable to provde sufficient volume to remove cuttings efficiently from a deep hole. The power unit is underpowered for deep holes (100 m +) which must be a major reason for past failures to retrieve heavy down-hole drilling equipment. A larger horsepower diesel motor is needed. There is no equipment for coring and widening the holes. A down-the-hole hammer bit or diamond-tipped coring bit, core barrels and a reamer need to be purchased. Tricone bits are unsuitable for drilling through thick and hard basalt as they wear out rapidly. A new kelly bar is required preferably machined from solid steel. The drilling rods are serviceable but there is only sufficient to drill to about 100 m. For future water bore drilling programs sufficient drilling rods are needed to cover drilling depths up to 200 m, preferably in 6 m lengths. Maximum lift on the mast crown is about 3 metric tonnes which needs to be remedied for deeper holes to allow for a lift of 4-5 metric tonnes using an extra system of pulleys on the mast; this, however, might require a new mast head. A few fishing tools are available such as a carrott (a spear tool for retrieving broken drilling rods) and a grip tool which can be used for a similar purpose. A tapered spoke is needed for opening the hole at depth. Holes currently drilled range from

13-16 cm in diameter. Polyvinyl casing of 10 cm diameter is used for lining water bores and is readily available on the Island. Larger diameter drill holes required for production bores will need 15 cm plain casing especially brought to the Island. Slotting can be achieved on the Island.

It is understood that current drilling rates are as follows:

soft rock drilling	$40.00/metre*
hard rock drilling	$35.00/hour*

As the rate of drilling in hard rock conditions is more variable than for soft rock conditions the rate is quoted on an hourly basis. It is estimated that to overhaul the drilling rig to make it serviceable enough to drill with ease a 100 m hole will cost about $15,000*.

At first sight, it appears that the quickest and perhaps easiest method of carrying out a drilling program is to utilise the rig on Norfolk Island. The main advantages are knowledge of local conditions and no air or sea transport costs. Disadvantages at the present time are (a) the present condition and lack of drilling equipment which indicates the rig does not have the capability to drill deep holes without break-downs and considerable stand-by costs and (b) limited experience by personnel on the Island to carry out the specifications that will be required for drilling production bores.

The main recommendation in this report is a deep drilling program to prove or other wise the existence of deep groundwater. It is therefore recommended that, prior to the detailed planning of a drilling program, an experienced water bore drilling supervisor visit Norfolk Island to:

(a) report on the most practical drilling methods and equipment best suited for the hydrogeological conditions on Norfolk Island, in particular for the development of bedrock aquifers.

(b) advise on the merits or otherwise of the alternative drilling schemes outlined briefly in this report; comment on the most cost effective drilling program best suited to develop bedrock aquifers on Norfolk Island.

(c) report on the present capacity of the drilling rig on the island

* the estimates are given only as a guide to costs. They are based on drilling rates and equipment costs current in 1981.

to undertake a drilling program to prove basal groundwater at depths exceeding 100 metres. In the event that the island rig is not well enough equipped or in a condition to do this task, cost an overhaul program that will bring the drilling rig to an operating level capable of implementing such a program.

APPENDIX 4

BUDGET ESTIMATES FOR DRILLING AND EQUIPPING PRODUCTION BORES

To develop deep groundwater all holes need to be initially test-drilled for the provision of hydrogeological data on the existence and nature of bedrock aquifers. After test drilling complete and equip the bores as appropriate for production.

For constructing and equipping a production bore, costs need to account for reaming out the hole, insertion of large diameter casing, sand or gravelpacking if needed, pump purchase and installation, protective concrete seal, access rights and if necessary land rental or purchase agreements. An arbitrary estimate is that 50% of the cost of a test hole needs to be added to cover these items.

Allowances for additional expenditure must include where appropriate transport costs of drilling equipment to and from Norfolk Island and purchase or repair of equipment to cover breakdown failure. These items are excluded from the budget as it is a subjective exercise to cost them without knowing when a drilling program can be funded.

Drilling costs given below are based on the assumption that the holes in bedrock will be fully cored and drilled under contract by a truck mounted rotary drill following the drilling and completion procedures already outlined in an earlier section of this report (p 38).

(1) Drilling and equipping four deep production bores in the Broken Bridge -Mission Creek area to serve the immediate needs of the Burnt Pine - Middlegate complex.

(a) Drilling: Four 15 cm-diameter bores to depths of about 100 m @ \$90.00/metre : 4 x 100 x 90 = \$36.000.

(b) Casing: Supply and insertion of plain and slotted PVC casing @ $10.00/metre : 4 x 100 x 10 = $4 000.

(c) Completion: Aquifer tests (multistage and single rate tests) and water quality monitoring is estimated at $4 000 for all holes.

Total estimate of test drilling and completion program:
$36 000
$ 4 000
$ 4 000
$44 000 or $11 000/hole

(d) Equipping and production: The addition of 50% of the cost of each test hole is 4 x 5 500 = $22 000.

Total cost of four production bores:
$44 000
$22 000
$66 000

(2) Drilling and equipping eight deep production bores to provide communal watering points which could be expanded at some later date into an island-wide water supply system.

(a) Drilling: Eight 15 cm diameter bores to depths of about 100 m @ $90/metre : 8 x 100 x 90 = $72 000.

(b) Casing: Supply and insertion of plain and slotted PVC casing @ $10/metres : 8 x 100 x 10 = $8 000.

(c) Completion: Aquifer tests (multistage and single rate tests) and water quality monitoring is estimated at $8 000 for all holes.

Total estimated of test drilling and completion program:
$72 000
$ 8 000
$ 8 000
$88 000 or $11 000/hole

(d) Equipping and production: The addition of 50% of the cost of each test hole is 8 x 5 500 = $44 000.

Total cost of eight production bores:

$88 000
$44 000
$132 000

(3) Drilling and equipping six shallow production bores in the Broken Bridge - Mission Creek area to develop a second class water supply based on the exploitation of shallow groundwater from alluvial aquifers mainly along Mission Creek. Drilling to be undertaken by the truck-mounted rotary drill presently operational on the island which has the capability for tackling soft rock. The drilling rate quoted includes the supply and insertion of PVC casing, but assumes the holes will be uncored.

(a) Drilling: Six 15 cm diameter bores to depths of about 50 m @ $40/metre : 6 x 40 x 50 = $12 000.

(b) Completion: Aquifer tests (multistage and single rate tests) and water quality monitoring is estimated at $6 000 for all holes.

Total estimate of test drilling and completion program:

$12 000
$ 6 000
$18 000 or $3 000/hole

(c) Equipping and production: The addition of 50% of the cost of each test hole is 6 x 1 500 = $9 000

Total cost of six production bores:

$18 000
$ 9 000
$27 000

The estimates given above are based on drilling rates as at 1981; they do not include the construction of water storages, supply and power costs for linking and operating these production bores as part of a water supply scheme. As it is desirable to preserve some flexibility as to how deep a bore must be drilled at any particular site, the cost estimates given above are only a guide to provide options for preliminary planning of the drilling program.