REPORT 177

Burdekin Delta Underground Water Investigation, North Queensland 1962-1963

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DEPARTMENT OF MINERALS AND ENERGY
BUREAU OF MINERAL RESOURCES, GEOLOGY AND GEOPHYSICS

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SUMMARY

A geophysical survey was made in the Burdekin Delta, North Queensland, to assist the Irrigation & Water Supply Commission in its investigation of underground water resources in this important sugar-growing area. Gravity, seismic, resistivity, gamma-ray logging, and radioactive tracer techniques were used.

Gravity results revealed a fault buried beneath deltaic sediments, and also a remarkable negative anomaly. A hypothetical geological structure that would explain this anomaly has been computed.

Seismic results were used to draw a basement contour plan, basement being defined as the upper surface of material whose seismic velocity is 6700 ft/s or greater - i.e. effectively the base of unconsolidated deltaic sediments. Basement contours show a considerable deepening northwards from the river; to the south is a zone of relatively shallow bedrock. They also delineate deep channels and suggest possible underground connexions between Barratta Creek and the Burdekin River west of Kellys Mountain, and between Barratta Creek and the Burdekin Delta to the north.

From the resistivity work, contour maps were drawn to show the extent of salt-water intrusion at various depths. Detailed resistivity observations by depth probing and traversing of one area over a period of eight months suggest that salt-water intrusion is a very real problem. Comparison of some depth probes in October 1964 with those made at the same places in 1962 and 1963 confirm this idea.

By correlation of seismic, resistivity, borehole, and other information, cross-sections have been constructed to show the structural form of the delta, the main lithological units, and the probable distribution of groundwater of various qualitieswithin the deltaic deposits. A map has also been produced to show the distribution of permeable subsurface deposits suitable for artificial recharge.

Auger drilling, gamma-ray logging, and the use of radioactive tracers in pumping tests contributed to the study and correlation of near-surface deposits.

1. INTRODUCTION

GENERAL

The Burdekin Delta, in which Ayr is the biggest town, covers an area of some 250 square miles (Fig 1.) and is one of the large sugar producing areas of Queensland. The sugar cane growers use a large quantity of irrigation water which is pumped out of the Delta aquifers. However, a series of dry seasons has caused a

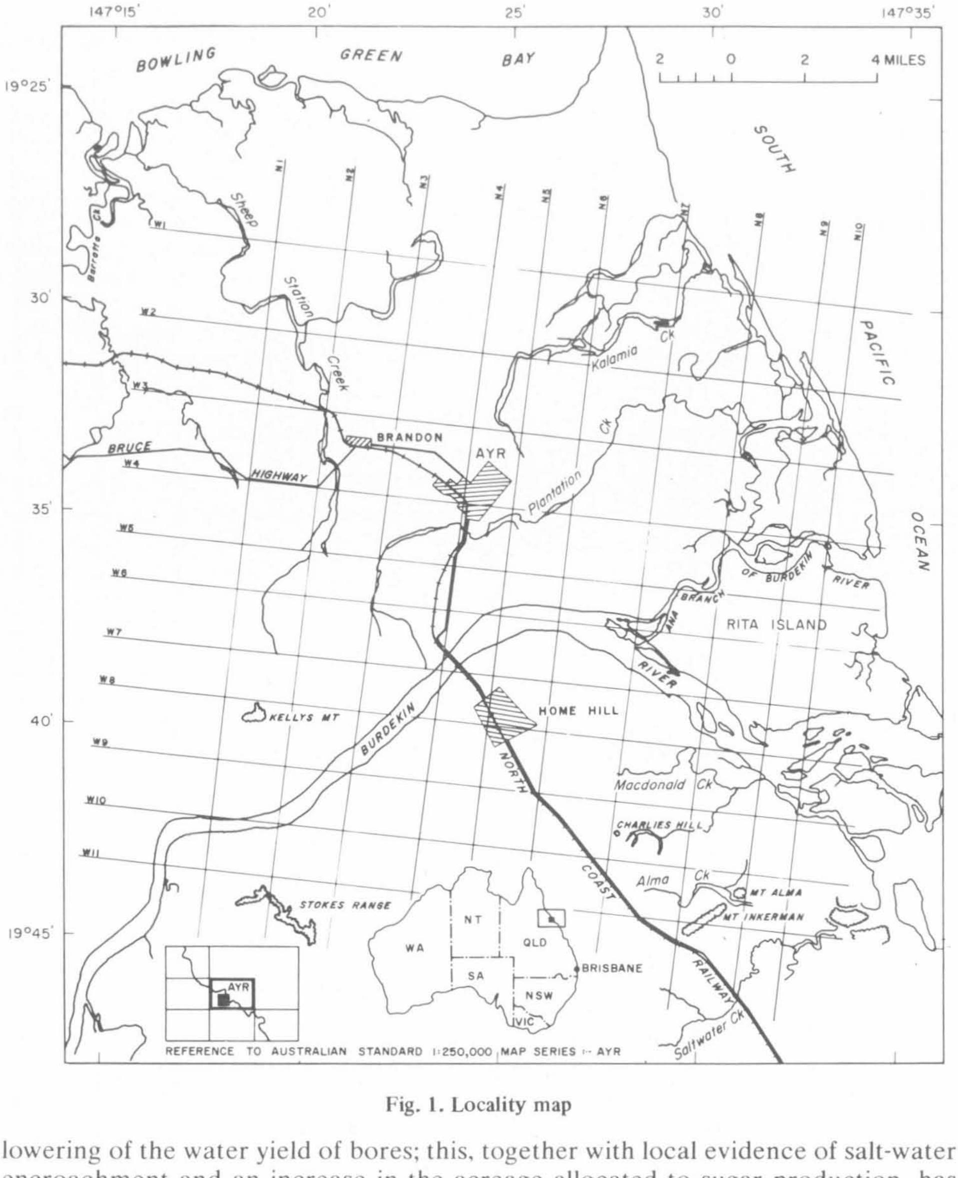


Fig. 1. Locality map

lowering of the water yield of bores; this, together with local evidence of salt-water encroachment and an increase in the acreage allocated to sugar production, has caused some concern about future supplies. Although hundreds of shallow bores and a number of deeper ones have been drilled, no bore logs were kept until about 1960, and most of the drilling information has been lost; thus whatever geological information is available is restricted to the near-surface. The first step to improve matters was to assemble the available geological information, and this was done by Watkins & Wolff (1960). Since then the Irrigation and Water Supply Commission (IWSC) has started to drill a grid of observation bores. Some of the drilling data was used in the preparation of a borehole map (Plate 2).

Before any major engineering projects, such as artificially increasing the aquifer recharge, building storage dams, or building dams to prevent inflow of salt water into the Delta, could be planned, more information of a general nature was required. To supply this information the Irrigation and Water Supply Commission of Queensland requested the Bureau of Mineral Resources (BMR) to make a geophysical investigation of the area. Because of the complexity of the problem and the size of the area, BMR sent several parties during 1962 and 1963, and applied four geophysical methods. Following the suggestions of the Commission's officers, more detailed investigation was made in some areas with serious salt-water encroachment problems, viz. the Merryplain Creek, Anabranch School, Sheep Station Creek, and Rita Island areas.

The surveys were undertaken not only to collect information as efficiently as possible but also:

(1) To test methods and their applicability to the problem.

(2) To test which sequence of methods should be used.

(3) To attempt to show how geophysical results may be integrated with geological and hydrological data and concepts to present a unified interpretation.

In November 1963, BMR and the Australian Atomic Energy Commission's Isotope Division carried out radioactive tracer tests close to pumping bores (Andrew, Ellis, Seatonberry & Wiebenga, 1965). The aim was to find out whether radioactive tracers could be efficiently used to estimate aquifer characteristics.

The Burdekin Delta has a dry tropical climate with a marked summer rainfall. The average annual rainfall is about 43 inches, but there are large variations in the yearly totals. Cyclones have caused daily falls up to 18 inches and monthly totals as high as 55 inches. The Burdekin River is noted for large variations in flow ranging from 1 300 000 cusecs for short periods to less than one cusec in the dry season, measured near Home Hill.

2. GEOLOGY AND HYDROLOGY OF THE BURDEKIN DELTA

As mentioned earlier, Watkins & Wolff (1960) assembled available information on the geology of the Delta area. The following material is extracted from their report.

> Whitehouse (undated) in considering the geology of the Burdekin River Basin pointed to the existence of three groups of rocks - the old granites; a series of interbedded lavas, tuffs and sediments; and later intrusive granites and porphyries.
>
> The delta area comprises a system of aquifers of sands and gravels variously separated by aquicludes of silts, silty-clays and clays. Bedrock where located has been shown to be mainly granite and related diorite. The coastal margin to the delta consists essentially of littoral deposits up to 3 miles wide.
>
> About 19 miles from the river mouth Stokes Range and Kelly's Mt, both some 600 ft high, with an interconnecting rock bar across the river, form the western boundary of the delta.
>
> Stokes Range is thought to represent a part of the Upper Devonian sequence of lavas and sediments known to the west.
>
> Mt Inkerman which rises to a height of about 700 feet above the surrounding country, some 8 miles south of Home Hill forms part of the southern limits of the delta.
>
> The Charley's Hill Inlier 3½ miles NW of Mt Inkerman, consists of a banded calc-silicate hornfels mass protruding above the delta plain. Some drillers have reported the occurrence of limestone in several bores in the Iona area.
>
> The Burdekin River draining an area of slightly over 50 000 square miles is one of the major river systems of Queensland. Its delta bounded by residual mountain ridges to the south and west consists of a broad alluvial plain generally less than 50 feet above sea-level.
>
> In dry periods the river is reduced to a braided pattern of narrow streams. With flooding of the river in the wet season a large portion of the delta is inundated. Former distribution channels trap much of the floodwater which overtops the levees . . . Sheep Station, Kalamia and Plantation Creeks and the Anabranch on the northern part of the delta represent progressive stages in the migration of an ancestral river . . . However, because of the permeability of the deltaic sediments it is frequently observed that flow reduces or disappears because of seepage before the sea is reached.

The deltaic sediments are considered to provide the principal storage; storage in the country rock and clay plain areas outside the delta is thought to be negligible. Recharge of any significance is provided from the following sources in order of their relative importance.

(1) Rainfall in the delta area
(2) Runoff from marginal drainage towards the delta
(3) Overtopping floods from the Burdekin River
(4) Outflow from the Burdekin River through its banks during periods of high flow.

In 1962 the Commission started to drill a large number of bores in a regular grid. Part of the information is contained in Plate 2, and where applicable has been used in this Report.

3. METHODS APPLIED

Gravity methods depend on density contrasts. They may be used as a reconnaissance tool, and it was expected that the gravity data would show a rough picture of the bedrock configuration. Further it was hoped that some information might be obtained about near-surface formations. Hence, gravity work was carried out during three months of 1962 and during six months of 1963. The results are discussed in Chapter 8.

Seismic refraction methods depend on sound-velocity contrasts between different geological formations. Seismic methods measure bedrock depth with an accuracy of 15 to 20 percent, and in many cases provide information about the nature of the rocks. Hence, seismic depth probes can, in many respects, replace drilling, and seismic depth probes may be used as controls for other methods such as resistivity.

Seismic refraction traversing was done for three months in 1962 at the following places:

(a) Across the river bed at 'The Rocks', between Kellys Mountain and Stokes Range, with the objective of determining the bedrock profile. From a profile, rough estimates can be made of the possible flow of water in the river and in the sands beneath.
(b) To the east of Kellys Mountain to check whether there is a northward flowing subsurface river branch.
(c) West of 'The Rocks', to check whether there is a northward-flowing subsurface river branch west of Kellys Mountain.

In 1963, ninety seismic depth probes were made in the Burdekin Delta, and twenty-two in the neighbouring Giru area. The information obtained made it possible to construct a bedrock contour plan.

With electrical methods the resistivities of subsurface layers are measured. Depth estimates are not certain; hence it is essential to combine electrical methods with seismic methods and borehole data, which provide depth control.

The resistivity of a rock depends on its porosity and also on the resistivity of the pore fluid, which is inversely proportional to salinity. Because the porosity of unconsolidated or semiconsolidated deposits varies only between narrow limits, the resistivity of unconsolidated deposits is a sensitive indicator of the salinity of the water that fills the pores. In 1962 about 60 electrical depth probes were made in the Burdekin Delta; in 1963 another 480 were made in the Delta and in the neighbouring Giru area. A further 35 depth probes were made during October 1964 in selected areas to investigate salt-water encroachment.

Gamma-ray logs were taken in cased boreholes, and records were made of variations in natural radiation. In sediments, varying levels of gamma radiation may be correlated with clay and sand.

During the investigation a Proline auger drill, with auger diameter about 3½ inches and mounted on a Chamberlain tractor, was used to drill shallow shot-holes for the seismic refraction work. The same drill was used to bore holes 60-70 feet deep to investigate the near-surface layers and the water.

4. GRAVITY METHOD

GENERAL

The gravity observations were made with a Worden gravity meter, Serial No. 61. Its calibration factor (0.09047 mGal per scale division) was measured on the Melbourne Calibration Range in May 1963 and checked against the interval between Townsville Pendulum Station and the Ayr base station (20.33 mGal) in July and December 1963. Ayr base station was in the centre of the bandstand in the Ayr War Memorial Gardens. The positions of gravity stations were determined by reference to the one inch to one mile map produced by the Irrigation and Water Supply Commission.

Three hundred and fifteen gravity stations were observed during the 1962 gravity survey and 1394 during the 1963 survey. The average density of gravity stations was six per square mile. The gravity traverses were arranged so that they formed a closed network. Closing errors in the loops of the network were computed and distributed; the largest closing error was 0.13 mGal.

ELEVATION

The elevations of 718 stations were measured by spirit levelling (see Plate 11). The elevations of the other 991 stations were measured by use of an elevation meter Model 204 made by the Western Geophysical Company. This instrument, an electromechanical device mounted on a vehicle, measures elevations by integrating the product of vehicle inclination and distance travelled. One hundred and twelve benchmarks were used as fixed points. This gave a check on the accuracy of the instrument; the greatest error found was 3.2 feet over a distance of two miles, and the root mean square error was 1.5 feet over an average distance of about 2.4 miles.

ELEVATION AND LATITUDE CORRECTIONS

The observed gravity values were reduced to sea level. The combined elevation correction factor is a combination of the free-air correction factor and the Bouguer correction factor. The latter is directly proportional to the density of near-surface rocks. To find this density Nettleton's 'density profile' method was used (Nettleton, 1940, p. 48). The density obtained was 1.9 g/cm^3; the corresponding elevation correction factor is 0.0698 mGal/ft. Latitude corrections were made for the differences from the latitude of Ayr base station (latitude: 19°34'40"), based on the International gravity formula.

BOUGUER ANOMALIES

The accuracy of the Bouguer anomaly values is affected by random errors and systematic errors. Random errors and their estimated magnitudes are:

Random error in observed gravity	±0.05 mGal
Error in elevation (±2 ft)	±0.14
Error in latitude (±0.1 miles)	±0.09

The root mean square of these random errors is ±0.17 mGal. A systematic error is involved in the density value adopted for elevation corrections. Calculation shows that an error of 0.2 g/cm^3 in the adopted density value would result in an error of 0.00255 mGal/ft in the elevation correction factor. This corresponds to an error of 0.24 mGal over the 93-foot range of elevations in the survey area.

REGIONAL AND RESIDUAL GRAVITY MAPS

The regional gravity values were computed by averaging Bouguer anomalies of eight points on a circle of radius 1.6 miles. The average values were computed for intersection points of a one mile square grid. A regional gravity map was constructed by contouring these regional values. Residual gravity values were derived by subtracting the regional gravity value from the Bouguer anomaly value at each gravity station; the results are shown as residual gravity contours in Plate 4. By removing the regional gravity anomalies, the gravity effects of near-surface geological features are shown more clearly.

5. SEISMIC METHOD

Equipment and Procedures

Three different sets of seismic equipment were used. The set used in 1962 was a TIC Model 621 24-channel reflection/refraction seismograph used in conjunction with two 12-channel Seismod variable-area display units and a 48-channel camera. Those used in 1963 were a Midwestern 12-channel seismograph and an SIE 24-channel seismograph with Seismod. The geophones were TIC 20-Hz geophones spaced 100 feet or 50 feet apart in 1962 and 50 feet apart in 1963.

Geophones are laid out in a straight line on the ground. Shots are fired at both ends of the line, and photographic record is made of the arrival of the vibrations of the shot at each geophone. Where a Seismod is used, the vibrations are displayed on the record in two different ways (see Fig. 2) : as an oscillating line, and as an expansion or contraction of a signal of normally constant width.

The line traces are used to pick the first arrival of energy at each geophone as shown in Figure 2. Corrections are applied to correct for the depth of burial of the shot, and the delay in the firing of the detonator after the shot break is recorded. The timing lines are at 10-millisecond intervals, with a heavier line every 50 milliseconds. The figures given on the record represent the time to the first break on the trace, which in this case is an upward movement.

The arrival times are plotted on a time-distance curve (Fig. 3), and the velocities are calculated from the gradient of the lines produced by joining the points together. To determine a velocity, at least three points are required, although an approximate figure may be obtained from two points. It is possible, however, to detect velocities from the Seismod traces on the lower part of the record, by looking for alignments in events arriving after the first breaks. In Figure 2 a velocity of 6400 ft/s is shown on the Seismod traces, and this has been inserted on the time-distance curve in Figure 3.

Calculations

The depth at each end of the spread may be obtained from the intercept times of the different velocities at the origin, which is taken at the shot-point. In Figure 3, the intercept times at the shot-point 11 +25 feet, for the shot whose record is in Figure 2, are given below with the velocities.

Intercept time (milliseconds)	Velocity (ft/s)
21	1000
52	2000
69	(6400) 6800
	(17500) 17000

The velocity of 6400 ft/s, shown in brackets, may be considered as being due to the same material as the velocity of 7500 ft/s recorded in the reverse direction. The variation of velocity is due to one shot being fired up the dip of the layer, and the other down the dip. The same reasoning applied to the velocity of 17 500 ft/s, which is associated with a velocity of 16 500 ft/s in the reverse direction. The true velocities of these layers are 6800 and 17 000 ft/s.

Using a procedure described by Dobrin (1962) it is possible to calculate the thickness of each layer. The results for Figures 2 and 3 are given below:

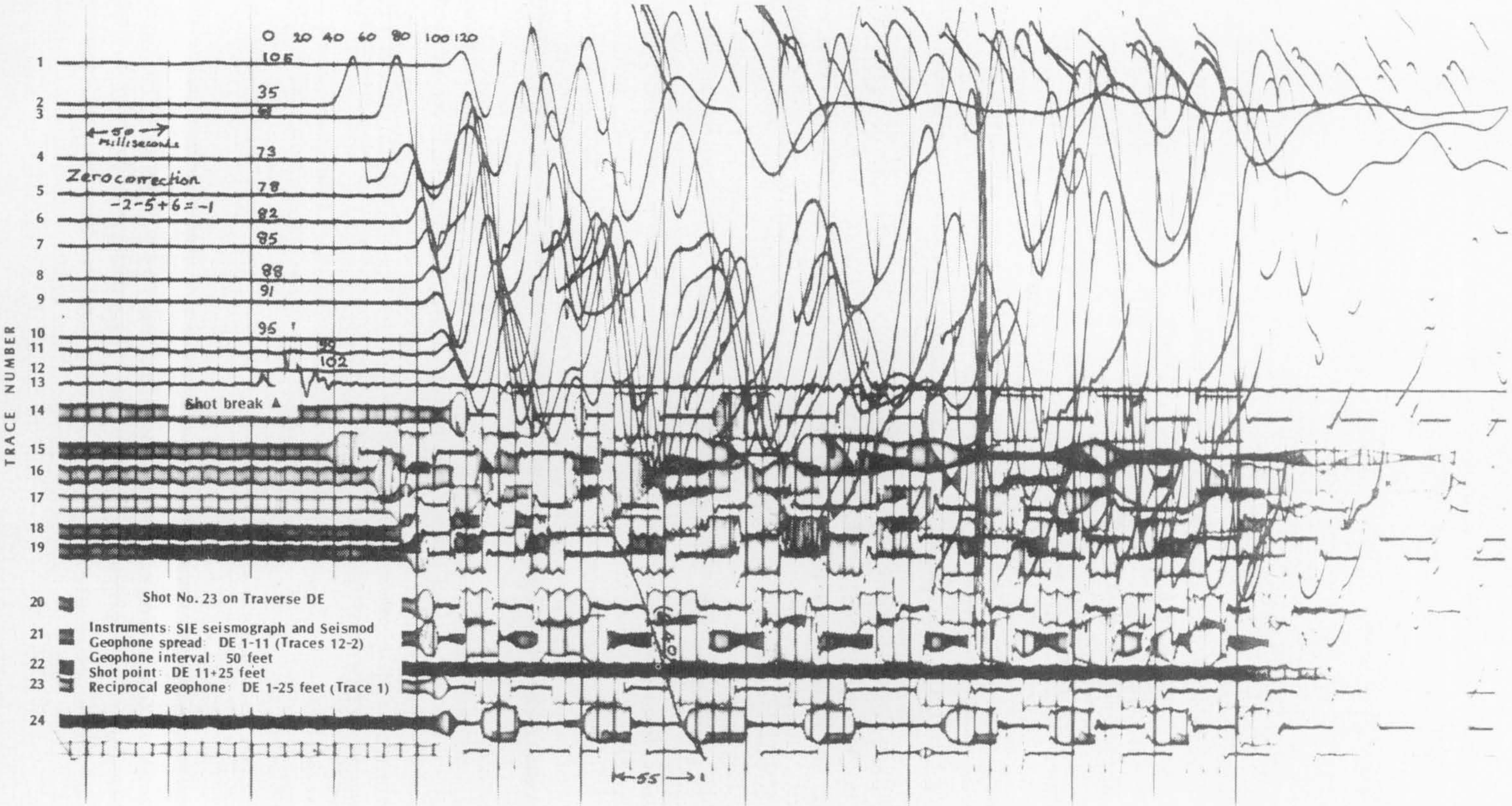


Fig. 2. Typical seismic refraction record

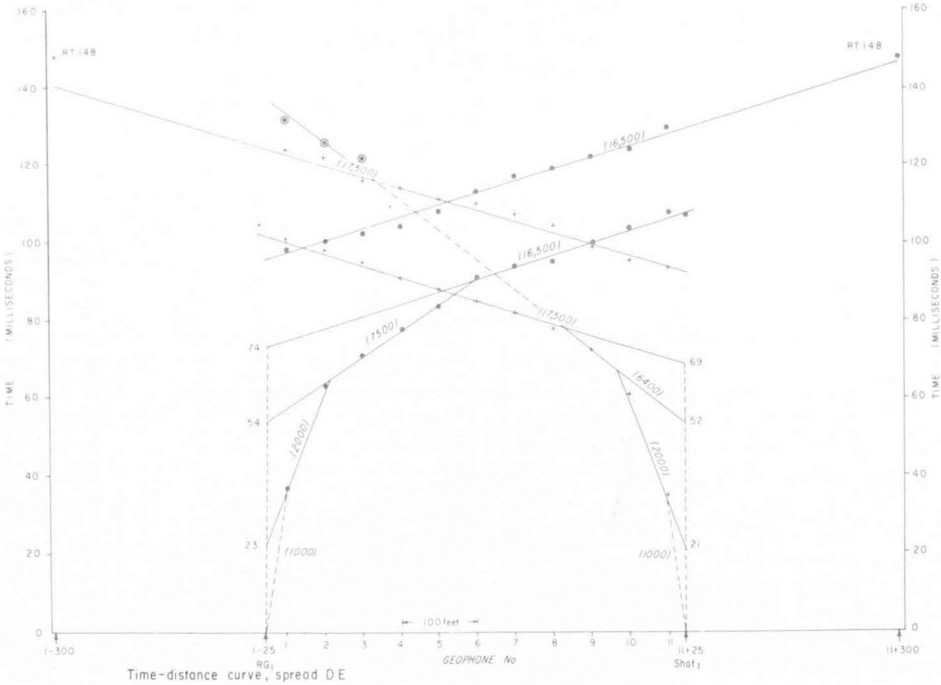


Fig. 3. Time-distance curve

Velocity (ft/s)	Thickness (ft)	Depth to bottom of layer
1000	11	11
2000	32	43
6800	57	100
17000		

The depth to the 17 000 ft/s layer is 100 ft, and the time taken for energy to travel to this layer and back to the surface is 69 milliseconds; hence the average velocity is 2900 ft/s from the surface to the 17 000 ft/s layer. Because of the large velocity contrast (2900 and 17 000 ft/s) the ray path through the 2900 ft/s overburden is assumed to be vertical.

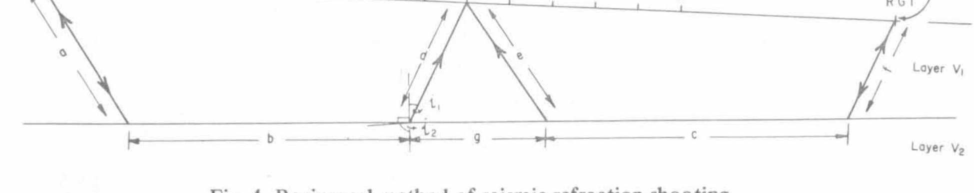


Fig. 4. Reciprocal method of seismic refraction shooting

Figure 4 shows a diagrammatic representation of seismic wave paths, from shots fired from S1 and S2. When shot S1 is fired, a reciprocal geophone, RG1, is placed on S2; and when S2 is fired, a reciprocal geophone, RG2, is placed on S1. The points marked as R.T. in Figure 3 are the reciprocal geophone times on spread DE.

The path followed by energy from S1 to geophone 6 is:

$$a + b + d \qquad (1)$$

and to RG1 is:

$$a + b + g + c + f \qquad (2)$$

The path followed by energy from S2 to geophone 6 is:

$$f + c + e \tag{3}$$

and to RG2 is:

$$a + b + g + c + f \tag{2}$$

If (1) and (3) are added and (2) is subtracted from the sum we have:

$$d + e - g \tag{4}$$

In a two-layer configuration (i.e. velocity *V1* in the upper layer and *V2* in the lower layer) the wave from S1, for example, is refracted along the interface, the critical angle of refraction (i_2) being 90°. From Snell's law, and taking the case where *V2* is much greater than *V1*,

$$\text{then } dl \longrightarrow 0$$
$$d, e \longrightarrow \text{thickness of } V1$$
$$g \longrightarrow 0$$

From (4) the thickness of *V1* becomes in this case $= (d + e)/2$.

The average velocity *Va* to the lowest refractor is given by:

$$Va = V2\,V1/(V2^2 - V1^2)^{1/2}$$

and again, assuming *V2* is much greater than *V1* as above,

$$Va \longrightarrow V1$$

Therefore the depth is approximately given by $V1(d + e)/2$.

In the time-distance curve illustrated in Figure 3, the reciprocal time is 148 msec. At geophone 10, the time taken from 1-300 ft is 124 msec, and from 11+300 ft is 95 msec; hence the time taken to travel to and from the refractor at geophone 10 is 124 + 95 - 148 = 71 msec. The time to travel down to the refractor is 35½ msec. The average velocity determined at geophone 11 is 2900 ft/s, so the depth at geophone 10 is 2.9 x 35.5 ft = 103 ft.

By interpolating between the average velocities at both ends of the spread it is possible to compute the depth at each geophone.

Accuracy

The measurement of times on the record depends on the sharpness of the first breaks and the accuracy of the zero correction; an accuracy of 1 to 2 msec should be possible.

The determination of velocities from the time-distance curve depends on the number of geophones that detect a layer of any velocity. The highest-velocity refractor can generally be determined to ±5%, but intermediate velocities may be subject to an error of ±20% where they are recorded on only two geophones. Where it is possible to determine the velocities from later events shown on the Seismod the error should be reduced to ±10%. Thin layers may not be detected, particularly where the velocity of an intermediate layer is lower than that of the overlying layer (called 'velocity reversal').

Therefore a thin layer of weathered bedrock on top of the fresh bedrock may not be detected as a first arrival in this area. In the continuous traverses shot in 1962 with 100-ft geophone spacing, a velocity of about 10 000 ft/s was frequently detected on the Seismod. The inclusion of this layer causes an increase in depth of about 15%. This layer was generally not observed in 1963, since much of the seismic work was in areas where the lower-velocity layers were thicker and would tend to mask the presence of a 10 000-ft/s layer on the seismic records; thus this layer may have been present in some cases, but not observed. The errors are summarized in Table 1. The total possible error will lie between the limits +16% and -22% assuming an equal probability of the Seismod showing or not showing a given velocity.

TABLE 1: ERRORS

Source of error	Amount of error
Reading times off record	±5%
High velocity measurement	±5%
Intermediate velocity measurement without Seismod	±20%
Intermediate velocity measurement with Seismod	±10%
Weathered layer missed out	-15%

INTERPRETATION OF SEISMIC VELOCITIES

The measured seismic velocities may be interpreted in geological terms as shown in Table 2. The velocities of unconsolidated material beneath the water-table and the velocities of bed-rock material are shown in Plate 5. Contour maps of the surface of consolidated material are shown in Plates 11 and 12.

TABLE 2: INTERPRETATION OF SEISMIC VELOCITIES

Velocity range, ft/s	Material
1000- 2000	Sand, clay, sandy clay and soil above the water-table.
2000- 5700 (*)	Sand, clay, sandy clay and gravel, below the water-table.
5700- 6700 (**)	Semiconsolidated sediments, or very weathered bedrock.
6700- 8500 (**)	Consolidated sediments or weathered bedrock.
8500-14 000	Slightly weathered bedrock or limestone.
14 000-20 000	Fresh bedrock.

Notes to Table 2

(*) Previous surveys (Wiebenga & Mann, 1962; Wiebenga, Polak & Andrew, 1963) have shown that in the range 2000 to 5700 ft/s the velocity is related to clay content, the higher velocities being associated with low clay content and the lower velocities with high clay content. Good aquifers have tended to show velocities in the range 4500 to 5700 ft/s.

(**) Although seismic velocities may not specifically indicate good aquifers, these formations could still yield appreciable amounts of water.

6. RESISTIVITY METHOD

Several different resistivity meters were used during the survey; they were:

A.C. Geophysical Megger, 0-30 ohm, frequency 8-10 Hz.
A.C. Megger Earth Tester, 0-3000 ohm, frequency 50 Hz.
A.C. Tellohm Meter, 0-10 000 ohm, frequency 110 Hz.
A.C. YEW Earth Resistance Tester, 0-300 ohm, frequency 95 Hz.
D.C. BMR Type A Resistivity Meter, 0-100 000 ohm.
D.C. BMR Type RM.1 Resistivity Meter, 0-10 000 ohm.

The Megger Earth Tester, Tellohm meter, and YEW meter were used mainly for traversing. The other meters were used for depth probes.

Although the A.C. meters have less interference from contacts between the electrodes and the ground, and also from telluric currents, they have other disadvantages. The extent to which good readings can be obtained from any meter depends on the amount of current that is put into the ground, as the size of the measured potential determines the accuracy of the observed resistance. At large spacing a large current is required to produce measurable results. Of the A.C. meters only the Geophysical Megger generates sufficient current for use with spacings up to 3000 feet between current electrodes; the other A.C. meters are accurate only out to a spacing of about 300 feet between current electrodes, in the Burdekin area.

Two resistivity methods were used: resistivity traversing and resistivity depth probing. Resistivity traversing determines horizontal variations of electrical resistivity, while depth probes determine vertical variations.

RESISTIVITY TRAVERSING

An array of four electrodes with constant spacing of 50 ft between them was moved over the ground, and readings were taken at intervals of 50 or 100 feet. The variations of reading observed are due mainly to variations in resistivity in the top

30 feet of the ground beneath the traverse. The line of electrodes may be either along the line of the traverse, or at right angles to it, depending on the nature of the boundary that it is hoped to identify from the traversing.

The traversing in the Burdekin survey was done to delineate salt water fronts at shallow depths; the results are described in Chapters 12 and 13.

RESISTIVITY DEPTH PROBING

The resistivity depth probes were made using three different electrode configurations: the Wenner configuration, the Lee configuration, and the Schlumberger configuration. They are shown diagrammatically in Figure 5.

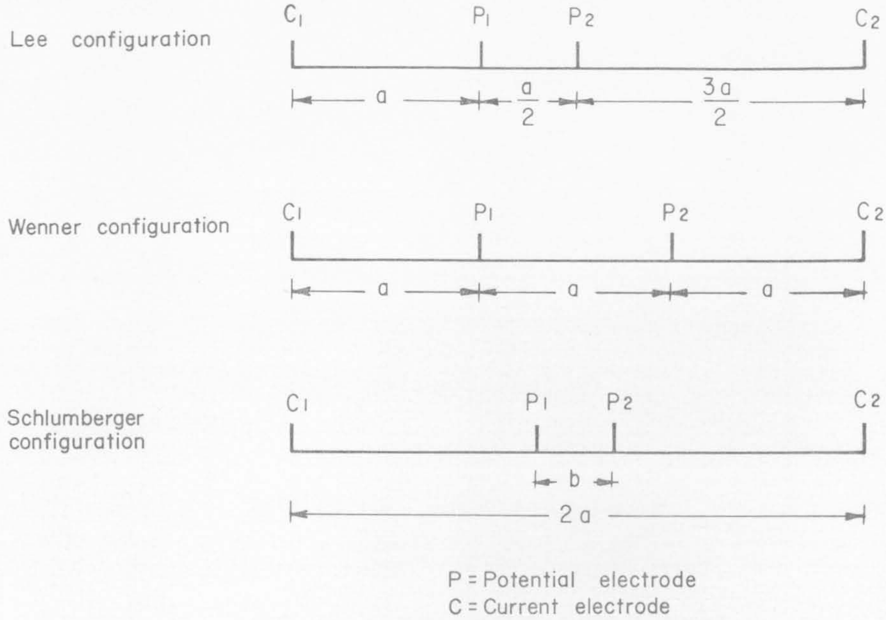


Fig. 5. Electrode configurations

In the Wenner configuration the four electrodes are always equally spaced in a straight line. A reading is taken, then the electrodes are all moved out to wider spacing, then another reading is taken, etc. The Lee configuration differs from this in that one of the inner electrodes is replaced by a central electrode, which remains fixed for all readings. In the Schlumberger configuration the two inner electrodes are at first kept close together while a series of readings is taken at progressively increasing separation of the outer electrodes. This continues until the potential reading becomes small; the outer electrodes then remain fixed while a repeat reading is made with the inner electrodes more widely separated. Once again the inner electrodes remain fixed while the outer ones are separated until the process has to be repeated. The separation between inner electrodes is generally between one-fifth and one-tenth of the total length of spread.

DIFFERENCE BETWEEN ELECTRODE CONFIGURATIONS

The difference between the Lee and Wenner methods is simple: the difference of potential between potential electrodes in the Lee configuration is exactly half the difference in potential between potential electrodes in the Wenner configuration, as the separation in the Lee configuration is a symmetrical half of the separation in the Wenner configuration. By doubling the reading obtained with the Lee configuration, the results can be treated in the same way as those of the Wenner configuration.

The difference between the Wenner and Schlumberger methods is described by Andrew & Wiebenga (1965). There it is shown that for all practical purposes the shape of the master curves used in the interpretation of field curves is the same, with a shift of origin owing to the fact that the electrode spacing variable *a* is half the length of the spread in the Schlumberger case, and one-third in the Wenner case.

In this survey the same interpretational techniques were applied to all types of curve.

INTERPRETATION OF RESISTIVITY RESULTS

Figures 6 and 7 show a selection of depth probe curves obtained in the Burdekin Delta.To obtain the curves for interpretation the readings are converted to apparent resistivity values by means of a factor that depends on the electrode spacing; the log of the apparent resistivity is then plotted against the log of the spacing. It can be seen from the figures that there are a number of different kinds of curve, each representing a different set of subsurface layers.

As the interpretation of resistivity curves involves the interpretation of a potential field, it is not possible to obtain a unique solution from resistivity depth probes alone. There are an infinite number of possible distributions of resistivity with depth that can give rise to the same depth probe curve. In this survey, however, seismic or drilling results usually provide some depth control that make it possible to interpret the resistivity results with greater reliability.

Two methods of interpretation were used on the results of this survey.

(1) *Repeated use of two-layer Master Curves (after Roman) for multi-layer problems.* This technique, probably first devised by J. Zuschlag of ABEM, is based on a set of two-layer curves that have been prepared from equations for potential (see e.g. Parasnis, 1962, p.72). A set of two-layer 'type curves' is shown in Figure 8. Using these curves it is possible to obtain a solution for a simple case where two horizontal layers of different resistivity are present. Where more than two layers are present, the first two layers can be represented by a single layer.

Considering only thick layers (meaning thick on log scale), two main groups of problems exist: (a) where a low-resistivity layer lies between two layers of relatively high resistivity; and (b) where a high-resistivity layer lies between two layers of relatively low resistivity.

The problem of a low-resistivity layer between two layers of higher resistivity is solved by using Hummel's principle (Hummel, 1932), in which the two upper layers of thickness h_1 and h_2, with resistivities ρ_1 and ρ_2, are replaced by one layer of thickness $(h_1 + h_2)$ with resistivity ρ_a according to the 'parallel resistance' relation (Fig. 9):

$$(h_1 + h_2)/\ \rho_a = h_1/\ \rho_1 + h_2/\ \rho_2 \qquad (1)$$

Figure 10 is a presentation of equation (1) on the log scale, giving log $[(h_1 + h_2)/h_1]$ versus log $[\ \rho_a/\ \rho_1]$ for different values of K where

$$K = (\ \rho_2 - \ \rho_1)/(\ \rho_2 + \ \rho_1)$$

These curves are known as 'help curves'.

For a low-resistivity layer between two high-resistivity layers $\rho_2 < \rho_1$, K is negative, and the left part of Figure 10 is used. Equation (1) remains equally true if $h_2/\ \rho_2$ is replaced by n h_2/n ρ_2; i.e. the layer with resistivity ρ_2 and thickness h_2 may be replaced by a thicker layer of higher resistivity. A particular field curve can result from an infinite number of resistive layer configurations; therefore to obtain an accurate interpretation further control is necessary.

The problem of a high-resistivity layer between two lower-resistivity layers is solved by using Maillet's principle, in which two upper layers of thickness h_1 and h_2, resistivities ρ_1 and ρ_2, are replaced by one layer of thickness $(h_1 + h_2)$, resistivity ρ_a, according to the 'series resistance' relation:

$$(h_1 + h_2)\ \rho_a = h_1\ \rho_1 + h_2\ \rho_2 \qquad (2)$$

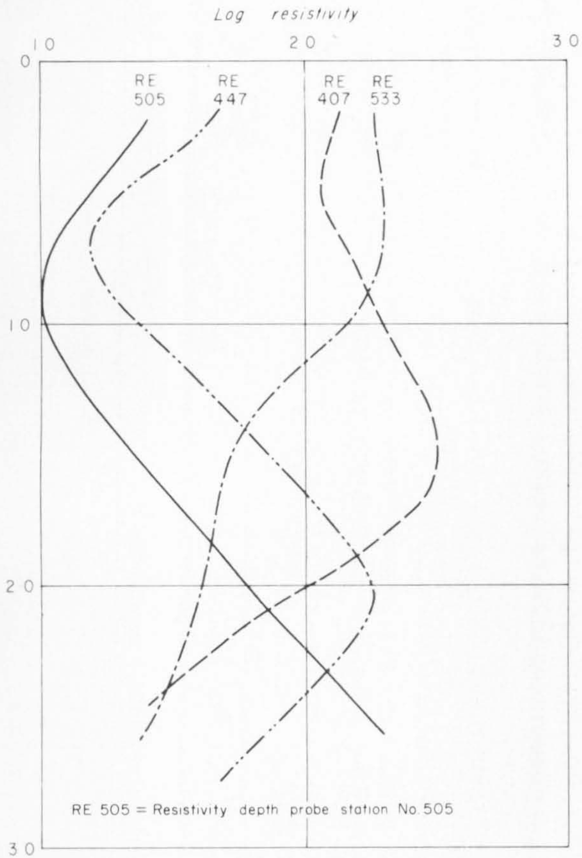


Fig. 6. Typical Schlumberger resistivity depth probe curves

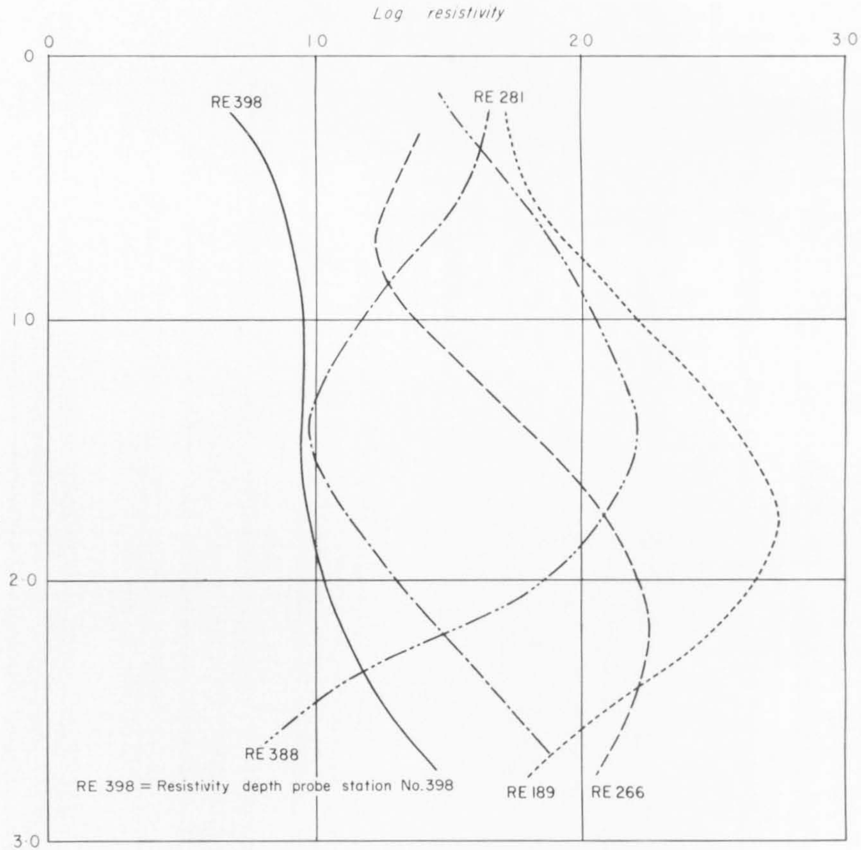


Fig. 7. Typical Wenner resistivity depth probe curves

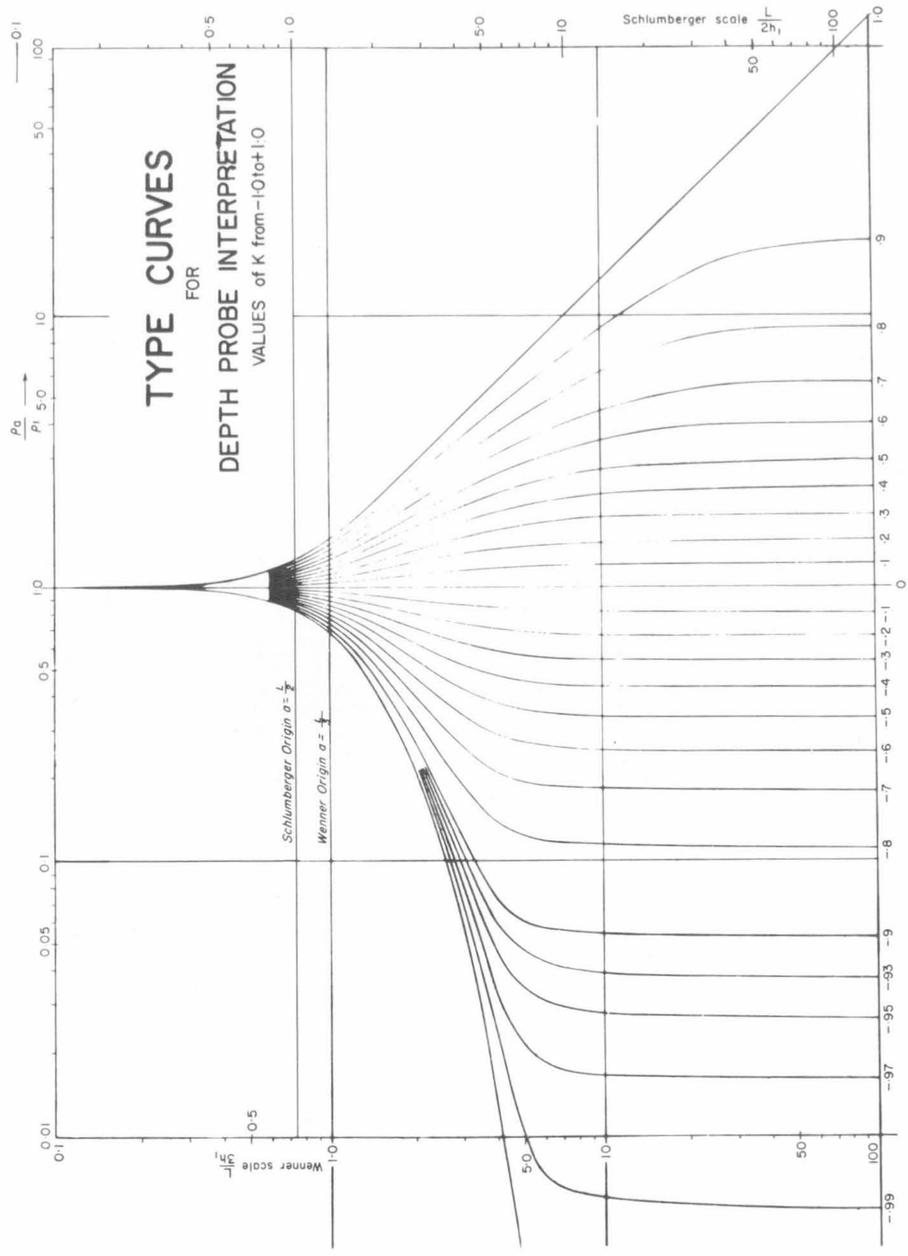


Fig. 8. Two-layer Type Curves for resistivity depth probe interpretation

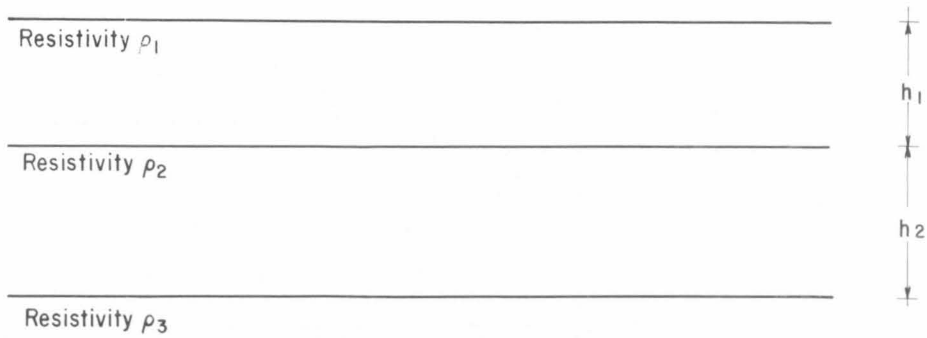


Fig. 9. Illustrating Hummel's principle

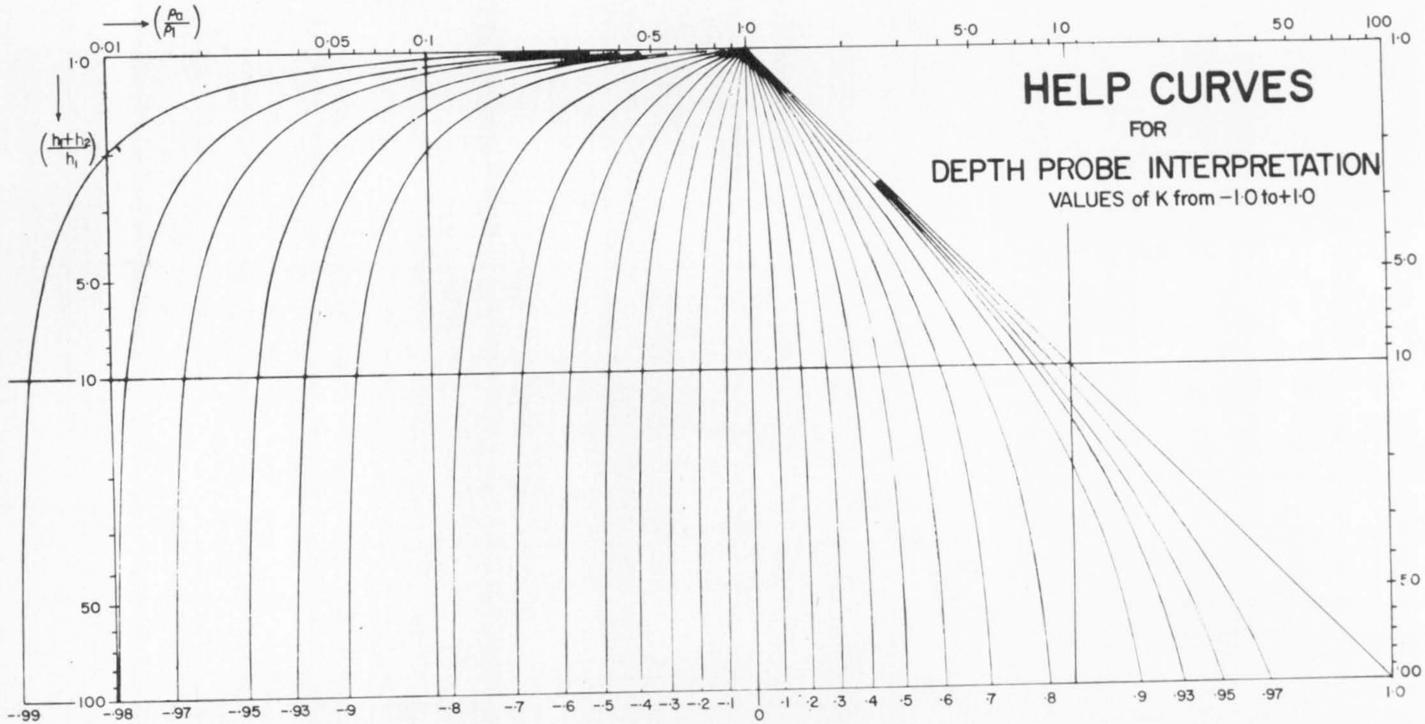


Fig. 10. Help Curves for interpreting resistivity depth probe curves

The left side of Figure 10 is turned symmetrically about the vertical axis so that -log ρ_a/ρ_1 becomes +log ρ_a/ρ_1 for positive values of $K = (\rho_2 - \rho_1)/(\rho_2 + \rho_1)$, giving a plot of log [$\rho_a/\rho_1$] versus log [$(h_1 + h_2)/h_1$].

The same basic ambiguity, i.e. that found in the use of Hummel's principle, obviously applies also and confirms what was stated above: resistivity measurements cannot give accurate depths without additional controls.

The way in which the Type Curves and Help Curves are used in the interpretation is shown in Figure 11. Here the first part of the resistivity curve can be fitted to the Type Curve $K = +0.5$, with the Wenner origin of the Type Curve at the point A. This gives a depth of 4.7 ft, and a resistivity for the first layer of 93

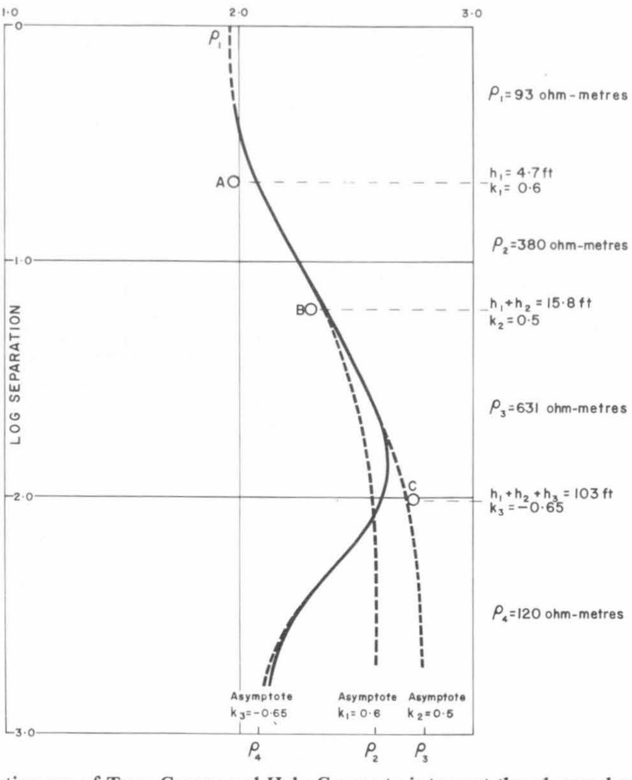


Fig. 11. Illustrating use of Type Curves and Help Curves to interpret the observed resistivity curve at RE 235

ohm-metres from the origin of the curves, and for the second layer of 380 ohm-metres from the asymptote of the line $K = +0.5$, until another Type Curve fits a lower part of the observed curve; this happens at point B where Type Curve $K = +0.5$ fits the observed curve. This gives a depth to the bottom layer of the second layer of 15.8 ft and a resistivity for the third layer of 631 ohm-metres from the asymptote of the curve for $K = +0.5$. The origin of the Help Curves is then placed at point B, and the origin of the Type Curves is moved down the Help Curve for $K = +0.5$ until a fit is again obtained at point C for Type Curve $K = -0.65$, giving a depth of 103 ft for the bottom of the third layer and a resistivity of 120 ohm-metres for the fourth layer from the asymptote of Type Curve $K = -0.65$. The result of the interpretation is expressed as a solid line in Figure 12.

(2) *Three-layer Master Curves.* The other interpretation technique used is based on a method described by Wetzel & McMurry (1936). This method involves a series of three-layer curves calculated from assumed resistivities in thin layers of material. Figure 13 shows some of the curves based on their calculations. A transparent print of the curves is superimposed on the observed curve, and the curve that fits best is selected. For the observed curve in Figure 11, the curve

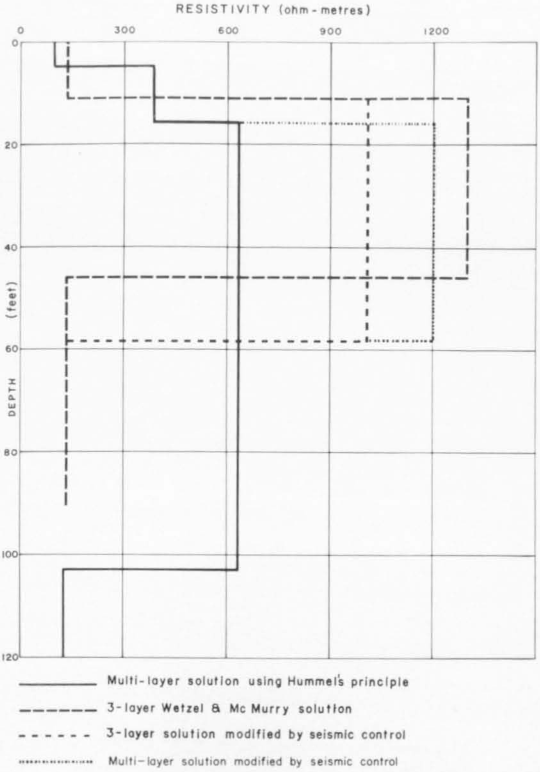


Fig. 12. Interpretations of the resistivity curve at RE 235

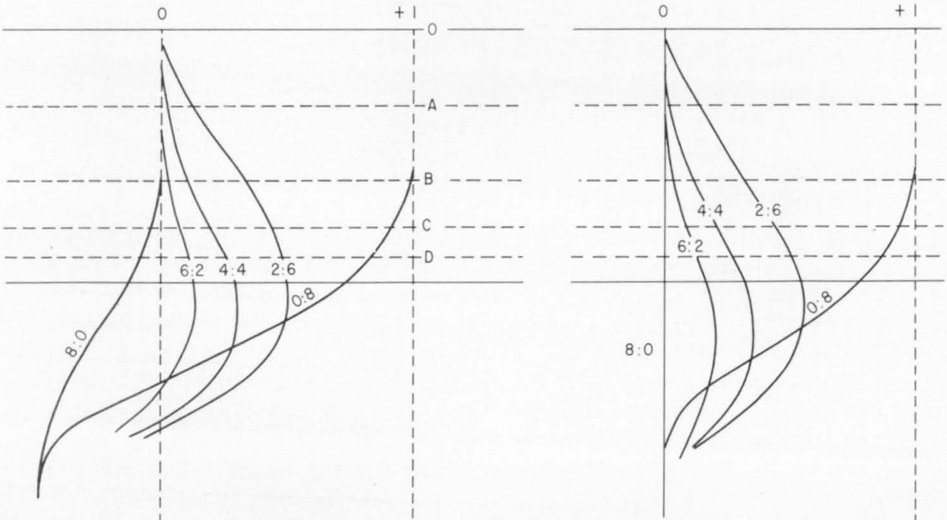


Fig. 13. Three-layer resistivity curves after Wetzel & McMurry (1936)

marked 2:6 in set E4 (Fig. 13) is the best fit, and depths of 11 ft and 46 ft are obtained for the boundaries. The resistivity of the first layer is obtained from the zero line in the curve, which in this case gives a value of 130 ohm-metres. The resistivity of the other two layers can be determined from the ratios given with the curves, in the case of E4 the ratio ρ_1: ρ_2: ρ_3 is 1:10:1, so the resistivity of the second layer will be 1300 ohm-metres and that of the third layer 130 ohm-metres. The interpretation is shown as a dashed line in Figure 12.

The interpretations obtained by these methods usually provide a rough limit to the range of probable interpretations. The three-layer results will tend to give depths that are too small, and the Roman curves will tend to give depths that are too large. The use of some depth control should lead to more accurate results.

Application of Depth Control

The seismic results should give depths to an accuracy of about 20%, which is better than can be obtained from resistivity alone. At RE235 (Figs. 11 and 12) there is a seismic boundary at 57 ft between unconsolidated material and weathered bedrock. The water in the weathered bedrock is likely to be more saline than the water in the unconsolidated material, so this seismic boundary probably represents the lower boundary of the high-resistivity layer.

According to the multi-layer resistivity interpretation the base of the high-resistivity layer occurs at 103 ft; according to the three-layer interpretation, at 46 ft. Each of these interpretations can be modified to agree with the seismic measurements by use of the Maillet 'series resistance' relation (Equation 2 above) as follows.

In the multi-layer solution the single layer of resistivity 631 ohm-metres from 15.8 to 103 ft is replaced by a layer of resistivity ρ_a from 15.8 to 57 ft and a layer of resistivity 120 ohm-metres from 57 to 103 ft.

From Equation (2),

$$41.2\ \rho_a + 46 \times 120 = 87.2 \times 631$$

$$\text{i.e. } \rho_a = 1200 \text{ ohm-metres.}$$

In the three-layer solution the layer of resistivity 1300 ohm-metres from 11 to 46 ft, which overlies material of resistivity 130 ohm-metres, is replaced by a layer of resistivity ρ_a from 11 to 57 ft. From Equation (2),

$$46\ \rho_a = 35 \times 1300 + 11 \times 130$$

$$\text{i.e. } \rho_a = 1040 \text{ ohm-metres}$$

These two results agree reasonably well but the modified three-layer solution is preferred because it involves a smaller modification to the depth. All these interpretations are shown in Figure 12.

Meaning of Resistivity Values

In the case of sand and gravel, the resistivity of the solid material is extremely high and the resistivity of the material in situ depends almost entirely on the resistivity of pore fluid, the extent to which the pores are saturated, and the way in which the individual grains are in contact. Dry sand at resistivity depth probe RE 555 has a resistivity exceeding 20 000 ohm-metres, the highest measured in these tests; but fully saturated sands were found to have resistivities ranging from about 30 to 200 ohm-metres. Clays, on the other hand, commonly have a high water content, the water being held within the clay structure because of the very low permeability (hydraulic conductivity); i.e., the water is not free to move within the body of clay particles. Hence, salt generated by weathering of rock into clay minerals has little chance to be flushed out by fresh water. Neither are clay lenses or mixtures of sand and clay deposited in a saline marine environment likely to be flushed out by fresh water at any later stage in the geological history, because water flows around the zones of very low hydraulic conductivity. Therefore, formations of clay, even when mixed with fresh-water sand or within the moist, semi-dry zone, will generally show much lower resistivity than fresh water, e.g. 5 to 6 ohm-metres as against 40 to 50 ohm-metres.

The delta sediments range from pure sand through various mixtures of clay and sand to pure clay. Hence, the low resistivity measured in individual sediments may be due in part to saline water in either sand or clay. Resistivities in the range from say 200 to 20 000 ohm-metres would correlate with sand and gravel containing variable amounts of fresh water ranging from fully saturated through various degrees of dampness to dry sand.

In material such as sand and gravel, in which the resistivity of the solid material is very high, if the resistivity of the interstitial fluid is constant, the resistivity measured depends mainly on the porosity of the material, which may range from about 20 to 40 percent. Wiebenga (1955) determined an empirical relation:

$$\log(\rho_a/\rho_w) = -1.25 \log V$$

where ρ_a = resistivity of the matrix/water aggregate

ρ_w = resistivity of the water

V = porosity expressed as a fraction of one.

This relation is shown in Figure 14. The factor 1.25 is not strictly constant because it varies with clay content and porosity.

From the resistivity of water obtained by the above method for fully saturated material, the total dissolved salt content may be calculated from the relation:

$$\log S = 3.68 - 0.92 \log \rho_w$$ (Dyson & Wiebenga, 1957)

where S = salt content in parts per million.

The same relation is expressed graphically in Figure 15.

This is an empirical relation determined from water samples in the Alice Springs area, but Wiebenga (1955) has shown that the nature of the dissolved salt does not greatly affect the relation.

If no data other than resistivity measurements are available, the resistivity of water-saturated unconsolidated rock, if it has a low clay content, can be used to estimate the salinity of the groundwater. Table 3 compares the resistivity of the materials with the salinity of the pore solution.

TABLE 3: RESISTIVITY OF ROCK VERSUS SALINITY OF PORE SOLUTION, FOR ROCKS OF AVERAGE POROSITY

Resistivity of saturated rock ohm-metres	Total dissolved salts in pore solution, p.p.m.	Classification of water
Less than 6	more than 3000	salt
6 to 20	3000 to 1000	brackish
more than 20	less than 1000	fresh

However, clay or soft shale and salt-water sand or sandstone cover the same resistivity range and are not distinguishable in resistivity methods.

Although it was not possible in this area to measure resistivities of the various sediments on freshly exposed surfaces, some tests carried out on similar sediments adjacent to large open cuts at Yallourn, Victoria, in 1944 (R.F. Thyer, 1944 pers. comm.) are relevant. Overburden shovels were continually exposing fresh faces of the overburden which comprises sand, gravel, clay, and sandy clay containing various proportions of clay which contained a relatively high moisture content although they were above the water-table. The values of specific resistivities obtained in these tests are tabulated below, in ohm-metres:

Material	Number of tests	Range of values	Average	Notes
Clay	9	5.0-8.0	6.3	tests at bore sites suggest that clay may have a value as low as 2.5
Clayey sand	15	10.8-28	14.5	predominantly clay
Sandy clay	15	81.5-500	296	predominantly sand
Sand	4	862-3030	2200	freshly exposed and damp

The clays in the above tests were from an essentially freshwater environment. In the presence of salt or brackish water, clays tend to absorb salt and their resistivity is substantially lower.

In interpreting the results of the resistivity tests in the Burdekin River delta the following criteria have been used:

Resistivity range, ohm-m	
exceeding 200	sand with variable amounts of fresh water, the higher the resistivity the lower the percentage saturation
30-200	sand saturated with fresh water
18-40	freshwater sands with a variable clay content
9-20	sands and clays with brackish water
less than 5	sands and clays with salt water.

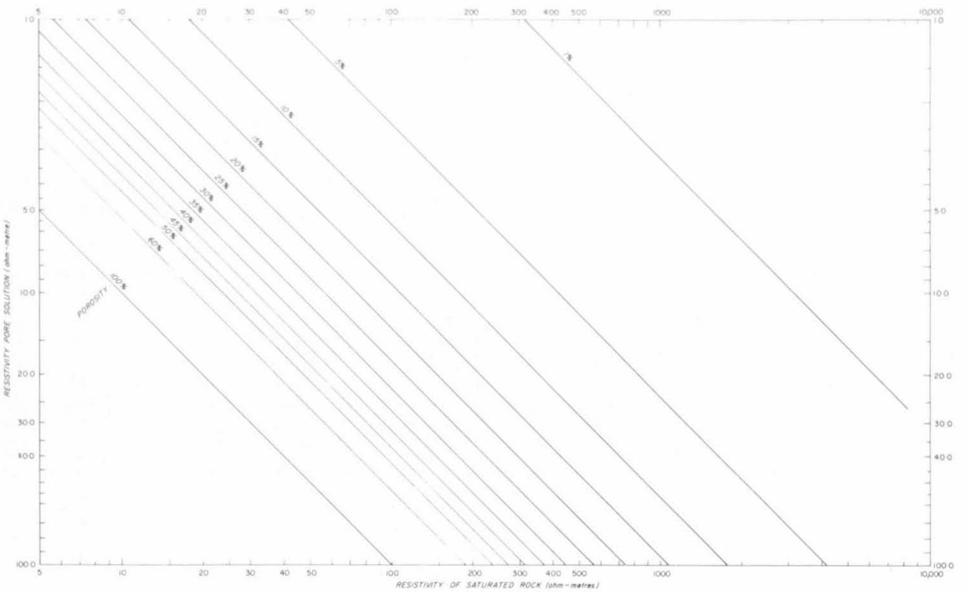


Fig. 14. Relation between porosity and resistivities of pore fluid and saturated rock

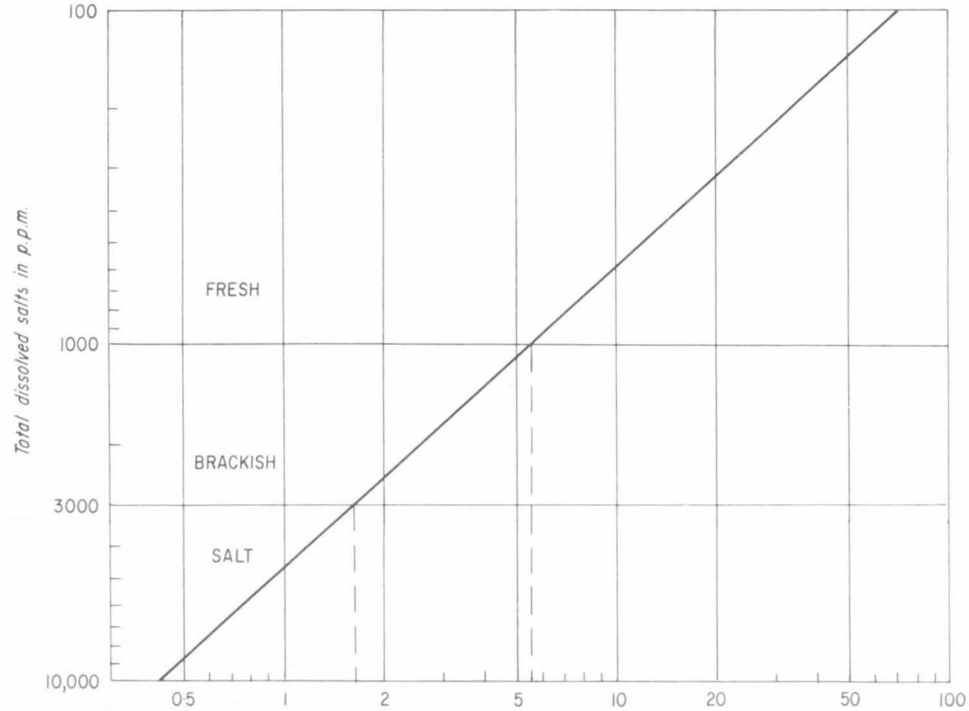


Fig. 15. Diagram for converting water resistivity to salinity

DIRECT MEASUREMENTS OF WATER RESISTIVITY

A number of resistivity measurements were made throughout the Burdekin delta by both BMR and IWSC on water samples collected at the surface and at various depths underground. These resistivity values may be expressed also in terms of salt dissolved per unit volume, i.e. grains per gallon (g.p.g.), or parts per million (p.p.m.)

BMR employed two methods in obtaining these measurements, the first of which is the same as that used by the Commission.

Method 1. Water samples were collected at the surface or from the surface of the underground water-table by lowering a suitably designed bailer into available boreholes. The resistance across the electrodes of a Wenner-type arrangement in a mud-cell was measured using a Megger Earth Tester. The resistivity (in ohm-metres) of the sample was then derived from the measured resistance by applying the calibration constant for the mud-cell.

Method 2. A small calibrated probe designed on the principle of the mud-cell was lowered into boreholes. Temperature was read simultaneously so that resistivity values could be corrected to a standard temperature 20°C. For this correction the following empirical equation was used:

$$\log \rho_{20} = \log \rho_t - 0.009\,(20\text{-}t)$$

This equation holds in the range 10°C to 40°C and is expressed graphically in Figure 16.

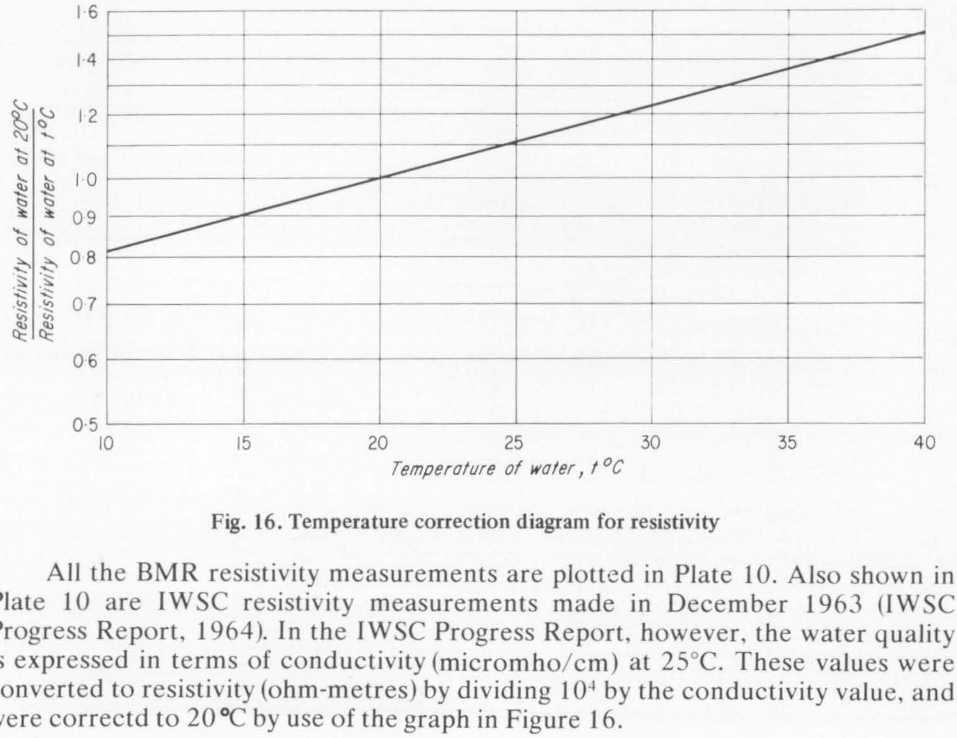


Fig. 16. Temperature correction diagram for resistivity

All the BMR resistivity measurements are plotted in Plate 10. Also shown in Plate 10 are IWSC resistivity measurements made in December 1963 (IWSC Progress Report, 1964). In the IWSC Progress Report, however, the water quality is expressed in terms of conductivity (micromho/cm) at 25°C. These values were converted to resistivity (ohm-metres) by dividing 10^4 by the conductivity value, and were correctd to 20°C by use of the graph in Figure 16.

7. GAMMA-RAY LOGGING

A 500-foot Widco gamma-ray probe was used in conjunction with an Esterline-Angus recorder. The probe consists of a scintillation crystal and a preamplifier. The amplified pulses pass up the cable that supports the probe, and at the surface they are counted and shown on a recorder. The results are presented as a graph of count rate against depth.

INTERPRETATION

A typical gamma-ray log is shown in Figure 17. Because of the presence of radioactive potassium in clay there is a greater amount of gamma radiation emitted from clay than from sand; thus high readings can be correlated with clay, and low readings with sand. In Figure 17 there is sand to 27ft, a thin layer of clay from 27 to 30ft, probably sandy clay from 30 to 44ft, clay from 44 to 54ft, sandy clay from 54 to 62ft, and then sand and gravel down to the bottom of the hole.

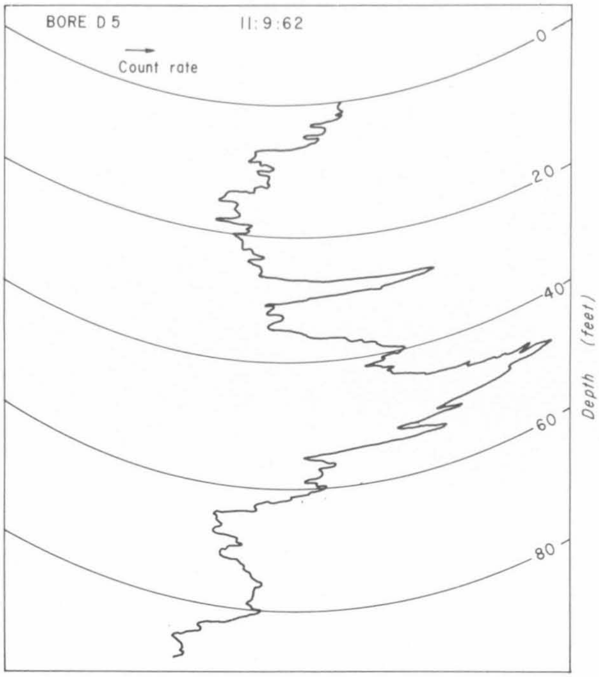


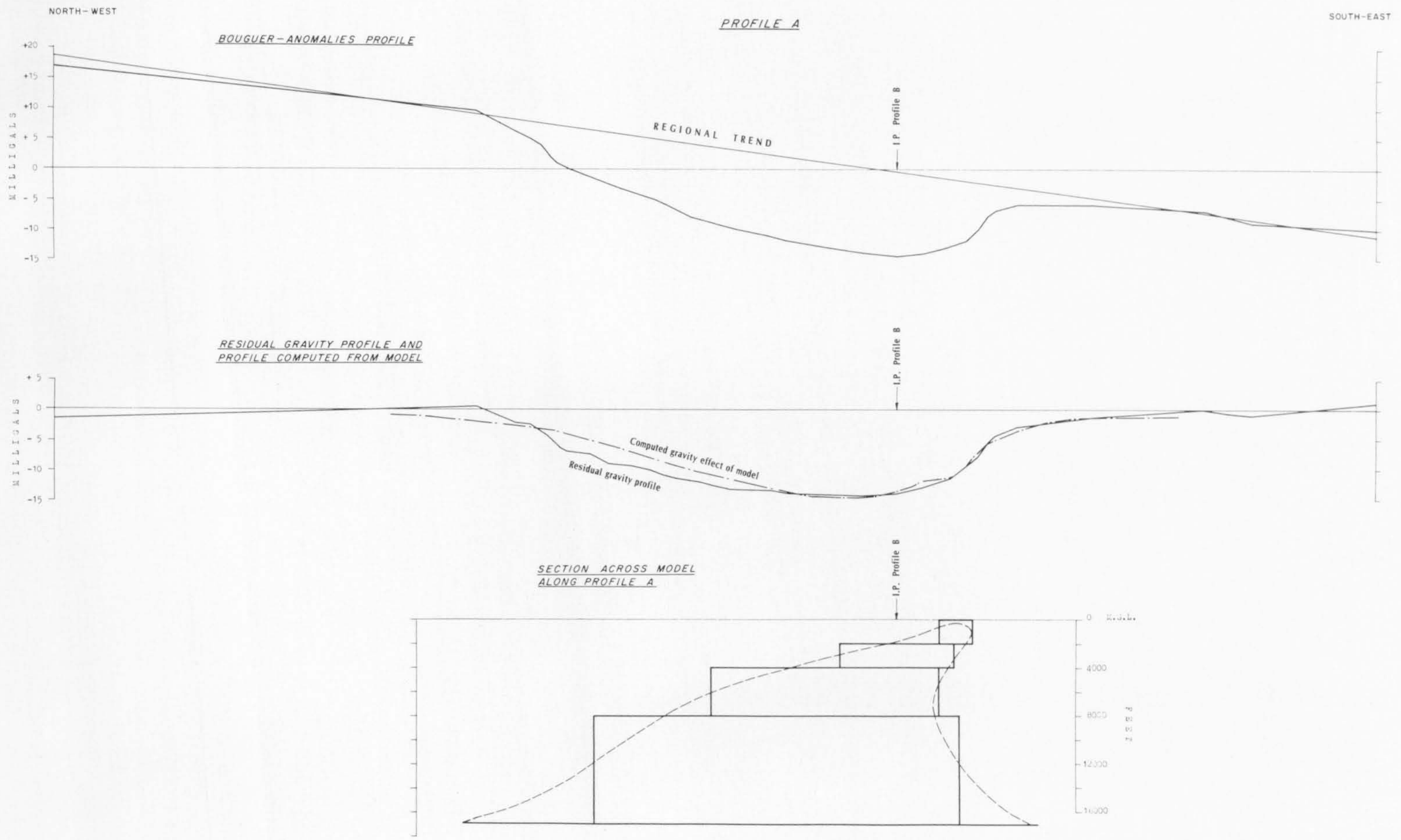
Fig. 17. Typical gamma-ray log

In investigations where a detailed knowledge of the lithology of delta sediments is required, the use of gamma-ray logging in boreholes is generally more reliable and cheaper than conventional sampling methods.

8. GRAVITY RESULTS

The Bouguer anomaly contour map (Plate 3) shows a regional trend consisting of a decrease in gravity values from west to east. The main disturbance of this regional trend is a roughly circular negative anomaly west of Home Hill. The anomaly is asymmetrical; the gradients are higher south and east of the centre than to the west.

Figure 18 shows an attempt to interpret the Home Hill anomaly. On NW-SE and NE-SW sections through the peak of the anomaly the Bouguer anomaly profile is drawn together with the regional anomaly computed by averaging Bouguer anomaly values. By subtracting the regional values from the Bouguer values a residual anomaly is obtained. A possible source of the residual anomaly is expressed as a set of horizontal disc-shaped bodies of density $0.2 g/cm^3$ greater than the surrounding rock. This method of interpreting anomalies has been described by Nettleton (1940); no unique solution is possible in gravity interpretation, but the model adopted probably gives some idea of the shape of the body - perhaps a low-density intrusion - that causes the anomaly.


NORTH-WEST
PROFILE A
SOUTH-EAST
BOUGUER-ANOMALIES PROFILE
MILLIGALS
+20
+15
+10
+ 5
0
- 5
-10
-15
REGIONAL TREND
I.P. Profile B
RESIDUAL GRAVITY PROFILE AND
PROFILE COMPUTED FROM MODEL
MILLIGALS
+ 5
0
- 5
-10
-15
Computed gravity effect of model
Residual gravity profile
I.P. Profile B
SECTION ACROSS MODEL
ALONG PROFILE A
I.P. Profile B
0 M.S.L.
4000
8000
12000
16000
FEET

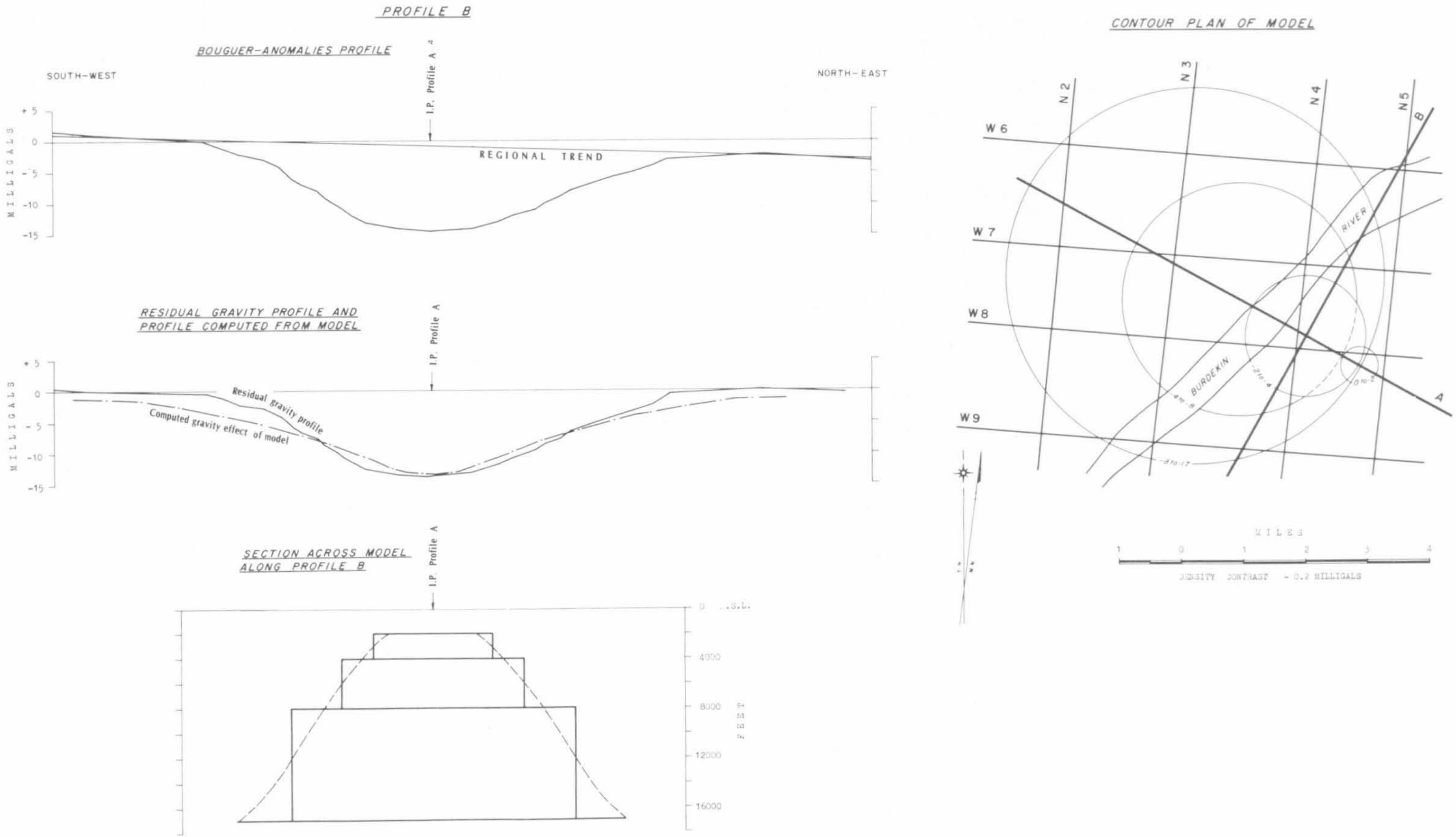


Fig. 18. Interpretation of Home Hill gravity anomaly

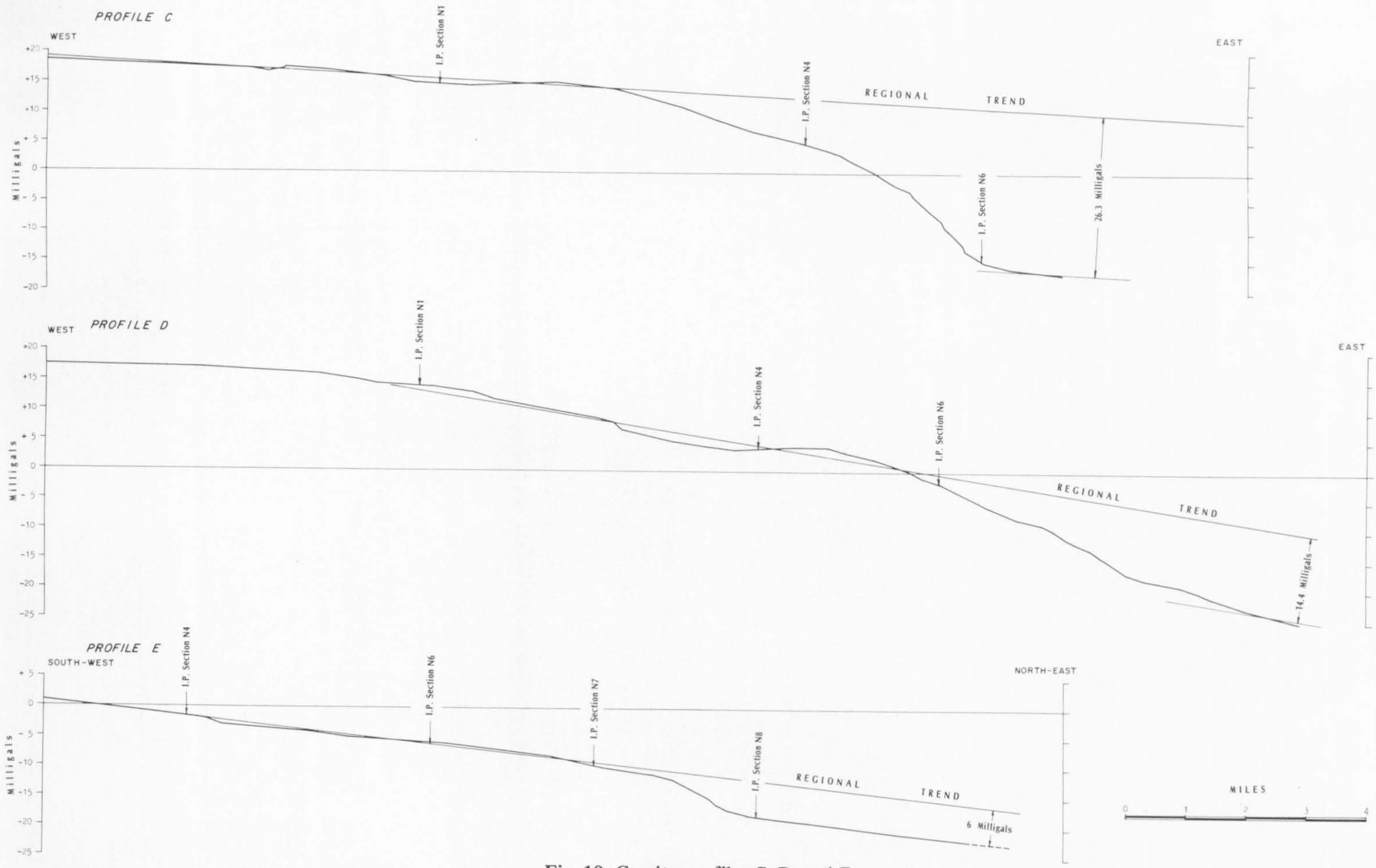


Fig. 19. Gravity profiles C, D, and E

The Bouguer anomaly contour map shows a zone of high gravity gradients on the eastern side of the area (Plate 3). This zone crosses the line W1 at about half a mile west of W1/N6 and can be followed in a south-southeast direction towards W6/N8.

One simple model which produced a similar gravity effect is a semi-infinite horizontal slab, the geological equivalent of which is a fault. For unit density contrast, one milligal of gravity effect corresponds to a vertical throw of approximately 78 ft (Nettleton, 1949, p. 115). For a density contrast of σ g/cm^3 and gravity effect Δg mGal, the throw of the fault (T) will be given by:

$$T \simeq 78 \ \Delta g/\sigma$$

Three profiles (Fig. 19) were drawn across the zone of high gravity gradients. After removing the regional trend, the gravity decrease on Profile C is 26.3 mGal, on Profile D is 14.4 mGal, and on Profile E is 6.0 mGal. The corresponding throws along the three profiles are shown below (downthrow to the east on each profile).

Density contrast. g/cm^3	Throw of fault (feet) On Profile C	On Profile D	On Profile E
0.2	10 300	5 600	2 300
0.3	6 800	3 700	1 600
0.4	5 100	2 800	1 200
0.5	4 100	2 200	940

The above results suggest that the fault is a hinge fault, the throw being greater in the north than in the south.

Nettleton (1940, p. 113) has shown that the maximum gravity gradient produced by a semi-infinite horizontal slab is given by $2G \ \sigma \ T/Z$ milligals per mile, where

G = gravitational constant
σ = density contrast, g/cm^3
T = thickness of slab (throw of fault), ft
Z = depth to centre plane of slab, ft

The formula can be used to compute Z, although Bancroft (1960) shows that it is strictly applicable only where T is small compared with Z. Measured maximum gradients and calculated values of Z for the three profiles are given below:

	Maximum gradient mGal/mile	Depth to centre of fault Z, ft
Profile C	8	5500
Profile D	4	6000
Profile E	4.5	2200

Summarizing: The gravity results show a regional gravity trend consisting of a decrease in gravity from west to east. The regional trend is disturbed principally by a roughly circular gravity low west of Home Hill; this low may be produced by a low-density intrusion. The zone of high gravity gradients in the eastern part of the area suggests a fault traversing the country in a north-northwest direction. This appears to be a hinge fault with greater throw in the north than in the south.

9. SEISMIC RESULTS

BASEMENT CONTOUR PLAN

Plate 7 shows the 'basement' contour plan constructed from seismic depth probes and seismic traverses. 'Basement' is effectively the base of the unconsolidated deltaic sediments, and is here defined as rock with longitudinal seismic velocity 6700 ft/s or greater. This includes consolidated sediments and weathered igneous rocks which are believed not to be sufficiently porous and permeable to act as good aquifers or to provide a path for subsurface drainage. Probably because of their higher clay content, weathered basement rocks are aquicludes which may contain appreciable amounts of salt, and which cannot easily be flushed out by fresh water. Hence the upper layers within the basement, but above the fresh basement rock, are indicated in many cases as low-resistivity layers in depth probing.

The basement contour plan shows topography with many subsurface drainage channels (indicated by arrows) and ridges. For instance, the Burdekin has cut a subsurface channel back to The Rocks (W9/N1) which may be observed by following the zero contour. Farther northeast, near W8/N3, the subsurface channel splits into two: one branch goes north and one goes northeast until it joins the channels coming from Charlies Hill. Between W5/N5 and W6/N6 the contour lines can be drawn in various ways; the plate gives one likely version suggesting a subsurface channel in a northeasterly direction and one towards the north.

West of The Rocks, along Traverse S (cross-section W10) the seismic work suggests the presence of a subsurface channel which may be up to 100 ft deep and possibly provides an alternative channel for subsurface drainage into the Delta. The basement configuration in this locality should be examined in more detail to determine whether underground water from north of The Rocks enters the Burdekin Delta.

If the interpretation shown in Plate 7 is approximately true, the basement bar across the Burdekin River at The Rocks may serve to divert much of the flood waters northward into the Barratta Creek system. An alternative possibility is that the bed of the river has cut back along its course, and captured much of the flow that originally went into the Barratta Creek system. The contours suggest the presence of a fairly deep subsurface channel between the Barratta Creek system and the Burdekin Delta close to W5/N1. Part of the Delta recharge may thus come through this channel.

It is believed that many of the drainage channels could have been formed during the last Pleistocene glacial period (Fairbridge, 1961) when the sea retreated, resulting in a maximum sea level drop of about 330 ft relative to the present sea level (the 325-ft depth contour in Plate 7). The assumptions made here are that the coastal area has been stable, and that eustatic changes in sea level were worldwide.

During the glaciation period, the downward water-level gradient in the erosion channels must have been relatively steep and hence the water velocities relatively high, so that in the main only the coarser sand and gravel would be deposited. Therefore it may be expected that the erosion channels contain formations with coarse material. As the sea level rose in post-glacial time, these channels became buried with deltaic sediments as the shoreline advanced steadily seawards.

If sufficient fresh water comes into the delta by natural causes (rain and floods) the subsurface channels carry fresh water and the salt water is flushed out. But when the freshwater resources are depleted by artificial and natural causes during the dry season, the same subsurface channels will form entrance channels for salt sea water, the extent of penetration being a function of sea levels and the elevations of the subsurface channels. The zero contour line forms a kind of natural boundary of the delta. If all the fresh water is taken out (or pumped out) of the delta, sea water will eventually reach the zero contour line, which borders Charlies Hill, Stokes Range, The Rocks, and Kellys Mountain. The movement of salt water in the delta will largely be a function of the Ghyben-Herzberg relation (see Chapter 10).

The upper layers of the subsurface basement ridges consist of weathered rocks and consolidated sediments, which form aquicludes. In resistivity depth probing they may be indicated as 'low-resistivity layers' in comparison with the high-resistivity basement below (e.g. near W8/N2 to N3, W8/N7 to N8, and W4/N6).

No correlation has been found between the basement contour map based on the seismic work (Plate 7) and the Home Hill negative gravity anomaly. This can be explained by the fact that the deepest refractor detected by seismic work is only a few hundred feet deep. The Home Hill gravity low on the other hand is probably due to an igneous intrusion that is considerably deeper, though a small part of it may come near the surface (see Figure 18).

Plate 6 gives the approximate depth of basement below ground surface, which may be of practical use in a drilling program.

Summarizing: The basement contour plan shows the presence of subsurface channels and ridges, possibly formed during the last Pleistocene glacial period. These channels probably contain highly permeable material, viz. sand and gravel, which may also act as limited entrance ways for salt water when the freshwater resources are depleted. At The Rocks, the subsurface topography suggests that only part of the water is fed directly into the delta. The remainder flows northwards into the Barratta Creek system. The Burdekin Delta may also be partly recharged from the Barratta Creek system through a subsurface channel about seven miles north of The Rocks and the same distance west of Ayr. If the fresh water were completely pumped out from the delta without recharge through subsurface channels, salt sea water would creep inland until it reached approximately to the zero basement contour.

SEISMIC VELOCITIES IN BASEMENT

Plate 5 shows the approximate seismic velocities in the fresh basement rock; they generally range from 14 000 to 20 000 ft/s. Seismic control is better in some areas than in others, so contours may be more accurate in some areas.

A remarkable zone of lower seismic velocity is centred west of Home Hill around W7/N3, indicated by hatching in Plate 5. This zone may be associated with the gravity low, which was interpreted as a lower-density igneous intrusion or a volcanic pipe; e.g. the lower basement velocities may be associated with volcanics or dykes and sills. A zone of minimum velocities located through FK, AA, DG, DH, and DM coincides with a subsurface erosion channel (W6-8/N3).

Zones of relatively low basement velocity which are possibly associated with subsurface channels or valleys are located near W10/N6 (BE and BK) and W9/N9 (BL, BR, and BQ).

Another zone where basement velocities are slightly lower than in the surrounding area lies between EE and FF, northeast of the fault suggested by a gravity anomaly. Possibly this zone could be associated with the fault.

Summarizing: The basement velocities considered above do not add valuable information to the hydrology of the area. However, the association of lower basement velocities with geological features based on gravity and seismic data confirms the validity of the general interpretation.

SEISMIC VELOCITIES IN WATER-SATURATED UNCONSOLIDATED SEDIMENTS ABOVE THE BASEMENT

In Plate 5 the seismic velocities in the refractor immediately above the basement (defined as material with longitudinal velocity 6700 ft/s or greater) are shown in brackets at the respective seismic stations; these velocities are in the range between 4000 and 6700 ft/s. In unconsolidated sediments the velocities in water-saturated clay or sand and clay mixtures are generally between 2000 and 4500 ft/s depending on the amount of clay in the mixture. Water-saturated coarse sand and gravel usually have velocities in the range 4500 to 5700 ft/s. Between 5700 and 6700 ft/s the material represented may be semiconsolidated sediments or very weathered bedrock.

In the Stokes Range area and the area south of Home Hill the refractors above basement commonly have seismic velocities between 5700 and 6700 ft/s, probably representing very weathered bedrock material. Plate 5 shows a number of examples where the zones with velocities 4500-5700 ft/s, which are interpreted as water-saturated coarse sand and gravel, coincide with subsurface channels indicated in Plate 7, e.g.:

(i) Between W5/N1 and W5/N3, where a subsurface channel from the Barratta Creek system to the Burdekin Delta is indicated.

(ii) Near W8/N4, between DD and BG, where there is a subsurface erosion gully towards the east. Basement is shallow, so the material in the refractor above the basement may be very weathered bedrock material; however, since a subsurface channel has been defined here in Plate 7, it seems likely that the infilling material is coarse sand or gravel.

(iii) Near W9/N6, between BV and BK. Near the latter station basement is relatively shallow; this zone may therefore in part be very weathered bedrock (about BK) and in part unconsolidated or semiconsolidated coarse aquifer material.

10. RESISTIVITY RESULTS

Resistivity depth probes were made at 575 sites during 1962 (60 sites), 1963 (480 sites), and 1964 (35 sites) in an area of 250 square miles, extending 8 miles east, 8 miles west, 6 miles south, and 10 miles north of Home Hill. This includes most of the sugar cane farming areas of Ayr and Home Hill in the Burdekin River delta.

The results of the resistivity tests have been interpreted in terms of the thickness of the various sedimentary layers and their respective resistivities. As explained in Chapter 6, these resistivities can be related to the type of sediments (e.g. whether clay or sand), their relative permeabilities, and the salinity of the water they contain. In this way it has been possible to use the resistivity data to map certain parameters which are important in assessing the water resources of the delta area. These include:

(a) The distribution of sandy and clayey zones which are shown in Plate 12. The sandy zones are believed to be suitable for recharge.

(b) The distribution of saline and brackish groundwater which together with the depth of the relevant aquifers is shown in Plate 9.

(c) A map showing areas of fresh, brackish, and saline water, in Plate 10. This has been prepared from measurements of the resistivity of water samples from throughout the area.

About 20 cross-sections divided more or less equally between north-south and east-west traverses covering the delta area were prepared in which results of the resistivity depth probes were compared with seismic and gravity data. These cross-sections are not presented in this Report but the data have been used in the preparation of the above-mentioned maps. However, four additional sections in the vicinity of Home Hill and Ayr covering the central part of the delta and including about 15 percent of the resistivity tests will be described in detail. These compare the results of observations made in 1962, 1963, and 1964 and are typical of the general range of resistivity tests. These four traverses have been called 1964/1, 1964/2, 1964/3, and 1964/4 and their positions are shown in Plate 8.

A comparison of the observations made at different times reveals some remarkable changes in resistivity which are attributed to changes in amount and salt content of the water contained in the underlying sediments. It is known that with prolonged pumping of fresh water from some bores the water becomes progressively more saline as salt water, usually from lower levels, flows towards the bore to replace the water which has been pumped from it. A similar movement of saline water to replace fresh water may also result from seasonal variations in the amount of fresh water available. The movement of salt water into beds formerly filled with fresh water is known as salt-water encroachment, and it is a serious problem in certain parts of the Burdekin Delta.

The resistivity tests made in 1964 were mainly to check on changes in resistivity that may have occurred since the earlier tests in 1962 and 1963.

1962/1963 DEPTH PROBE DATA

Plate 8 shows the places where resistivity depth probes were made. Plate 9 shows the locations and depths of formations that contained water with more than 1000 p.p.m. of dissolved salt as determined by the resistivity results. The results were obtained over a period of 18 months from August 1962 to December 1963, mostly between March and July 1963. This means that at any given time the boundaries may not be exactly as shown but the variations should not be excessive. It should be noted that without stratigraphic control it is often difficult to differentiate between a clay and a brackish water sand or sandy clay in resistivity data; therefore, some areas shown as brackish or salty may represent clay formations. There are several examples of this in Plate 9, one of which occurs northeast of Home Hill (i.e. W6-7/N5-6); here the low-resistivity formation is representative of a clay rather than a saline water sand. Another example is shown at W6/N3 west of Plantation Creek; farther south near Stokes Range and Kellys Mountain there are small scattered areas which probably represent brackish clay derived from near-surface bedrock, rather than groundwater of marine origin. It should be noted that in a freshwater environment such clay zones stand out clearly, but of course in a saline area they do not. Further, distribution of data over the delta is not uniform, and therefore some boundaries may be drawn more accurately than others. Restraint should therefore be exercised in subsequent deductions. Also, unshaded areas may contain fresh water or may be dry.

The use of the hatching for a given range on the map means that saline water is present within the range, but it is possible that some fresh water is also present.

If the topographical elevation contour plan (Plate 11) is superimposed on the salinity plan (Plate 9), a tendency may be observed for fresh groundwater to occur in the higher areas, and the lower parts or the lagoons tend to be saline. This can be explained partly by reason of the surface encroachment of salt water inland along channels for a limited distance (dependent on changes in sea level and on elevation of the channels); partly by the flushing-out of salt from the formations on higher ground by rainwater or by flooding; but probably also by an effect of the Ghyben-Herzberg Relation, which relates salt-water encroachment to the head of fresh water above the sea level (Fig. 20). This states that in the case of a

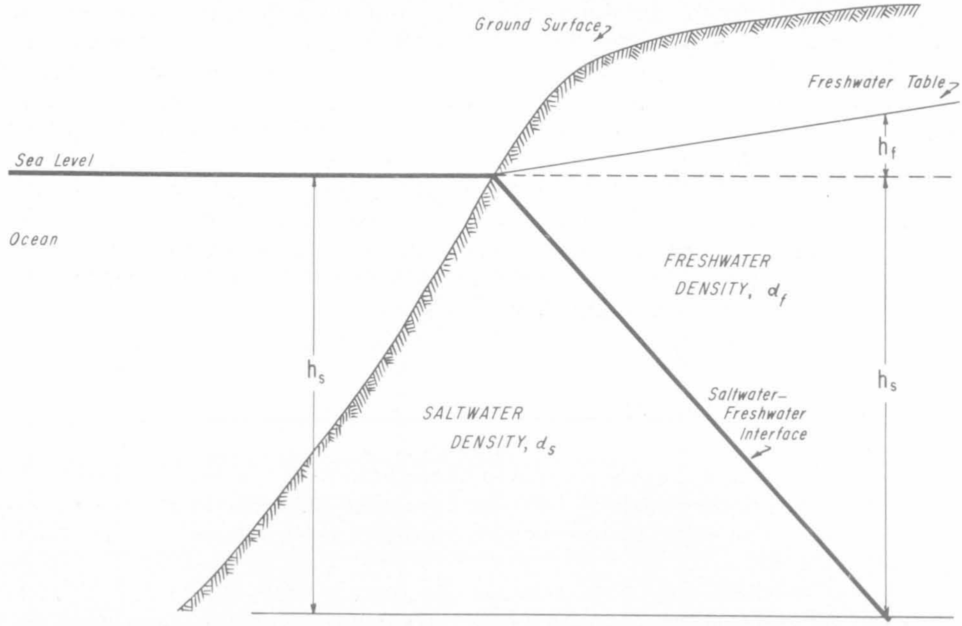


Fig. 20. Idealized sketch showing Ghyben-Hertzberg relation

homogeneous coastal aquifer, at a point inland where the water-table is at a level *hf* above sea level, then the top surface of the encroaching salt-water wedge at that point will be approximately a distance $hf/(d_s-1)$ below sea level, d_s being the specific gravity of salt water. This assumes that the unconfined aquifer is homogeneous and that there is no marked flow within the freshwater body (Todd, 1959, p. 279). For $d_s = 1.025$, $hf/(d_s-1) = 40\ hf$.

Examples of localities where salt water appears to come in along topographical depressions are near W3/N2, between W3/N4 and W3/N5, W3/N6, W4/N6, and from the Burdekin River (W6/N6) and the Anabranch (W5/N7).

Examples of places where fresh water occurs through a large part of the section at places where the ground is relatively higher are near W1/N4, between W4/N3 and W4/N4, between W3/N5 and W3/N6, and near W5/N6 and W7/N6.

Some of the features of Plate 9 can be correlated with features shown in the basement contour plan (Plate 7). The area northeast of W5/N6 where there is salt water only below 75 ft follows the line of a major valley in the bedrock. This suggests that the valley contains highly permeable material and that fresh water flowing out of the valley is flushing out the salt water near the surface, leaving the salt water only below 75 ft depth. This mechanism operates simultaneously with the salt-water encroachment as described by the Ghyben-Herzberg Relation. If readings in valleys or lagoons were taken at the end of the dry season there would probably be salt water throughout the stratigraphic section, as in the absence of any quantity of fresh water, the salt water would be able to encroach from the sea.

The isolated low-resistivity areas south of Home Hill between W10 and W11 are probably caused by salts in the weathered bedrock, probably partly limestone or shell banks. These shell banks would give rise to carbonate-rich water as opposed to the chloride-rich sea-water (see below). The isolated saline areas elsewhere, e.g. near W6/N3, W8/N4, and W5/N7, are probably due to remanent salt in clay; this salt is unlikely to affect irrigation water drawn from more permeable horizons. Whilst there is a tendency for clay to absorb salts, flushing-out of the material will be slow because of its low permeability, and also will be impeded by base exchange, which causes deflocculation and a reduction in permeability.

1963 WATER RESISTIVITY DATA

Plate 10 shows the distribution of saline and brackish water based on water samples collected by both the IWSC and BMR. Zones of water that is fresh but contains a significant amount of dissolved salts (6-12 ohm-metres) are also defined. The data are unevenly distributed over the delta and contain information collected during a period of several months in 1963. No precise information with regard to the depth at which subsurface samples were collected is given; hence care should be taken in interpreting the distribution of water quality as shown in Plate 10. The surface encroachment of salt water is, however, clearly shown on the seaward edge of the delta. South of the Burdekin River, water with resistivity 6-12 ohm-metres extends in a broad zone from Stokes Range east through Charlies Hill. This is taken as a direct reflection of the shallowness of bedrock.

1964 DEPTH PROBE DATA

TRAVERSE 1964/1 (Plate 13)

This is a north-south traverse approximately 6 miles long centred about 5 miles west of Ayr and roughly parallel to Sheep Station Creek. On this traverse six resistivity depth probes made in 1964 are compared with nine made in 1963 and three in 1962. The depth to basement as shown in Plate 7 based on the seismic results is also shown.

At the northern end of the traverse, Resistivity Depth Probe 611 (RE 611) observed in 1964 is compared with RE 338 which is only a few hundred feet away and observed in 1963. The top 50 ft of RE 611 has a resistivity of 560 ohm-m which probably corresponds to moist or dry sand. This overlies material with a resistivity of less than 1 ohm-m, which must be saturated with salt water. The interpreted depth to brackish or saline water in RE 611 is about 90 ft shallower than in RE 338, which signifies an upward movement of the freshwater/saltwater interface by about this amount during the 15 months between the observations.

Resistivity depth probes RE 337 (May 1963), RE 610 (October 1964), and RE 53 (October 1962) are all close to Sheep Station Creek in an area of very low surface elevation which may be subjected occasionally to inundation with salt water. Apart from one or two feet of the surface soil which has a relatively high resistivity, the near-surface sediments in RE 337 at least to a depth of 70 ft have resistivities ranging from 1 to 4 ohm-m indicating saturation by salt water. The upper 25 ft at RE 610 also has a low resistivity (1.6 ohm-m) corresponding to saline water saturation, but this overlies a zone with a resistivity more then 30 ohm-m which indicates the presence of fresh water. The resistivities measured at RE 53 in October 1962 are all high from the surface downwards (900, 630, and 950 ohm-m) suggesting that sediments are sandy and at that time to a depth of at least some tens of feet contained only a small amount of fresh water.

At RE 632 about half a mile west of the Creek, the upper 70 ft has a resistivity of 60 ohm-m corresponding to sandy sediments saturated with fresh water which overlie a zone of brackish or salt water.

Resistivity depth probes RE 353 (May 1963) and RE 56 (October 1962) are about 1000 ft apart and half a mile west of Sheep Station Creek. Although the observations were made 17 months apart the resistivity sections and presumably the underground water conditions were practically the same. Both have a moderately brackish water zone (6 and 10 ohm-m respectively) about 30 ft thick underlying about 3 ft of moist surface soil. The brackish zone is underlain by a hundred or more feet of sandy sediments saturated with water of moderately good quality (14 and 21 ohm-m respectively).

Depth Probe RE 336 (May 1963), which is about half a mile farther south and nearer the Creek, has a zone of relatively high resistivity from surface to about 60 ft which is interpreted as moist to dry sandy sediments overlying a zone saturated with salt water (5 ohm-m).

Still farther south and close to the western bank of the Creek are RE 335 (May 1963) and RE 631 (October 1964), which have remarkably different characteristics. Beneath about 3 ft of wet surface soil RE 335 shows a zone 130 ft thick with a resistivity of 170 ohm-m which is believed to correspond to sandy sediments saturated with fresh water. This in turn is underlain by a zone over 100 ft thick containing slightly brackish water. In contrast, RE 631 has a surface zone about 80 ft thick of moist or dry sand overlying a zone saturated with salt water.

Farther south and scattered over an area of about one square mile, are RE 55, RE 105, RE 106, and RE 633 all on the relatively high ground between Sheep Station Creek and Barratta Creek. At RE 106 (April 1963) the near-surface sediments to a depth of about 130 ft are moistened only with fresh water (resistivity 684 ohm-m). In contrast to this, RE 55 (October 1962), RE 105 (April 1963), and RE 633 (October 1963) all show an upper zone about 30 ft thick with resistivity ranging from 10-20 ohm-m, overlying a thick zone with resistivities ranging from 32 to 82 ohm-m. This pattern is interpreted as a near-surface zone containing a high proportion of clay saturated with moderately brackish water overlying a more sandy zone containing water of better quality.

At RE 634 (October 1964) near the southern end of the traverse on relatively high ground about 1½ miles west of Sheep Station Creek, the section is very similar to that at RE 105 except that the near-surface layer extends to a depth of 50 ft.

The results of RE 100 and RE 101 (both April 1963) are similar in that they have a zone of high resistivity (1780 and 2000 ohm-m respectively) which extends to a depth of 80 to 90 ft and is underlain by a zone of slightly lower resistivity. The upper zone appears to be slightly moist sand which overlies sand with a somewhat higher moisture content.

Very few of the zones interpreted from the Resistivity Depth Probes penetrate below the basement as indicated by the seismic results. Where they do, as for example at RE 335, RE 55, RE 106, and RE 100 and 101, the interpreted resistivity values are moderately high, indicating that the weathered bedrock contains fresh water.

TRAVERSE 1964/2 (Plate 14)

This traverse extends from about 2 miles east of Ayr in a southeasterly direction for about 8 miles. It incorporates the results of 19 resistivity depth probes which are shown in relation to a bedrock profile based on the seismic interpretation and compared with 5 shallow bore-holes.

At the northern end adjacent to Plantation Creek, resistivity depth probe RE 625 (October 1964) may be compared with RE 384 (June 1963). These are both characterized by 2 or 3 relatively thin layers to maximum depth of about 12 ft with moderately high resistivities in the range 15 to 274 ohm-m underlain by a layer 60 ft thick at RE 625 and 30 ft at RE 384 with a resistivity of 10 and 12 ohm-m respectively. This layer is underlain by one with relatively high resistivity. The section is interpreted as a thin near-surface layer saturated with fresh water underlain by one predominantly of clay containing salty or brackish water which in turn overlies a freshwater layer. At RE 625, the bottom freshwater layer is underlain by a low-resistivity layer which corresponds to weathered bedrock saturated with salt water.

A group of three resistivity depth probes about one mile southeast of Plantation Creek, namely RE 203 (April 1963) and RE 204 (October 1964) show some significant differences. At RE 203 there is a surface layer 10 ft thick of resistivity 27 ohm-m which is saturated with fresh water. Similar surface layers at RE 626 and RE 204 are much thinner but the zone 45 ft thick and of resistivity 188 ohm-m immediately beneath the surface layer at RE 204 is probably also saturated with fresh water. Beneath the surface layer at RE 203 and RE 626 is a deep zone 60 to 100 ft thick with a resistivity of 5 and 8 ohm-m respectively, corresponding to a clayey formation saturated with brackish or moderately saline water. The deep zone in RE 204 with a resistivity of 12 ohm-m appears to be a brackish clay similar to the shallower brackish zones in the other two tests. The presence of thick clayey formations is supported by the geological section in bore D7 near these test sites, which is predominantly sandy clay and clay.

Resistivity sections in the next seven resistivity depth probes at the southeast, namely RE 85, RE 623, RE 82, RE 381, RE 600, RE 31, and RE 263, are basically similar in that they have a thick upper zone ranging in thickness from about 50 to 100 ft with moderately high resistivities ranging from 280 to 1200 ohm-m. This overlies a zone with a much lower resistivity ranging from 4 to 14 ohm-m which may be correlated with a zone at the bottom of RE 204.

These sections are interpreted as a relatively thick upper zone that is essentially sandy and contains fresh water in amounts ranging from highly saturated to practically dry. This zone is underlain by one saturated with brackish to saline water which probably has a relatively high clay content.

Resistivity depth probes RE 391 (June 1963) and RE 262 (May 1963) are similar in character. They have a thin upper zone 8 to 10 ft thick of moderately high resistivity ranging from 10 to 38 ohm-m which, because the near-surface layers are known from drilling results to be sand, is interpreted as a sandy layer saturated with fresh water. This overlies a zone about 70 ft thick, of resistivity about 4 ohm-m, which corresponds to a sandy formation with saline water. In RE 391 this is underlain by a zone 90 ft thick containing brackish water (11 ohm-m) and finally by a saline zone with a resistivity 3 ohm-m which according to seismic evidence corresponds with the top of weathered bedrock. A similar saline zone is present in RE 262, but the thick zone above the bedrock has a much higher resistivity (80 ohm-m) in RE 391 and appears to contain fresh water.

Results of the five resistivity depth probes on Rita Island at the southeastern end of the traverse, namely RE 602, RE 531, RE 259, RE 394, and RE 629, are similar in that with the exception of a very thin layer (less than 2 ft thick) at the surface in RE 602 and RE 629, with a resistivity of 19 and 11 ohm-m respectively, the upper zones have all a relatively high resistivity to a depth ranging from 15 to 55 ft. These, with the possible exception of RE 394, overlie a formation containing salt water. The near-surface resistivities in RE 394 are exceptionally high (up to 10 000 ohm-m) which may account for the estimated resistivity of the lowest zone in this test (less than 20 ohm-m) being abnormally high for a salt-water zone. The picture presented by these five tests is of a sandy zone containing fresh water near the surface, but having a generally low percentage saturation, in places practically zero, overlying a thick formation saturated with salt water.

The picture is supported in the vicinity of the southern end of the traverse by the results of a number of resistivity depth probes which are not shown on the section. E.g. RE 601 has two upper layers with resistivities of 100 and 400 ohm-m respectively to a depth to about 60 ft overlying a formation saturated with salt water; RE 256 has upper zones ranging in resistivity from 40 to 1150 ohm-m interpreted as sand containing fresh water with a variable degree of saturation, overlying a salt-water zone. To the limits of the depths tested by RE 26, the upper zones have higher resistivity (800 and 1600 ohm-m) and are interpreted as moist fresh water zones; RE 630 has an upper zone of resistivity 570 ohm-m to a depth of 40 ft overlying a salt-water zone, and the upper zones in RE 260, to a depth of about 100 ft, have resistivities ranging from 10 to 86 ohm-m corresponding to a predominantly sandy formation saturated with fresh water which overlies a salt-water zone.

The low-resistivity zones in the lowest parts of RE 625, RE 203, RE 391, and RE 262 indicate that the upper part of the weathered bedrock indicated by the seismic results contains salt water.

TRAVERSE 1964/3

Traverse 1964/3 extends roughly seven miles south-southwest from a point about 4 miles east-northeast of Ayr and about 1 mile east of Plantation Creek. At the southern end it crosses the Burdekin River. The traverse incorporates results of 21 resistivity depth probes, 7 observed in 1964, 12 in 1963, and 2 in 1962; these are compared with depths to bedrock interpreted from the seismic results and the geological section revealed by eight boreholes.

At the northern end RE 208, RE 207, and RE 206 (all April 1963) have similar characteristics, namely a change at depths of 50, 90, and 100 ft respectively from moderately high resistivities (16, 22, and 78 ohm-m) to very low resistivities (1 to 3 ohm-m). The upper layer in each case is believed to contain variable proportions of clay, saturated with fresh water which overlies a salt-water zone.

Resistivity depth probes RE 628 (October 1964) and RE 386 (June 1963) are within a few hundred feet of one another but are notably different in character. In RE 386 the individual layers down to the limits of the test (somewhat in excess of 160 ft) have relatively high resistivities ranging from 29 to 158 ohm-m corresponding to sandy formations saturated with fresh water. On the other hand RE 628, observed some 18 months later, showed a pronounced change from an upper zone of high resistivity (500 ohm-m) indicating a moist freshwater sand to extremely low resistivities of less than 1 ohm-m corresponding to salt-water saturation at a depth of about 50 ft. It is suggested that over this time there has been an encroachment of salt water and a serious depletion of the amount of fresh water available.

RE 27 about a quarter of a mile from RE 386 and observed in September 1962 has similar characteristics to RE 386 to the limits of the depth assessed by the test, indicating that at this time the upper layers were saturated with fresh water. The results of the resistivity depth probe RE 627 are very similar to RE 628; the freshwater/saltwater interface appears to be about 60 ft deep. The upper zone in RE 627, however, has a somewhat higher resistivity (1140 ohm-m) than in RE 628. The salt content of the underlying zone in RE 627 also appears to be somewhat less than in RE 628.

Apart from two very thin near-surface layers of moderate resistivity the whole of the zones tested by RE 28 to a depth of about 200 ft has a moderately high resistivity (280 ohm-m). Nearby bores indicate that the geological section is predominantly sandy so that these resistivities are evidently due to sandy formations saturated with fresh water - a further confirmation of the thick zone of fresh water that was evident at the time of the 1962 tests.

The results of RE 624 and RE 85 which are about one-third of a mile apart are very similar although the observations were made 18 months apart. The upper zone, saturated with fresh water, has resistivities of 295 and 280 ohm-m respectively overlying zones with resistivities of 5 and 8 ohm-m respectively representing locally shallow salt-water conditions. RE 623 is a further one-third of a mile south of RE 85 and although the freshwater/saltwater interface is 20 ft deeper than in RE 85 the resistivity values of the upper layer zones are much the same.

The group of four resistivity depth probes near the northern bank of the Burdekin River namely RE 87, RE 83, and RE 84 (March 1963) and RE 622 (October 1964) show a wide range in depth to the resistivity contrast that marks the change from fresh water to salt or brackish water. This depth is about 100 ft in RE 87, about 85 ft in RE 622 and about 65 ft in RE 84. At RE 83, relatively high resistivities corresponding to freshwater saturation extend to the depth limits of the test, i.e. somewhat in excess of 120 ft. The higher resistivities of the top layers, apparently unchanged during the three years of surveying, suggest a continual discharge of fresh water from the Burdekin into the aquifers in this locality.

The resistivity in the upper zone between the Burdekin River and Plantation Creek ranges from about 20 ohm-m to over 1000 ohm-m, and as drilling results suggest that the formations are mostly sandy, it seems likely that the ranges of resistivity indicate fresh water with a variable degree of water saturation, the formations of highest resistivities being practically dry.

To the south of the Burdekin River a number of shallow bores indicate that to the depth of several tens of feet the formations are interbedded clay and sand, the clay portion predominating. This is reflected in the resistivity results at RE 609 and RE 298, which both have upper layers of resistivity about 30 ohm-m from 20 to 30 ft thick interpreted as clay or sandy clay saturated with fresh water. At RE 609 this is underlain by a layer with a resistivity greater than 200 ohm-m which is probably sand saturated with fresh water. At RE 298 the underlying layer some 80 feet thick has a resistivity of only 14 ohm-m which indicates either brackish-water sand or perhaps a formation with a very high clay content.

At RE 297, farther south, there is an upper layer about 10 ft thick with a resistivity of 25 ohm-m which is presumably clay saturated with fresh water. This is underlain by a formation about 30 ft thick with a resistivity of 250 ohm-m and by a further zone of resistivity 50 ohm-m. These are presumably sandy zones saturated with fresh water, the upper one having relatively low percentage saturation.

Apart from a surface layer 15 ft thick of resistivity 4.5 ohm-m at RE 617, this test and the one at RE 300 at the southern end of the traverse are very similar to RE 297. The formations have a relatively higher resistivity ranging from 76 to 760 ohm-m, which indicates that they are wholly or partly saturated with fresh water; i.e. continually recharged by fresh water from the Burdekin River.

These two tests are the only ones on the section line where the results extend below the basement surface indicated by the seismic results. The zones beneath this depth have resistivities of 250 and 175 ohm-m respectively, and are presumably weathered bedrock.

Three other resistivity depth probes, RE 608, RE 607, and RE 606 (all October 1964) about 1½ miles north of the traverse at its southern end provided significant results although they are not shown on the section line. RE 607 shows a freshwater zone to a depth of about 20 ft overlying a brackish zone (resistivity 9 ohm-m). The results of RE 608 are similar except that the near-surface zone of fresh water is only about 7 ft thick and the underlying zone has a slightly higher resistivity (11 ohm-m) which may be a brackish-water sand or clay. At RE 606 the underlying formations, to the depth tested, appear to be saturated with fresh water.

The deepest resistivity zones at RE 300 and RE 617 at the southern end of the traverse are the only ones that extend to the depth of the basement surface indicated by the seismic results. Their relatively high resistivity indicates that the bedrock at that depth is only slightly weathered.

TRAVERSE 1964/4

Traverse 1964/4 is 9½ miles long and extends from a point on the bank of Seaforth Creek about 7½ miles east-northeast from Ayr in a general south-southwesterly direction to a point about 3 miles due east of Home Hill. About midway the traverse crosses the Burdekin River near its junction with its Anabranch. The traverse incorporates the results of 28 resistivity depth probes, 6 observed in 1964, 17 in 1963, and 5 in 1962, and these are compared with a basement profile interpreted from the seismic results and with the geological logs of 8 boreholes.

Resistivity depth probe RE 72 is close to Seaforth Creek, a branch of Plantation Creek, and apart from a surface layer about 8 ft thick which is probably dry soil the resistivities observed are extremely low and indicate salt-water saturation. At RE 73, the resistivities are moderately high (10 to 27 ohm-m) to a depth of about 30 ft, indicating slightly brackish water or perhaps a clayey formation. Below this is a formation with a resistivity of 80 ohm-m, presumably mainly sand saturated with fresh water.

The group of tests RE 375, RE 74, and RE 603, although observed at different times, have similar characteristics. Each has near-surface layers of moderately high resistivity to depths of 10, 20, and 25 ft respectively which presumably contain fresh water overlying a saline formation with a resistivity ranging from less than 1 to 7 ohm-m. Resistivities at RE 75 and RE 1 are relatively high (41 to 185 ohm-m) to the limits of the depths tested, i.e. somewhat in excess of 50 ft. Nearby bores indicate a sandy section, and the resistivities indicate that this is saturated with fresh water. At RE 76 resistivity results indicate that this freshwater sand is underlain to a depth of about 55 feet by a salt-water zone.

The results at RE 77 and RE 78 each indicate a change at a depth of about 80 ft from an upper zone with a resistivity of 48 and 70 ohm-m respectively, which is interpreted as a sandy zone saturated with fresh water, to a formation with a resistivity of 3 ohm-m or less which must be highly saline.

The results of the tests at RE 604 and RE 34 have similar general characteristics to those at RE 77 and RE 78, namely a relatively thick upper zone of high resistivity overlying a formation with a very low resistivity and saturated with salt water, except that the resistivity of the upper zone (200 to 780 ohm-m) is significantly higher, thus indicating lower percentage saturation, and the depth to the freshwater/saltwater interface is slightly shallower.

In direct contrast to the results at RE 604, RE 34, RE 77, and RE 78 are the results of the tests carried out more or less midway between these groups at RE 79. At this site, to the limits of the depth tests (about 250 ft), the resistivities are uniformly high ranging from 98 to 340 ohm-m and there is no indication of the salt-water zone which occurs at depths from 60 to 80 ft below the surface at the other sites. The surface elevation at the individual sites is much the same, so if the lithology of the underlying sediments were constant one would expect similar results. A probable explanation is that at RE 79 the formations are predominantly highly permeable sand and gravel which have allowed movement of fresh water through them, whereas at the other test sites the material with a relatively low resistivity contains impermeable clay with a high salt content. The thick section of sand and gravel under RE 79 may indicate that this lies over a subsurface channel.

A resistivity depth probe at RE 32 shows a 10-ft surface layer with a resistivity of 16 ohm-m, probably slightly clayey sand saturated with fresh water, underlain by two layers 30 and 60 ft thick with resistivities of 5 and 6 ohm-m respectively. These are interpreted either as sandy formations containing salt water or as moderately saline clay. This overlies a salt-water zone with a resistivity of about 1 ohm-m. This is in marked contrast to the resistivity sections at RE 34 about 3000 ft to the north and RE 381, RE 31, and RE 600 about 4000 ft farther south, which all have thick high-resistivity zones in their upper parts.

The group of three tests near the northern bank of the Burdekin River—RE 381 (June 1963), RE 31 (September 1962), and RE 600 (October 1964) — are similar in that they all have an upper zone of high resistivity overlying a formation of relatively low or very low resistivity corresponding to brackish or salt-water saturation. The upper zone, ranging in resistivity from 180 to 1200 ohm-m, is believed to be predominantly moist sand containing fresh water with a variable degree of saturtion, and the depth to the freshwater/saline-water interface is progressively shallower with time — about 120 ft at RE 31 (September 1962), 70 ft at RE 381 (June 1963), and 60 ft at RE 600 (October 1964). Although these test sites are about 1000 ft apart it is believed that the progressive rise of the salt-water level is evidence of salt-water encroachment; however, the changes at depth to low-resistivity values may equally be due to changes from a sandy section to a predominantly clayey one, which of course would not change with time.

On the south bank of the River, results of the tests at RE 305 and RE 614 are similar with relative high-resistivity zones (10 to 151 ohm-m) extending respectively to 50 and 40 ft from the surface overlying formations with a resistivity of 17 and 10 ohm-m. These are possibly sandy formations saturated with slightly brackish water, but the relatively low resistivity may also be due to a formation with a high clay content.

The relatively low resistivities recorded in the upper layers of RE 302, namely 13 ohm-m to 2 ft, 18 ohm-m to 3 ft, and 9 ohm-m to 85 ft, are probably due to high clay content in the formation, because the sediments intersected in the upper part of the nearby bore F8 were clay.

At RE 303 the relatively high resistivity observed suggests that the formations to the limits of the depth tested contain fresh water, changes in resistivity being related partly to variations in clay content and partly to the degree of water saturation. At RE 616 a resistivity of 135 ohm-m was recorded to a depth of about 100 ft corresponding to a sandy formation containing fresh water. At RE 304 the resistivities are similar to those recorded at RE 302 and presumably are due to a similar cause, namely clayey formations saturated with moderately brackish water.

Apart from a 3-ft surface layer of low resistivity which was probably due to saline clay, the resistivities recorded in RE 214 to a depth of 55 ft suggest the presence of fresh water in a formation with a variable clay content. This overlies a formation with a resistivity of 5 ohm-m which possibly contains a high percentage of saline or brackish clay and may possibly represent weathered bedrock.

The section of RE 618 is mainly brackish (10 ohm-m) with a freshwater surface layer down to 15 ft. This is similar to the sections in RE 213 and RE 50 except that the uppermost layer in RE 213 appears to have a high clay content and the lower zone a high concentration of salt water. At RE 212 relatively high resistivities were recorded at the limits of the depth tested, suggesting sandy formations saturated with fresh water.

Four other depth probes observed in 1964 on the southern bank of the Burdekin River but not included in traverse 1964/4 are RE 615, 1½ miles east of the traverse; RE 619, 1 mile east; RE 605, 3 miles east; and RE 620, 1¾ miles east. The upper parts of RE 619 and RE 605 have three or more layers to a depth of about 40 ft with resistivities ranging from 3 to 9 ohm-m, corresponding to a saline or brackish formation with probably a high clay content. RE 615 appears to have a freshwater zone about 30 ft thick overlying a brackish formation. At RE 620 the upper 7 ft has a low resistivity which is believed to be due to brackish water from recent irrigation; this overlies about 20 ft of dry formation which in turn overlies a saline formation.

Basement as indicated by the seismic results shallows to a depth of about 80 ft 2 miles south of the River, and most of the resistivity tests on the southern part of the traverse have included the upper part of the basement section in the zones tested. The resistivities corresponding to this uppermost part of the basement range from 5 ohm-m at RE 212 to 1000 ohm-m and presumably reflect the degree of weathering to which the basement rocks have been subjected. Except for RE 214 (5 ohm-m) and RE 616 (less than 15 ohm-m), either the water in this weathered bedrock is fresh or the weathering is only slight.

Summarizing: The interpretation of the resistivity depth probes is complicated by the fact that no clear distinction can be made between low resistivity due to saline water in sand and that due to clay lenses which have absorbed some salt but which occur in a freshwater zone. With the exception of a few test sites on or near the bank of tidal salt-water creeks, where very low resistivities in surface layers are almost certainly due to salt water, those sites where relatively low resistivities have been recorded in upper layers are most likely to be areas of high clay content or zones of salt-water encroachment along creeks. Those formations whose resistivities exceed about 50 ohm-m are most probably sandy formations containing fresh water with a variable percentage saturation, the higher the resistivity the lower the saturation.

On the basis of these broad classifications, it has been possible to divide the delta area into zones in which the near-surface layers are predominantly sandy with high permeability, and therefore suitable for recharging the underlying aquifers, and those where the clay content would restrict the entry of recharged water. These zones are shown in Plate 12 and are discussed in detail in Chapter 12.

The results of the tests made in 1964 have been compared with earlier ones made in 1963 and 1962 in the search for evidence of change in the level of freshwater/saltwater interfaces, but the results are inconclusive. Few if any of the repeated observations were made at the exact sites of the earlier ones, and the results from the boreholes shown on the various traverses indicate that the lithology of the delta sediments varies markedly in quite short distances. At test sites only a few hundred feet apart there could be major differences in the geological sections, which would be reflectd in the results of the resistivity depth probes. Nevertheless at a few places, for example at the northern end of Traverse 1964/1 (RE 611 and RE 338), near the northern end of 1964/3 (RE 628 and RE 386), and possibly near the northern bank of the Burdekin River on Traverse 1964/4, the results suggest that the level of the salt-water horizon has risen substantially over a period of about 18 months prior to the tests in October 1964. Whether or not this evidence is reliable is perhaps of no great consequence; what is important is that the resistivity technique has been shown to have the facility of determining changes in resistivity at depth which in turn can be related to changes in the amount and resistivity of the water content in the underlying sediments. If encroachment of salt water into the freshwater aquifers is suspected, resistivity tests repeated at a number of key sites at say 6-monthly intervals should effectively monitor such encroachment.

11. PERMEABLE SUBSURFACE FORMATIONS FOR RECHARGE (Plate 12)

In planning artificial recharge projects where fresh groundwater is, or may become, depleted, the Commission requested a plan indicating zones of high permeability. In making this plan, only formations deeper than 10 to 15 ft below the surface were generally considered. Surface formations are often contaminated with salts, and generally it is difficult or impossible to interpret resistivity data on surface formations. Also, it is believed that many recharge projects use channels or furrows that penetrate through the top soil.

In addition to the principles noted in Chapter 6 the following was observed during field work:

(1) Near-surface formations with resistivities in excess of say 260 ohm-m are dry or partly dry; they consist mainly of dry or moist permeable sands.
(2) Clays or clayey formations, because of their low permeability, largely retain their pore water during prolonged dry periods.
(3) Clays deposited in a saline environment absorb salts which can only be very slowly flushed out as fresh water passes through the clay formation. Hence no clays were observed with resistivities as high as those of dry sands.

In the intermediate resistivity range of say 20 to 260 ohm-m the sediments with a high proportion of clay usually occupy the lower end of the range. Unambiguous distinction of clays from sands in this range may require additional information on the resistivity of the groundwater. The following examples may illustrate the principles used. If, in a specific locality, depth probes are made in the wet and dry seasons, resistivity values of clayey formations will remain approximately the same; however, resistivity values of sandy formations will rise markedly during the dry season because of water depletion. Generally, varying resistivities at different seasons indicate sand.

In a limited locality, the resistivity of the groundwater should not vary greatly. If, however, the resistivity depth probes indicate large variations of formation resistivity in the intermediate range (20 to 260 ohm-m) both vertically and laterally, the above principles may sometimes still be used, but for very low formation resistivities, i.e. less than 6 ohm-m, it is seldom possible to distinguish between salt-water sand and salt-water clay. In the latter case only drilling gives a definite answer.

Therefore, the following correlations may apply in resistivity depth probing:

(a) Resistivities greater than 260 ohm-m: dry sand or gravel formations.
(b) Resistivities 20 to 260 ohm-m: clay and sand usually may be recognized by applying the above-mentioned rules. The formation water is generally fresh.
(c) Resistivities 6 to 20 ohm-m: clay and sand may still be recognized although it is more difficult and sometimes impossible. The formation water is brackish.
(d) Resistivities of 6 ohm-m or less: salty clay generally cannot be distinguished from salt-water sand by resistivity methods alone.

Plate 12 shows a regular pattern of subsurface sandy zones suitable for recharge, separated by clayey zones. The sandy zones probably represent old river courses; the clayey zones old natural levee banks. Clayey zones along the Burdekin and Anabranch represent natural levees of the present Burdekin River. Sheep Station Creek and Kalamia Creek are located in sandy zones; Plantation Creek is in a sandy zone until it enters the clayey zone one mile east from Ayr.

Figure 7 of 'The Water Resources of the Burdekin delta' (IWSC, 1964) gives in a contour plan the rise of groundwater during the wet season from 20 January to 23 April 1963. It may be expected that after the water level has receded in the river, the water level in a clayey formation will fall more slowly than will the level in a sandy formation. The contour plan shows that places of maximum groundwater rise over the period January to April 1963 are located in the clayey zones indicated in Plate 12, viz. northwest of Home Hill, 3½ miles southwest of Plantation Creek, 3 miles east of Ayr near Plantation Creek, and 1½ miles southeast of Home Hill.

Judging from Plate 12 and also taking into account the basement contour plan (Plate 7) but disregarding technical or financial considerations, the best localities to recharge the delta probably would be:

(1) For the area north and south of Ayr, pump water into Plantation Creek near RE 341, W7/N4.

(2) For the area northwest of Anabranch, take water to between W5/N6 and W5/N7.
(3) For the Sheep Station Creek zone, pump water into Sheep Station Creek north of Kellys Mountain, near W7/N2 and near W5/N2 (from Plantation Creek).
(4) For Rita Island, pump water to Rita Island.
(5) For the Home Hill area, pump water to RE 266 between W9/N3 and W9/N4.
(6) For the sand zone south of Home Hill, pump water to RE 238 near W10/N5.

In this connexion the Sandpit Lagoon Diversion scheme (proposed by the IWSC in its report 'Replenishment of Underground Water Supplies, Burdekin Delta, Stage 1, 1964') might require some modification in the light of Plate 12. Further, if water known to collect annually at the Lake Plain were diverted towards RE 238, it would facilitate recharge of this area.

12. MERRYPLAIN CREEK AREA

INTRODUCTION

This area (Fig. 21) was investigated in detail to discover why the water from two bores with pumps (Bores 1 and 2) had become saline between June 1962 and June 1963.

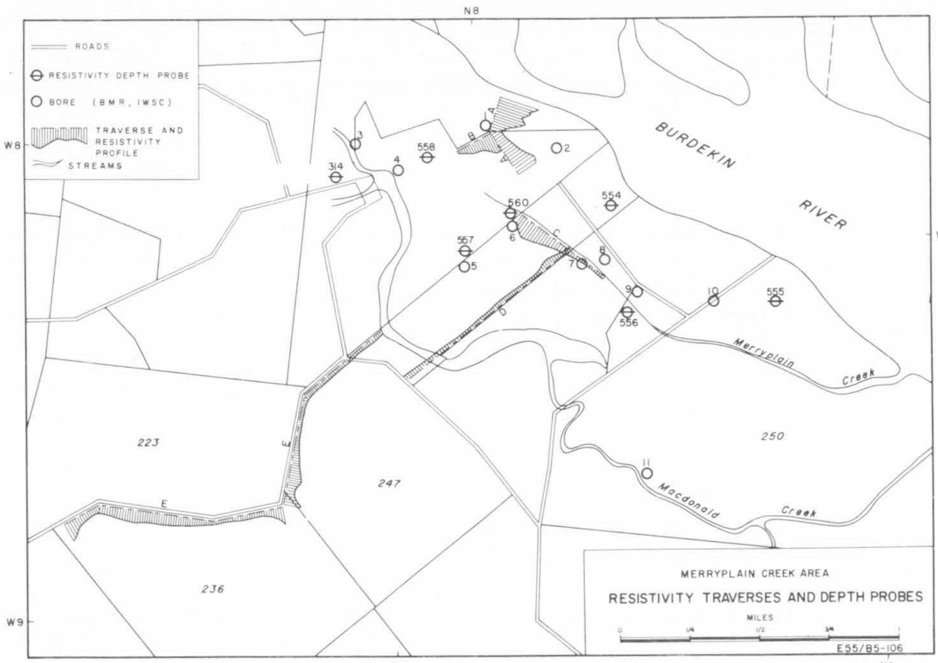


Fig. 21. Merryplain Creek area - resistivity traverses and depth probes

According to the local farmer, Bore 1 (depth about 30 ft) started as a freshwater bore used for irrigation. Since then the water has become saline, and the sugar yield per acre has dropped by about 30 percent. The area is bounded in the northeast by tne Burdekin River while Merryplain and Macdonald Creeks cross the area from west to east. Information on the area is given in the following table.

Bore No. (Plate 38)	Source of Information	Comments
1	Farmer	Bore water went saline June 1963, after rain; 18 ft to water, possibly brackish before.
2	Farmer	Bore water went saline at end of 1962; possibly brackish before.
3	IWSC	Hole drilled November 1963, water - 1000 p.p.m.
4	Farmer	Bore water - 700 p.p.m.
5	Farmer	Bore water - 1000 p.p.m.
6	Farmer	Bore water - 700 p.p.m.
7	Farmer	Unsuccessful test hole, salt water only.
8	Farmer	Bore water usable but brackish - 1000 p.p.m.
9	Farmer	Bore water usable but brackish - 1000 p.p.m.
10	Farmer	Bore water usable - 600 p.p.m.
11	IWSC	Salt water only.

The area between Merryplain Creek and the Burdekin River forms a naturally built-up levee of the river. The ground is between 20 and 30 ft higher northeast of Merryplain Creek than southwest of the creek. According to the local farmers the surface sediments northeast and southwest of Merryplain Creek consist of sand, or sand with clay. Airphotos indicate that east of Merryplain Creek the surface drainage is northward to the Burdekin River, and west of the creek it follows the creeks and lagoons in a general southeasterly direction.

RESULTS

Resistivity Traverses C, D, and E, resistivity depth probes, and borehole information show that west of Merryplain Creek salt water has penetrated inland near the surface and at depth as far as Traverse D. North of Traverse D, along Traverse C, resistivity values are higher and the layer of fresh water above salt water becomes thicker, as shown by a shallow bore and resistivity depth probe RE 560. Between the two creeks near RE 557 and RE 558 is a thick freshwater layer above salt water, indicated in Figure 21 as a zone of fresh water above saline water. However, farther west towards RE 314 near the creek, the freshwater layer becomes thin again.

Resistivity Traverses A and B near Bore 1 indicate that resistivities are low where lagoons cross the traverses; i.e. these lagoons allow salt water to move inland.

The distribution of salt and fresh water suggests that rain water soaks into the ground to form the freshwater layer in the wet season. With excessive pumping at the end of the dry season, fresh water is drawn out and salt water comes in through the subsurface. Possibly the creeks and lagoons function as important entrance channels for salt water, especially during high tides or tidal floods (the predicted maximum tide level variation at Townsville is about 13 ft, not taking into account variations due to cyclonic storms). In the following rainy season, fresh water soaks into the ground and depresses the interface between fresh and salt water as is required by the Ghyben-Herzberg relation.

In the area between Merryplain Creek and the river (see RE 554 and RE 555), the higher level of the ground surface leads to an increase in thickness of the layer of fresh water that lies on top of the salt water. This area is not cultivated and is very sandy, so a fairly high proportion of the local rainfall will permeate through to the watertable. In this area there are at least three irrigation pumps (Bores 8, 9, and 10), which produce water with a salinity of about 800 p.p.m. It is suspected that at the end of the dry season, or after a long period of pumping, this salinity increases, but water should be replenished with fresh water by rain during the wet season. During tidal floods this area usually remains above water.

Summarizing: The distribution of salt and fresh water suggests that creeks and lagoons act as important channels for salt-water encroachment. Rainwater probably forms the main source of recharge. Hence, if more fresh water is pumped from the aquifer than comes in by rainwater soaking into the ground, salt-water encroachment takes place. This has caused the salting-up of Bores 1 and 2. The remedy is to adjust the amount of pumping to the annual intake from rainfall in the area. Small dams made with a bulldozer during the dry season across the downstream parts of Merryplain and Macdonald Creeks might prevent tidal inflow of salt water.

13. ANABRANCH SCHOOL AREA

INTRODUCTION

This area, shown in Figure 22, was investigated in detail with a series of resistivity depth probes and resistivity traverses with a constant electrode

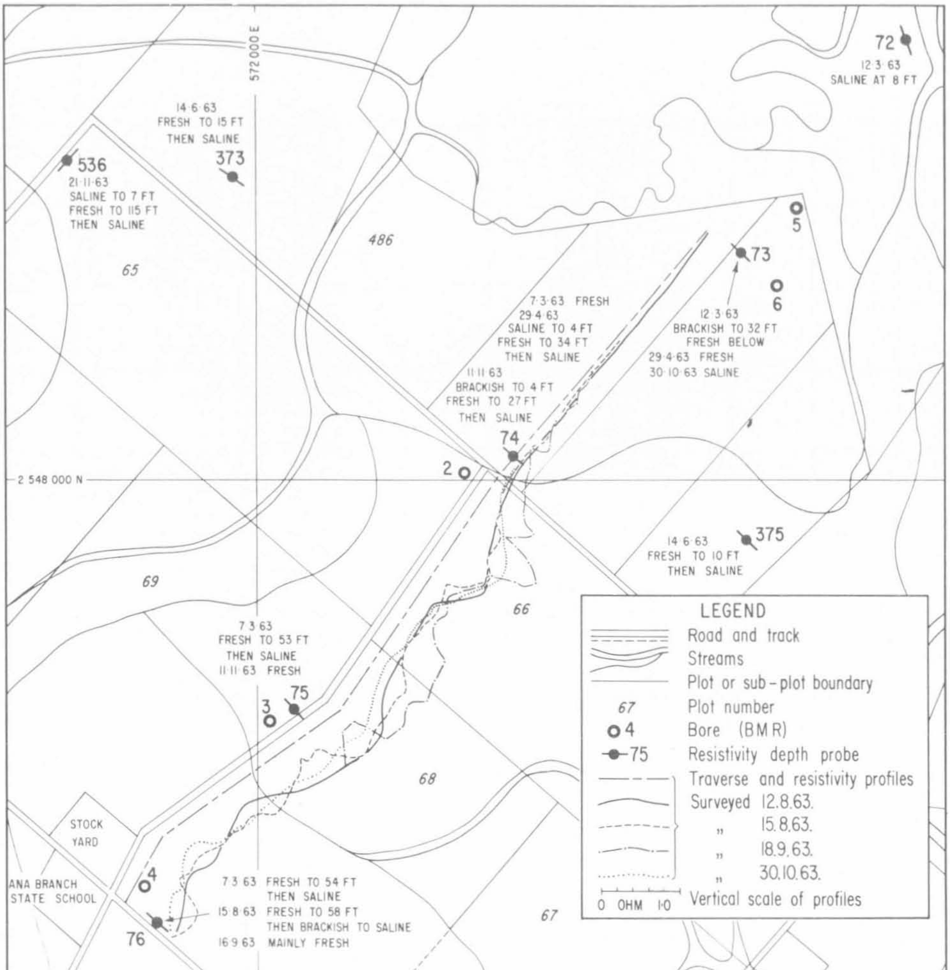


Fig. 22. Anabranch School area - resistivity traverses and depth probes

separation of 50 ft, and the measurements were repeated at intervals of several weeks.

Resistivity depth probes were repeated at a bore site during pumping tests to see whether the suspected movement of the freshwater/saltwater interface could be detected.

In another bore a series of fixed electrodes was used to measure the resistivity at different times to see how the salinity of the groundwater varied.

A series of shallow holes was drilled to supplement existing stratigraphic information. In boreholes BMR 17, 4, and 3 the section down to 30 ft is predominantly sandy; at BMR 2, 3, and 5 it is predominantly clay or mud.

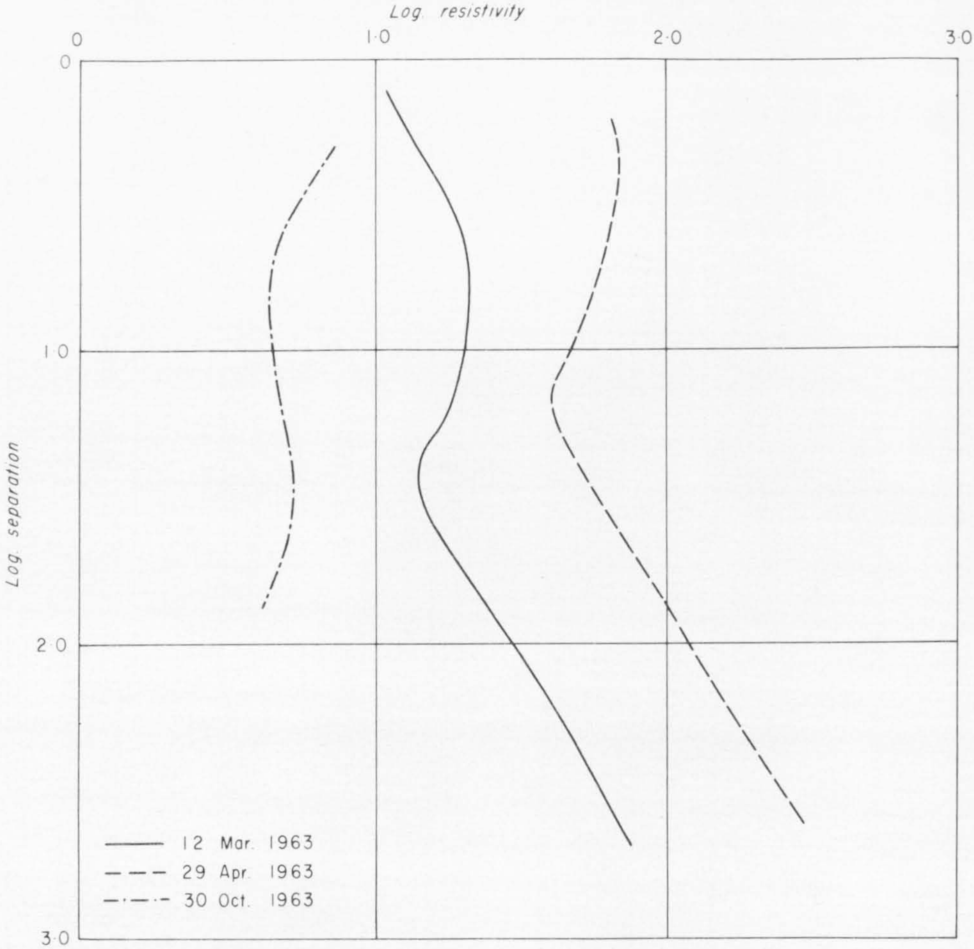


Fig. 23. RE 73 - depth probes at different dates

RESISTIVITY TRAVERSES

The results of resistivity traverses made with a fixed electrode separation of 50 ft between BMR 5 and BMR 4 at four different times between 12 August 1963 and 30 October 1963 are shown in Figure 22 using the traverse line as a reference level.

To the northeast of RE 74, where drilling has indicated predominantly clay or mud, the apparent resistivities measured are all very low and correspond to saline mud or clay. About 1000 feet southwest of RE 74 the apparent resistivities rise to maximum values, decrease still further to the southwest, to relatively low values at a distance of about 1600 ft, and increase once more to a maximum opposite RE 75. From this point southwest to RE 76 values remain relatively high, the high apparent resistivity values being probably due to two factors: firstly a rise in the level of the ground surface, resulting in an increase in the thickness of dry ground above the water-table; and secondly to a decrease in the salinity of the groundwater.

The highest reading at the maximum 1000 ft southwest of RE 74 was obtained on 18 September 1963. At this time the surface of the ground was drier than on 12 August and 15 August, but not as dry as on 30 October, which implies that the salinity of the groundwater had increased between September and October.

The generally low values about 1600 feet southwest of RE 74 are associated with a watercourse which, although not showing above the ground, appears to act

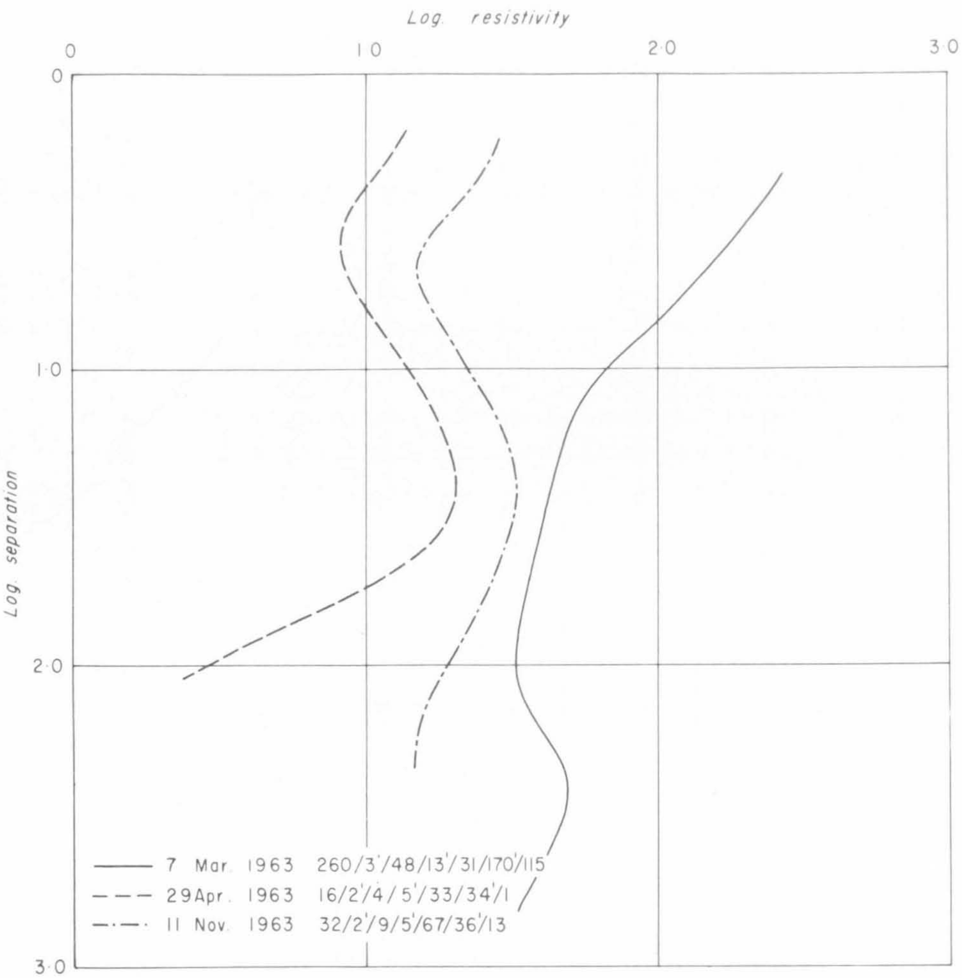


Fig. 24. RE 74 - depth probes at different dates

as a source of saline water below the ground. The maximum, near RE 75, is also associated with a slight topographic high, but between RE 75 and RE 76 there are no significant consistent variations in resistivity apart from a general increase which may indicate an improvement in water quality towards RE 76.

Repeated Resistivity Depth Probes

During 1963, depth probes at some points were repeated in an attempt to detect resistivity changes due to salt-water encroachment.

RE 73 (Fig. 23). Between 12 March and 29 April the resistivity at all levels increased, probably owing to salt being flushed from the sediments by fresh water as a result of the heavy rain that fell during this period. Although the measurements made on 30 October are of poor quality they are good enough to indicate that the resistivity of the groundwater fell by a factor of at least 10 over a period of six months, indicating a major encroachment of salt water.

RE 74 (Fig. 24). Between 7 March and 29 April the resistivity fell, suggesting that more saline water was washed into the area as a result of the rain. This depth probe is situated alongside a creek which flowed fresh water during the wet season and is in contact with tidal inlets periodically filled with salt water close by. By 11 November the quality of the water had improved, though it was still inferior to the quality in March. The depth probe interpretations given at the bottom of Fig. 24 (260/3'/48/13'/31/170'/115) mean a resistivity of 260 ohm-m to 3 ft, 48 ohm-m to 13 ft etc.

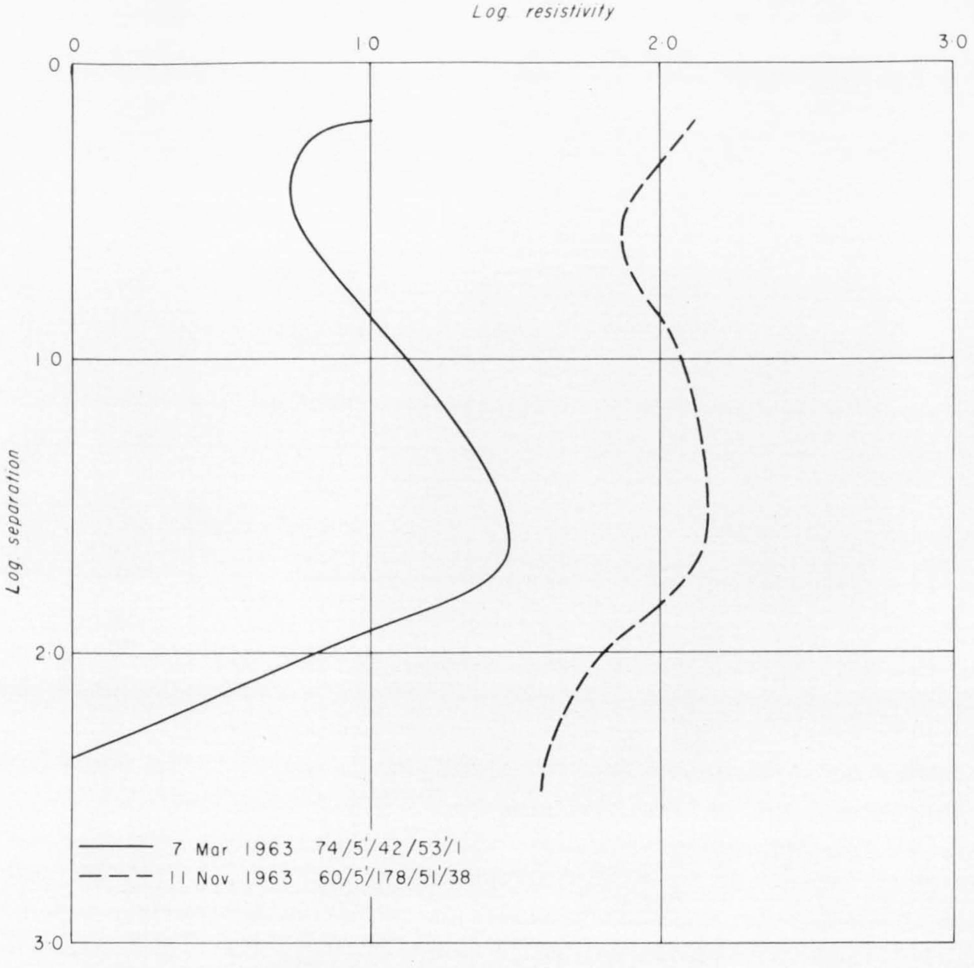


Fig. 25. RE 75 - depth probes at different dates

RE 75 (Fig. 25). Between 7 March and 11 November the water quality improved considerably. The resistivity below 50 ft increased from 1 ohm-m (representing a groundwater salinity of 9000 p.p.m.) to 38 ohm-m (representing a salinity of 800 p.p.m.).

RE 76 (Figs. 26, 27). Between 7 March and 15 August there was little change apart from a lowering of the level and a decrease in the salinity of the salt water. By 16 September there was a considerable difference; the top part of the curves showed a higher resistivity due to the drying-out of the near-surface material, while at intermediate depth there was a decrease in resistivity, indicating an increase in

FIXED PROBES

Fixed electrodes, consisting of bared wires wound round a 1" x 1" wooden pole at 1-foot intervals, were placed vertically in a borehole to a depth of about 20 ft, and successive groups of four electrodes were usd in a Wenner array to measure apparent resistivities. Figure 28 shows a plot of resistivity reading against depth for bore BMR 4 at various times. Readings above 7 ft are erratic, being above the water-table. The readings between 7 and 17 ft show the progressive decrease in resistivity, indicating a build-up of salt content in the water after the wet season. Another arrangement of fixed electrodes was used in conjunction with the pump test described below.

PUMPING INVESTIGATION

There is an irrigation pump adjacent to the centre of RE 76. On 16 and 17 September 1963, readings were taken at the depth probe while the pump was operating. The results of the readings are shown in Figure 27. The curve obtained before pumping and the two obtained during pumping were used to calculate the average curve for 16 September. (The other two readings were taken 1 hour and 2½ hours after pumping started.) After 10 hours pumping on 16 September the pump was stopped at 8 p.m., and restarted at 6 a.m. on 17 September. The two readings on 17 September were taken at 9.30 a.m. and at 3.45 p.m. It can be seen from the figure that initially the resistivity at depth increased, as saline water from the last time the pump had been used was flushed out. Thereafter the resistivity decreased again to below that of the initial level, indicating that salt water was once again being drawn into the aquifer from which the water was being pumped.

The salinity of water samples from a depth of about 50 ft increased from about 1100 p.p.m. to about 2000 p.p.m. in the course of the pumping.

CONCLUSION

This detailed investigation of a small area brings out four points:

1. The quality of water in the ground varies considerably with time, indicating that there is encroachment and recession of salt water into freshwater aquifers.
2. The mouth of the Burdekin River and surface creeks within the tidal zone may act as a source of salt water both at and below the ground surface.
3. Where salt water lies beneath fresh water without an aquiclude to separate them, pumping will cause a rise in the salinity of the groundwater.
4. The results suggest that detailed investigations of the nature described above should be correlated with pumping data from neighbouring pumps and with rainfall data.

14. SHEEP STATION CREEK AREA

INTRODUCTION

The small area under consideration is situated about four miles northwest of Brandon, bordering the littoral mudflats on the northern edge of the Burdekin Delta, and was investigated during 1963.

For those plots situated close by the creek, irrigation water is pumped from the bed of the flood channel, over which little water flows in the dry season and which is dissected by a number of minor channels as well as the meandering main channel. The quality of water pumped from these sources deteriorated sharply in the last quarter of 1963.

Work carried out included a constant-spacing resistivity traverse, depth probes, and water sampling. The table below summarizes the information locally obtained.

Bore Number	Source of Information	Comments
Bore 1	F. Castellango - farmer	Depth of spear 18 ft.
Bore 2	F. Castellango - farmer	Depth of spear 30 ft.
Bore 3	M. A. Toll - farmer	Depth of spears 30 ft. Water-table 4-10 ft. Pumping at 50 000 gall/hr.
Bore 4	M. A. Toll - farmer	Depth of spear 35 ft. Water-table 4-14 ft. Pumping from minor creek at 30 000 gall/hr. Water quality in early winter 342 p.p.m.

RESULTS

Water of good quality at depths down to 100 ft was proved at RE 356A in May 1963. In general, however, by November 1963 the area was one of brackish to salty water, particularly in and close to Sheep Station Creek, with fresh water in places at depths of 13 to 35 ft. The resistivity traverse TS1 (Fig. 29) demonstrates a correlation between resistivity highs and topographic highs across the stream channels which comprise the Sheep Station Creek system at this point. East of the main channel the traverse data suggest saline or brackish waters close to the surface, which is generally 10 ft lower than the topographic highs to the west. A pump is situated on the west bank of the main channel, from which brackish water is extracted at a depth of about 25 to 30 ft. The area is probably not tidal, except in the sense that tides may well force more brackish waters southward up the channel.

Such fresh water as exists in the immediate subsurface layers is probably replenished both by rain and by flood waters in the early months of the year, these effects being progressively obscured towards the end of the dry season. As in other areas marginal to littoral flats, the rate of pumping and the arrangement of spears are of critical importance to the water quality.

15. CONCLUSIONS

The results of the geophysical survey in the Burdekin Delta have shown the relative merits of the different techniques employed in this type of problem. The use of the gravity method, although of interest from a scientific point of view, has not furnished the practical information for which it was employed – namely, the form of the bedrock topography.

Seismic work has provided a great deal of information by delineating the basement topography and also by indicating the thicknesses and nature of consolidated bedrock, weathered bedrock, and potential aquifer layers. The seismic information on depth to bedrock generally agrees well with the available borehole data, and provides further control for the resistivity interpretations. The method of making seismic measurements at selected points rather than by using continuous traversing has enabled the whole area to be studied in sufficient detail at the minimum of cost.

Aided by seismic and stratigraphic control, resistivity has been used to differentiate between those areas suitable for artificial recharge (sands), and the contrasting low-permeability clay areas. Difficulty was experienced in differentiating between saline clay and sand except where the salinity of the pore-solution was known or where borehole information was available to provide both depth and porosity control. Repetition of resistivity work at selected marginal areas of the delta provides valuable information on salt-water encroachment; the use of fixed conductivity probes is of value in this connexion. Useful information has also been obtained by making gamma-ray logs in cased boreholes.

The contour plan of the basement (Plate 7) shows several channels within the delta which may be suitable for the distribution of any water put into them. It also shows that there is a possibility of water flowing from the Burdekin River into the Barratta Creek system to the west of Kellys Mountain. A future drilling program could resolve the nature and extent of such subsurface channels. There also

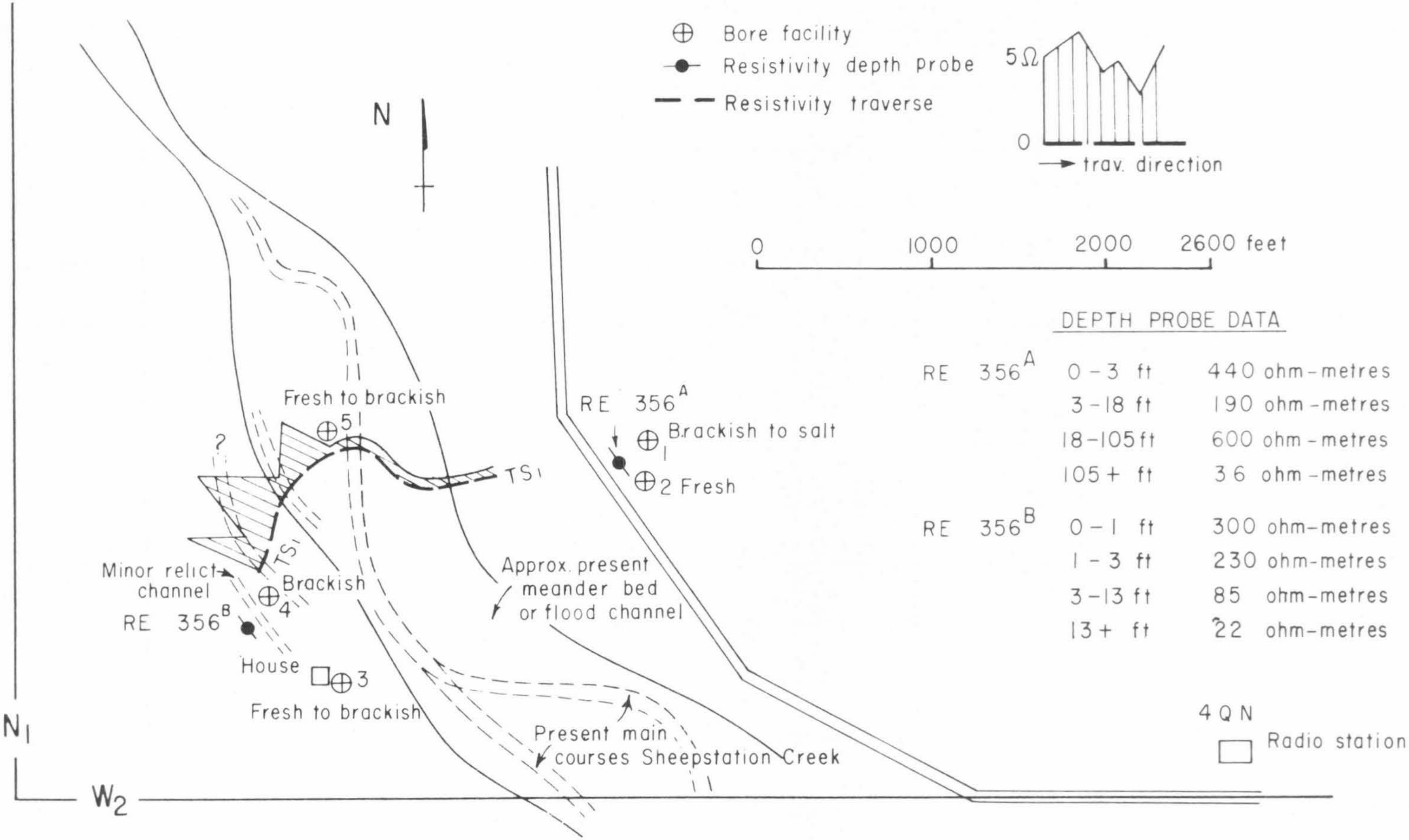


Fig. 29. Sheep Station Creek area - resistivity traverse and depth probe

appears to be a channel linking the Burdekin Delta area with the Barratta Creek system at W5/N1. Recent results from radioactive tracer tests show that the water in this channel is flowing northeast (Andrew et al., 1965).

Zones recommended as suitable for artificial recharge are indicated in Plate 12, where clay subsurface zones are differentiated from aquifers and particularly from dry or largely dry sand and gravel. The feasibility of recharge in such areas will be influenced by technical and economical considerations.

A number of surface dams have already been constructed to block off creeks and river channels; they have proved effective in helping to create freshwater zones by restricting the flow of fresh water outwards to the sea, and in some cases in restricting salt-water movements in tidal creeks.

It is significant that in 1963, which was a year of above average rainfall, there appears to have been a net increase in the amount of salt-water encroachment. To avoid further encroachment more fresh water will have to enter the aquifers. At present it appears that, even in times of flood, comparatively little water goes from the Burdekin River into the aquifers because of clay zones extending along part of the River.

16. REFERENCES

ANDREW, J.T.G., & WAINWRIGHT, M., 1964 - Giru underground water survey, Queensland 1963. *Bur. Miner. Resour. Aust. Rec.* 1964/111 (unpubl.).

ANDREW, J.T.G., & WIEBENGA, W.A., 1965 - Two-layer resistivity curves for the Wenner and Schlumberger electrode configurations. *Bur. Miner. Resour. Aust. Rec.* 1965/18 (unpubl.).

ANDREW, J.T.G., ELLIS, W.R., SEATONBERRY, B.W. & WIEBENGA, W.A., 1965 - The use of radioisotopes as groundwater tracers in the Burdekin Delta area of North Queensland, Australia. *Rep. Aust. At. En. Comm.* AAEC/E137.

BANCROFT, A.M., 1960 - Gravity anomalies over a buried step. *J. geophys. Res.* 65, 1630.

CALVERT, F.J., 1959 - Report on groundwater investigations Burdekin Delta, Burdekin River Basin to 30th September, 1959. *Irrigation & Water Supply Comm.* unpubl. report, reference from Watkins & Wolff, 1960.

CHRISTIAN, C.S., PATERSON, S.J., PERRY, R.A., SLATYER, R.O., STEWART, G.A., & TRAVES, D.M., 1953 - Survey of Townsville - Bowen region, North Queensland, 1950. *CSIRO Land Res. Ser.* No. 2.

DOBRIN, M.L., 1962 - GEOPHYSICAL PROSPECTING, 2nd ed., pp. 72-76. *New York, McGraw Hill.*

DYSON, D.F., & WIEBENGA, W.A., 1957 - Final report on geophysical investigations of underground water, Alice Springs, NT 1956. *Bur. Miner. Resour. Aust. Rec.* 1957/89 (unpubl.).

FAIRBRIDGE, R.W., 1961 - Eustatic changes in sea level. *In* PHYSICS AND CHEMISTRY OF THE EARTH, Chapter 4, p. 131.

GUYOD, H., 1947/1948 - Electrical logging developments in the USSR. Part 3, *World Oil*, Vol. 127 (10). Part 5, *World Oil*, Vol. 128 (2).

HUMMEL, J.N., 1932 - A theoretical study of apparent resistivity in surface potential methods. *Amer. Inst. Min. Metall. Trans. geophys. Prosp.* 97, 237.

I.W.S.C., 1964 - Progress report on the water resources of the Burdekin Delta, 1964. *Queensland Irrigation and Water Supply Commission.*

KUNETZ, G., undated - Principles of telluric prospecting. *Compagnie Generale de Geophysique.*

MAILLET, R., 1947 - The fundamental equations of electrical prospecting. *Geophysics*, 12, p. 529.

MOUNCE, W.D., & RUST, W.R., 1945 - Natural potentials in well logging. *Trans. Amer. Inst. Min. Metall. Eng.*, 164, pp. 288-294.

NETTLETON, L.L., 1940 - GEOPHYSICAL PROSPECTING FOR OIL. New York, McGraw-Hill.

NETTLETON, L.L., 1942 - Gravity and magnetic calculations. *Geophysics*, 7, pp. 293-310.

PARASNIS, D.S., 1962 - APPLIED GEOPHYSICS. Methuen Monograph.

SWARTZ, C.A., 1954 - Some geometrical properties of residual maps. *Geophysics*, 19, pp. 46-70.

TODD, D.K., 1959 - GROUND WATER HYDROLOGY. London, Wiley.

WATKINS, J.R., & WOLFF, K.W., 1960 - Burdekin Delta groundwater investigation, Interim Report. *Geol. Surv. Queensland.*

WETZEL, W.W., & McMURRY, H.V., 1936 - A set of curves to assist in the interpretation of the three-layer resistivity problem.

WHITEHOUSE, F.W., undated - A geological report on aspects of the Burdekin River Basin. Burdekin River Authority, unpublished report, reference from Watkins & Wolff, 1960.

WIEBENGA, W.A., 1955 - Geophysical investigations of water deposits, Western Australia. *Bur. Miner. Resour. Aust. Bull.* 30.

WIEBENGA, W.A., & MANN, P.E., 1962 - Bundaberg geophysical survey for underground water, Queensland 1960. *Bur. Miner. Resour. Aust. Rec.* 1962/74 (unpubl.).

KEY TO LOCATIONS OF RESISTIVITY DEPTH PROBES
e.g. Probe No. RE51 is near N3/W7

Probe	N	W	Probe	N	W	Probe	N	W	Probe	N	W
RE 1	8	4	RE 61	4	11	RE121	4	7	RE181	5	3
2	4	6	62	4	11	122	4	6	182	5	3
3	3	6	63	4	11	123	4	6	183	6	2
4	3	4	64	4	4	124	3	8	184	6	2
5	3	4	65	4	9	125	3	7	185	2	9
6	3	5	66	4	9	126	3	7	186	1	10
7	3	5	67	4	8	127	3	7	187	1	10
8	3	5	68	4	8	128	3	8	188	1	10
9	3	4	69	4	8	129	4	4	189	4	5
10	3	4	70	5	9	130	3	4	190	5	5
11	-	-	71	4	10	131	3	4	191	5	5
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21	1	6	81	7	5	141	4	4	201	3	8
22	3	10	82	7	5	142	4	4	202	2	9
23	3	10	83	7	5	143	4	4	203	6	5
24	3	10	84	6	5	144	6	8	204	6	4
25	-	-	85	6	5	145	6	8	205	6	4
26	-	-	86	6	4	146	6	8	206	7	4
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28	7	4	88	6	5	148	6	7	208	7	3
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59	-	-	119	4	7	179	6	3	239	5	11
60	4	10	120	4	7	180	5	3	240	6	10

Probe	N	W	Probe	N	W	Probe	N	W	Probe	N	W
RE241	5	11	RE301	7	7	RE361	7	9	RE421	8	9
242	6	11	302	7	7	362	8	10	422	7	9
243	6	8	303	7	7	363	8	10	423	5	9
244	6	8	304	7	8	364	6	2	424	5	8
245	6	11	305	7	7	365	7	2	425	7	11
246	6	11	306	7	7	366	6	2	426	7	11
247	6	11	307	8	7	367	7	3	427	5	10
248	7	11	308	2	5	368	7	3	428	8	10
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251	9	5	311	7	7	371	7	3	431	2	3
252	9	5	312	7	8	372	6	4	432	3	3
253	7	5	313	8	8	373	8	3	433	4	4
254	10	5	314	8	8	374	7	3	434	3	4
255	8	5	315	8	8	375	8	3	435	3	11
256	8	5	316	6	9	376	8	4	436	3	11
257	8	6	317	6	10	377	8	4	437	3	11
258	8	6	318	7	11	378	7	4	438	2	11
259	9	6	319	8	11	379	8	4	439	2	11
260	9	6	320	7	10	380	7	5	440	4	5
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262	8	6	322	7	10	382	4	3	442	4	3
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264	8	6	324	2	3	384	6	4	444	5	3
265	4	9	325	3	3	385	6	6	445	5	11
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267	3	9	327	4	4	387	7	4	447	6	11
268	3	9	328	4	4	388	7	4	448	6	11
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272	3	10	332	3	3	392	8	6			
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274	3	10	334	2	4	394	9	7	500	1	3
275	2	11	335	2	3	395	5	8			
276	2	10	336	2	3	396	7	8			
277	4	10	337	2	2	397	7	9			
278	2	10	338	2	2	398	8	9			
279	2	11	339	3	8	399	8	9	509	1	3
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281	1	11	341	4	7	401	8	10			
282	1	11	342	4	7	402	7	11			
283	1	10	343	6	4	403	8	11			
284	5	8	344	6	4	404	8	11			
285	5	9	345	6	4	405	8	11			
286	5	10	346	3	8	406	3	2			
287	4	10	347	3	8	407	3	2			
288	4	10	348	3	9	408	2	3			
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300	6	7	360	7	9	420	7	9	540	7	5

Probe	N	W	Probe	N	W	Probe	N	W	Probe	N	W
RE541	3	2	RE			RE611	2	2	RE631	3	4
542	3	2				612	2	1	632	2	3
543	3	2				613	6	2	633	1	4
544	4	2				614	7	7	634	1	5
545	8	8				615	8	7	635	2	4
546	7	10				616	7	7			
547	6	9				617	6	7			
548	9	11				618	7	8			
549	-	-				619	8	8			
550	8	10	600	7	6	620	8	8			
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552	9	9	602	8	6	622	6	5			
553	-	-	603	8	3	623	7	5			
554	9	8	604	7	5	624	7	4			
555	9	8	605	8	8	625	6	4			
556	9	8	606	6	6	626	6	4			
557	8	8	607	7	5	627	7	4			
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559	-	-	609	6	6	629	9	7			
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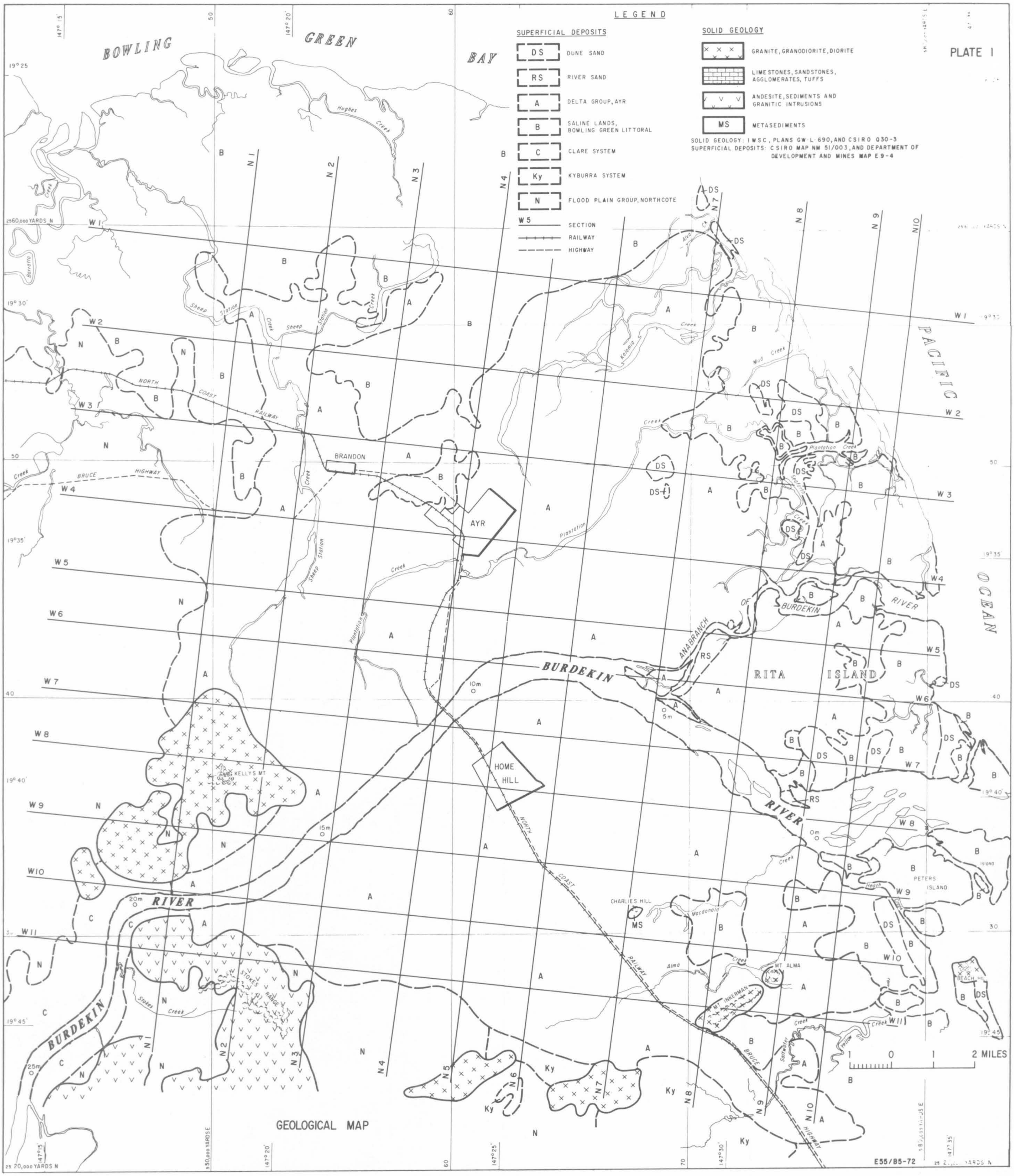


PLATE I
LEGEND
SUPERFICIAL DEPOSITS
DS DUNE SAND
RS RIVER SAND
A DELTA GROUP, AYR
B SALINE LANDS, BOWLING GREEN LITTORAL
C CLARE SYSTEM
Ky KYBURRA SYSTEM
N FLOOD PLAIN GROUP, NORTHCOTE
W5 SECTION
RAILWAY
HIGHWAY
SOLID GEOLOGY
GRANITE, GRANODIORITE, DIORITE
LIMESTONES, SANDSTONES, AGGLOMERATES, TUFFS
ANDESITE, SEDIMENTS AND GRANITIC INTRUSIONS
MS METASEDIMENTS
SOLID GEOLOGY: IWSC, PLANS GW-L-690, AND CSIRO Q30-3
SUPERFICIAL DEPOSITS: CSIRO MAP NM 51/003, AND DEPARTMENT OF DEVELOPMENT AND MINES MAP E9-4
BOWLING GREEN BAY
PACIFIC OCEAN
BURDEKIN RIVER
ANABRANCH OF BURDEKIN RIVER
RITA ISLAND
PETERS ISLAND
BRANDON
AYR
HOME HILL
KELLYS MT
STOKES RANGE
CHARLIES HILL
MT ALMA
MT INKERMAN
BEACH HILL
NORTH COAST RAILWAY
BRUCE HIGHWAY
Hughes Creek
Sheep Station Creek
Plantation Creek
Kalamia Creek
Mud Creek
Alva Creek
Macdonald Creek
Alma Creek
Stokes Creek
Saltwater Creek
Barratta Creek
1 0 1 2 MILES
GEOLOGICAL MAP
E55/B5-72

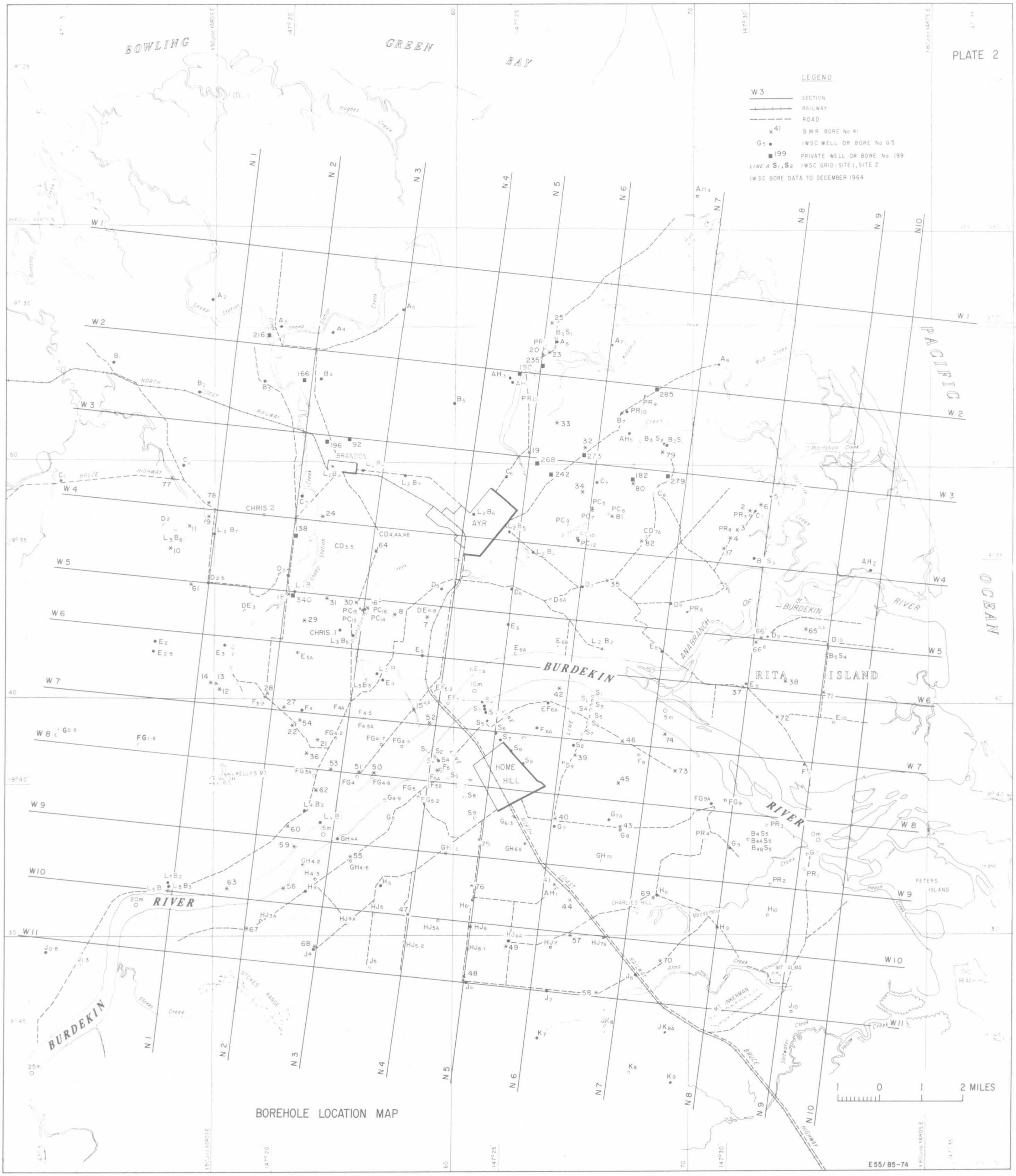
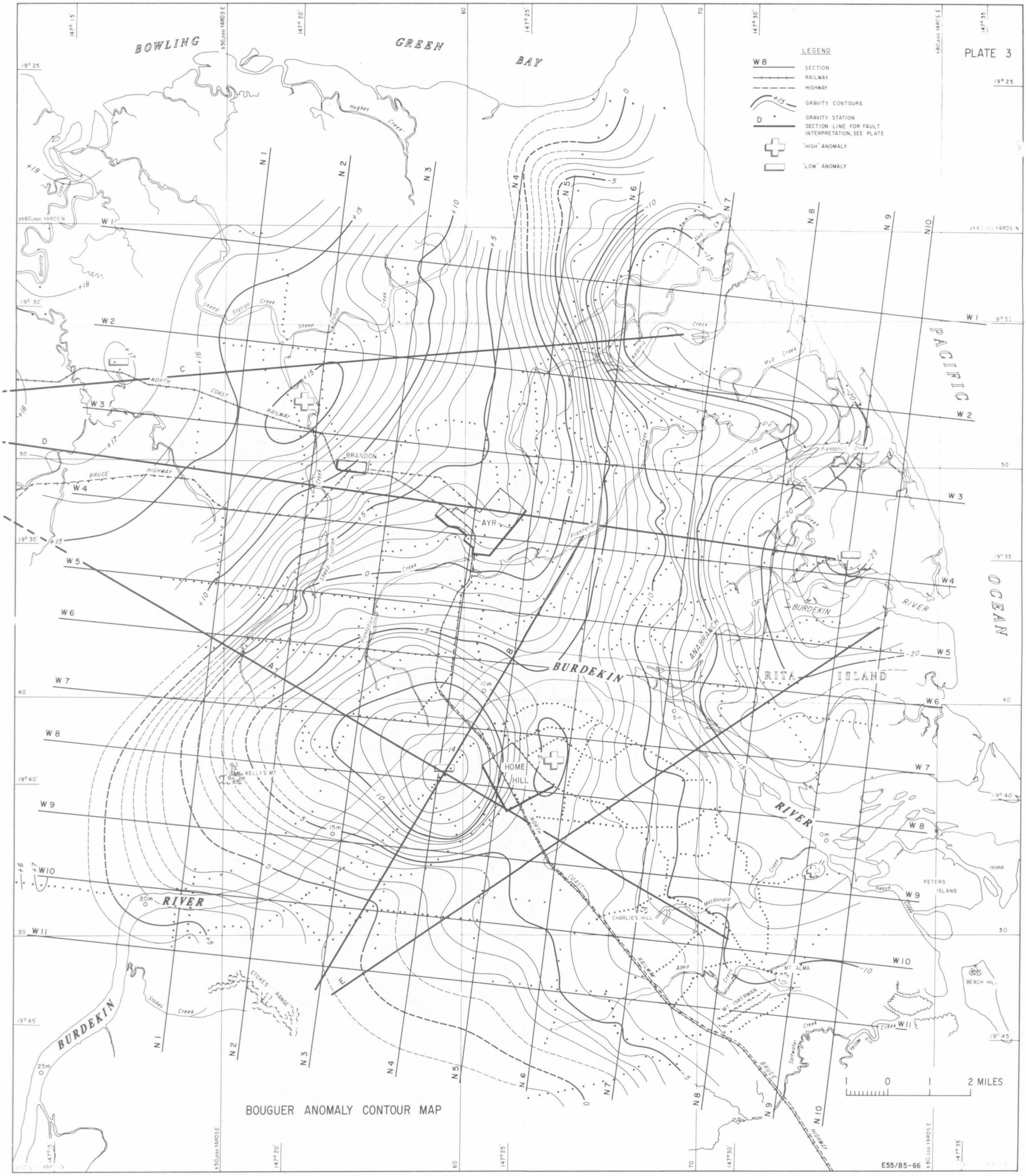


PLATE 2
LEGEND
W3 SECTION
RAILWAY
ROAD
41 B.M.R. BORE No 41
G5 IWSC WELL OR BORE No G5
199 PRIVATE WELL OR BORE No 199
LINE A S1, S2 IWSC GRID-SITE 1, SITE 2
IWSC BORE DATA TO DECEMBER 1964
BOWLING GREEN BAY
PACIFIC OCEAN
BURDEKIN RIVER
ANABRANCH OF BURDEKIN RIVER
RITA ISLAND
AYR
HOME HILL
BRANDON
PETERS ISLAND
CHARLIES HILL
MT ALMA
MT INKERMAN
NORTH COAST RAILWAY
BRUCE HIGHWAY
1 0 1 2 MILES
BOREHOLE LOCATION MAP
E55/B5-74



BOUGUER ANOMALY CONTOUR MAP


PLATE 4
LEGEND
W8 SECTION
RAILWAY
HIGHWAY
GRAVITY STATION
RESIDUAL GRAVITY CONTOURS
'HIGH' ANOMALY
'LOW' ANOMALY
BOWLING GREEN BAY
PACIFIC OCEAN
BRANDON
AYR
HOME HILL
BURDEKIN RIVER
RITA ISLAND
ANABRANCH OF BURDEKIN RIVER
NORTH COAST RAILWAY
BRUCE HIGHWAY
KELLYS MT
STOKES RANGE
CHARLES HILL
MT ALMA
MT INKERMAN
PETERS ISLAND
BEACH HILL
1 0 1 2 MILES
RESIDUAL GRAVITY CONTOUR MAP
E55/B5-42

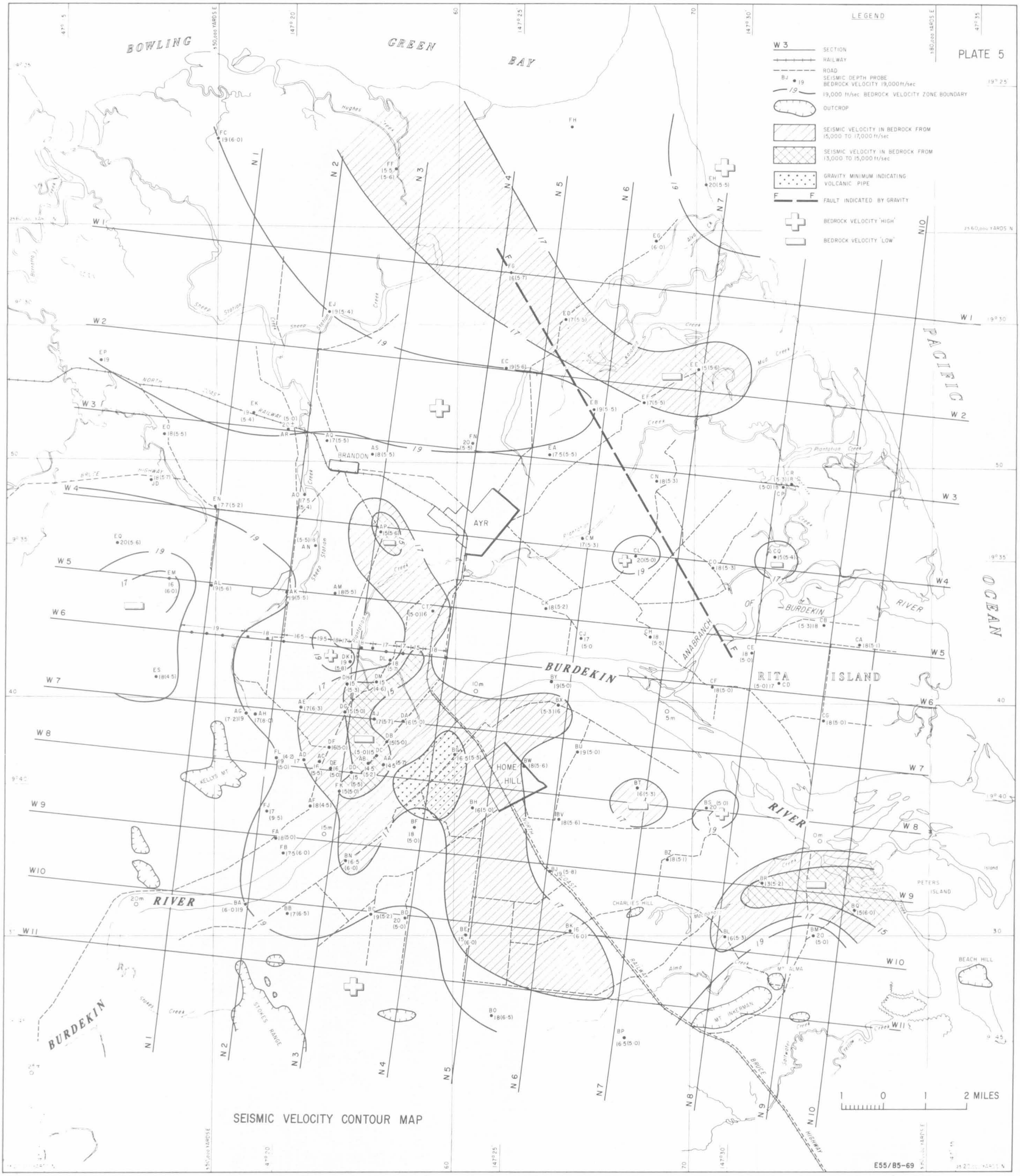
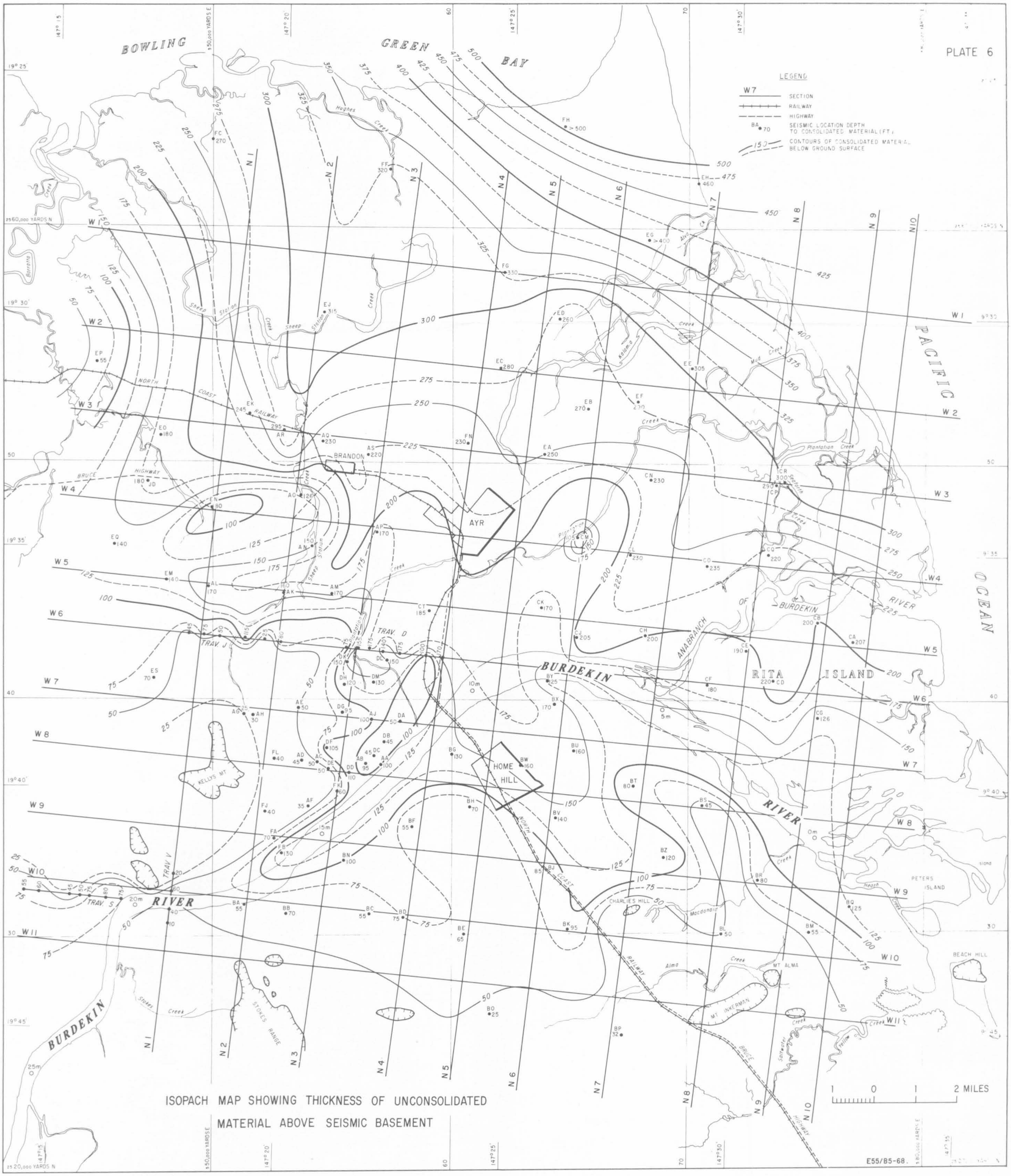
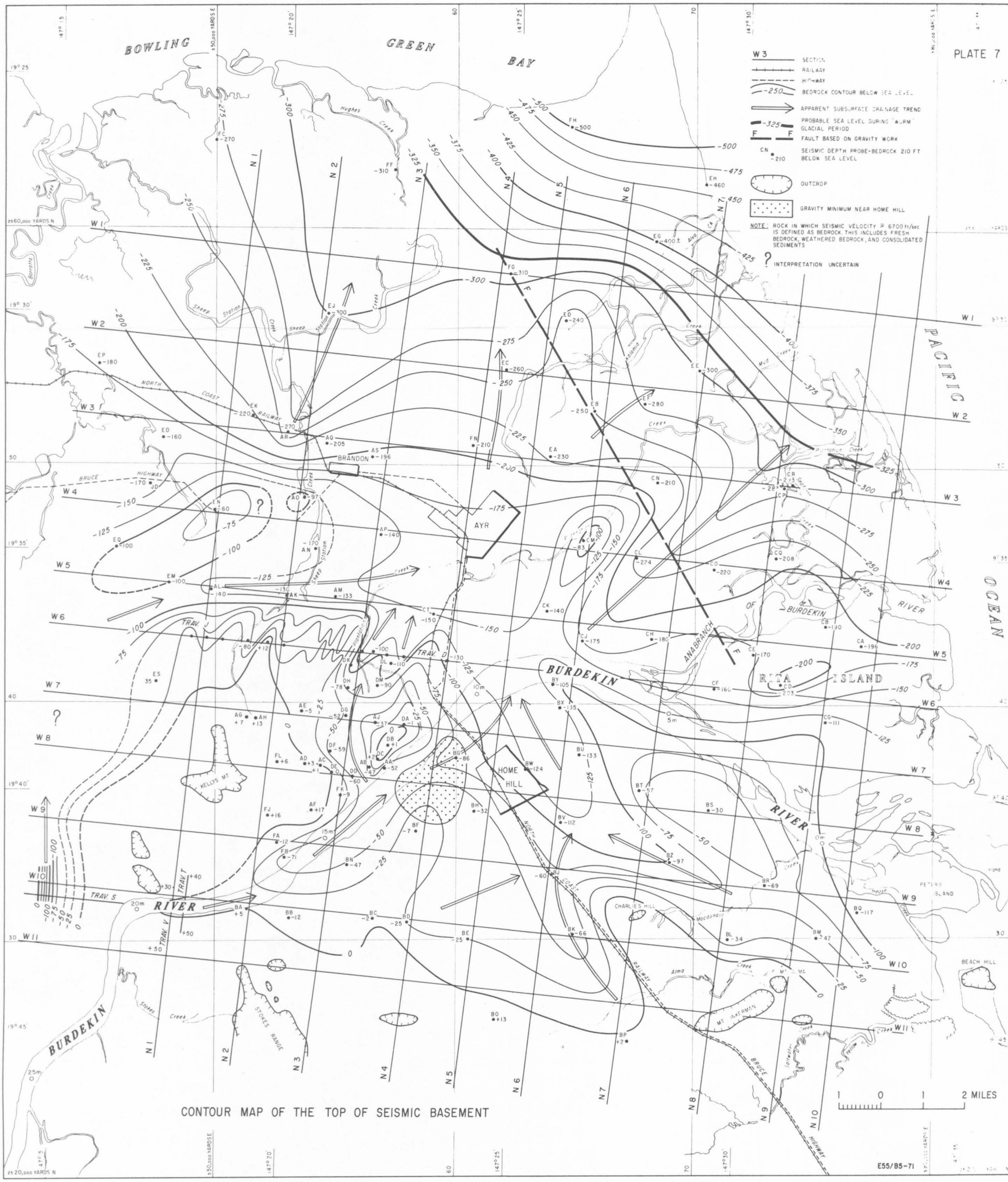


PLATE 5
LEGEND
SECTION
RAILWAY
ROAD
SEISMIC DEPTH PROBE
BEDROCK VELOCITY 19,000 ft/sec
19,000 ft/sec BEDROCK VELOCITY ZONE BOUNDARY
OUTCROP
SEISMIC VELOCITY IN BEDROCK FROM 15,000 TO 17,000 ft/sec
SEISMIC VELOCITY IN BEDROCK FROM 13,000 TO 15,000 ft/sec
GRAVITY MINIMUM INDICATING VOLCANIC PIPE
FAULT INDICATED BY GRAVITY
BEDROCK VELOCITY 'HIGH'
BEDROCK VELOCITY 'LOW'
BOWLING GREEN BAY
PACIFIC OCEAN
AYR
BRANDON
HOME HILL
BURDEKIN RIVER
ANABRANCH OF BURDEKIN RIVER
RITA ISLAND
KELLYS MT
STOKES RANGE
CHARLIES HILL
MT ALMA
MT INKERMAN
PETERS ISLAND
BEACH HILL
BRUCE HIGHWAY
1 0 1 2 MILES
SEISMIC VELOCITY CONTOUR MAP
E55/B5-69



ISOPACH MAP SHOWING THICKNESS OF UNCONSOLIDATED MATERIAL ABOVE SEISMIC BASEMENT

PLATE 7



CONTOUR MAP OF THE TOP OF SEISMIC BASEMENT

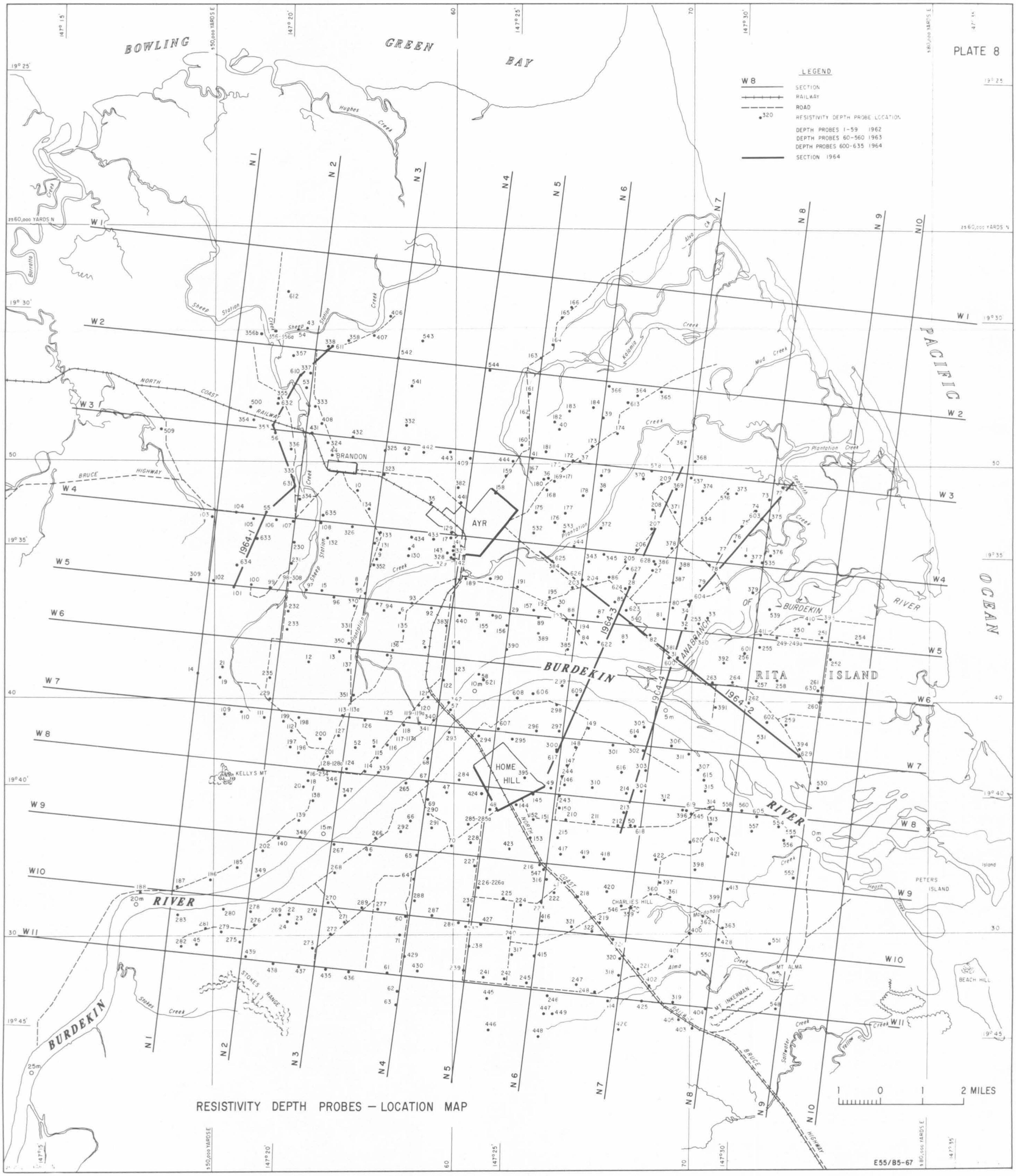
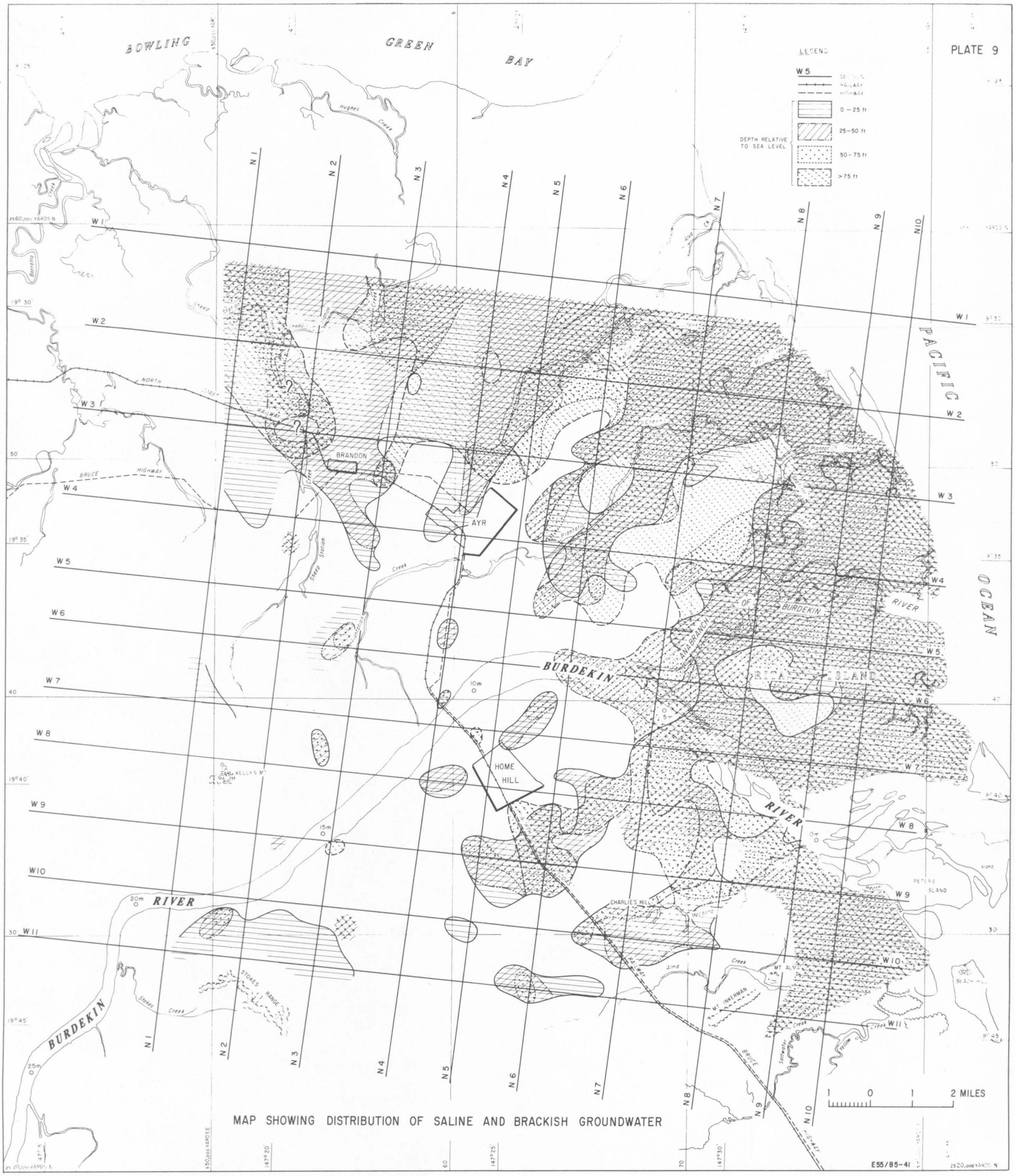


PLATE 8

RESISTIVITY DEPTH PROBES — LOCATION MAP

PLATE 9



MAP SHOWING DISTRIBUTION OF SALINE AND BRACKISH GROUNDWATER

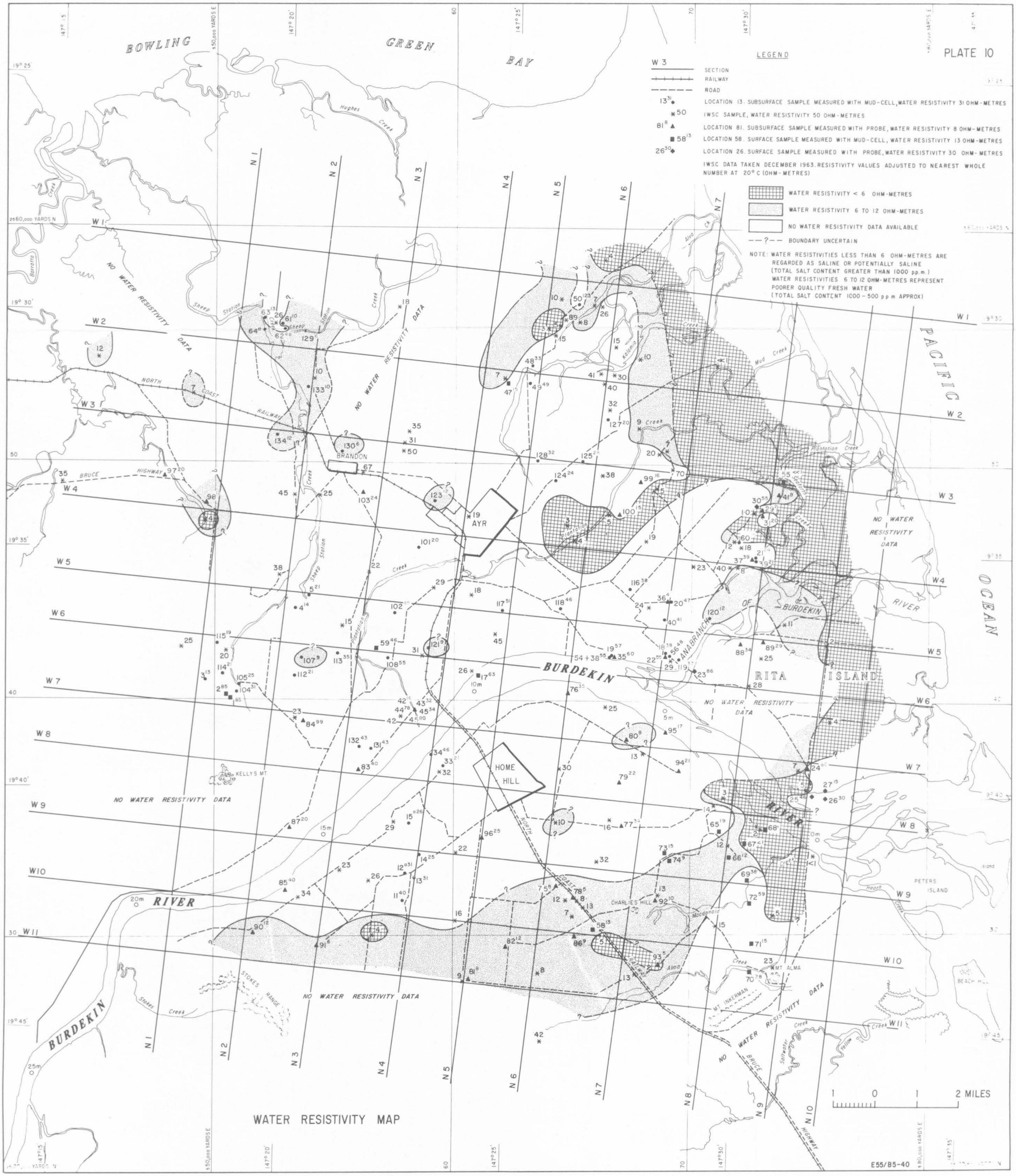


PLATE 10
LEGEND
W 3 SECTION
RAILWAY
ROAD
LOCATION 13. SUBSURFACE SAMPLE MEASURED WITH MUD-CELL, WATER RESISTIVITY 31 OHM-METRES
IWSC SAMPLE, WATER RESISTIVITY 50 OHM-METRES
LOCATION 81. SUBSURFACE SAMPLE MEASURED WITH PROBE, WATER RESISTIVITY 8 OHM-METRES
LOCATION 58. SURFACE SAMPLE MEASURED WITH MUD-CELL, WATER RESISTIVITY 13 OHM-METRES
LOCATION 26. SURFACE SAMPLE MEASURED WITH PROBE, WATER RESISTIVITY 30 OHM-METRES
IWSC DATA TAKEN DECEMBER 1963. RESISTIVITY VALUES ADJUSTED TO NEAREST WHOLE NUMBER AT 20° C (OHM-METRES)
WATER RESISTIVITY < 6 OHM-METRES
WATER RESISTIVITY 6 TO 12 OHM-METRES
NO WATER RESISTIVITY DATA AVAILABLE
BOUNDARY UNCERTAIN
NOTE: WATER RESISTIVITIES LESS THAN 6 OHM-METRES ARE REGARDED AS SALINE OR POTENTIALLY SALINE (TOTAL SALT CONTENT GREATER THAN 1000 p.p.m.)
WATER RESISTIVITIES 6 TO 12 OHM-METRES REPRESENT POORER QUALITY FRESH WATER (TOTAL SALT CONTENT 1000 - 500 p.p.m APPROX)
BOWLING GREEN BAY
PACIFIC OCEAN
NO WATER RESISTIVITY DATA
BRANDON
AYR
HOME HILL
BURDEKIN RIVER
ANABRANCH OF BURDEKIN RIVER
RITA ISLAND
PETERS ISLAND
CHARLIES HILL
MT ALMA
MT INKERMAN
BEACH HILL
KELLYS MT
STOKES RANGE
BRUCE HIGHWAY
NORTH COAST RAILWAY
1 0 1 2 MILES
WATER RESISTIVITY MAP
E55/85-40

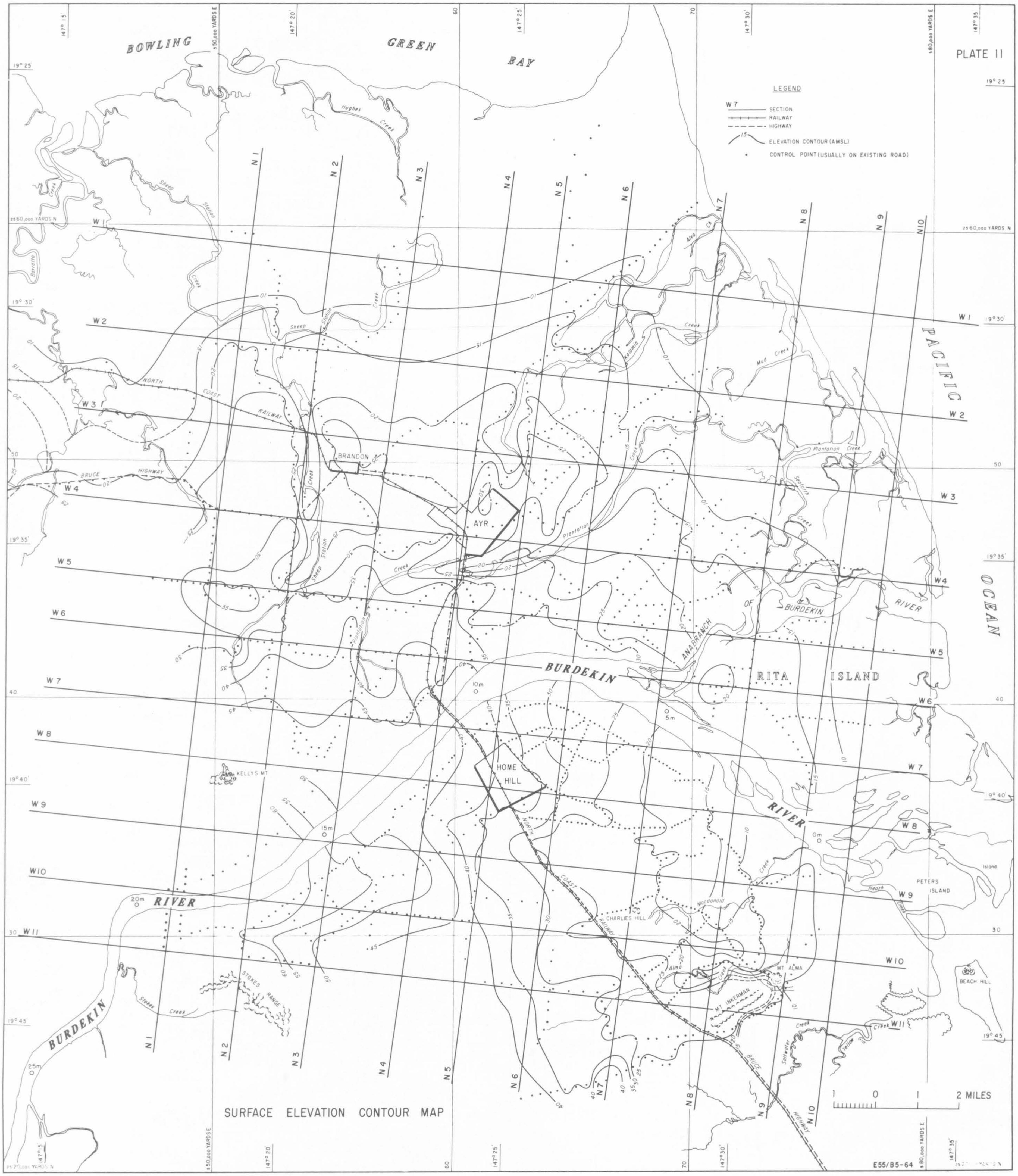
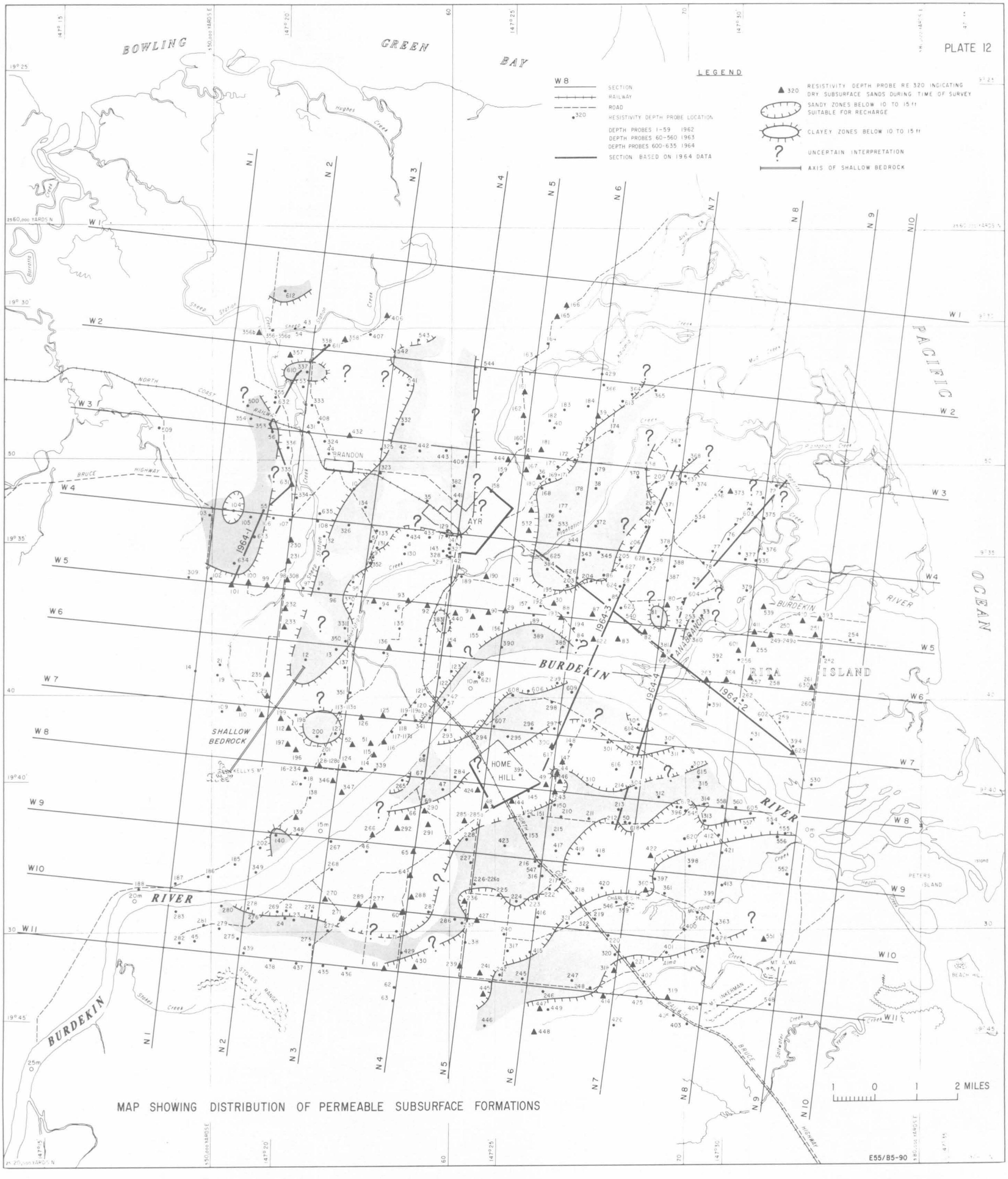


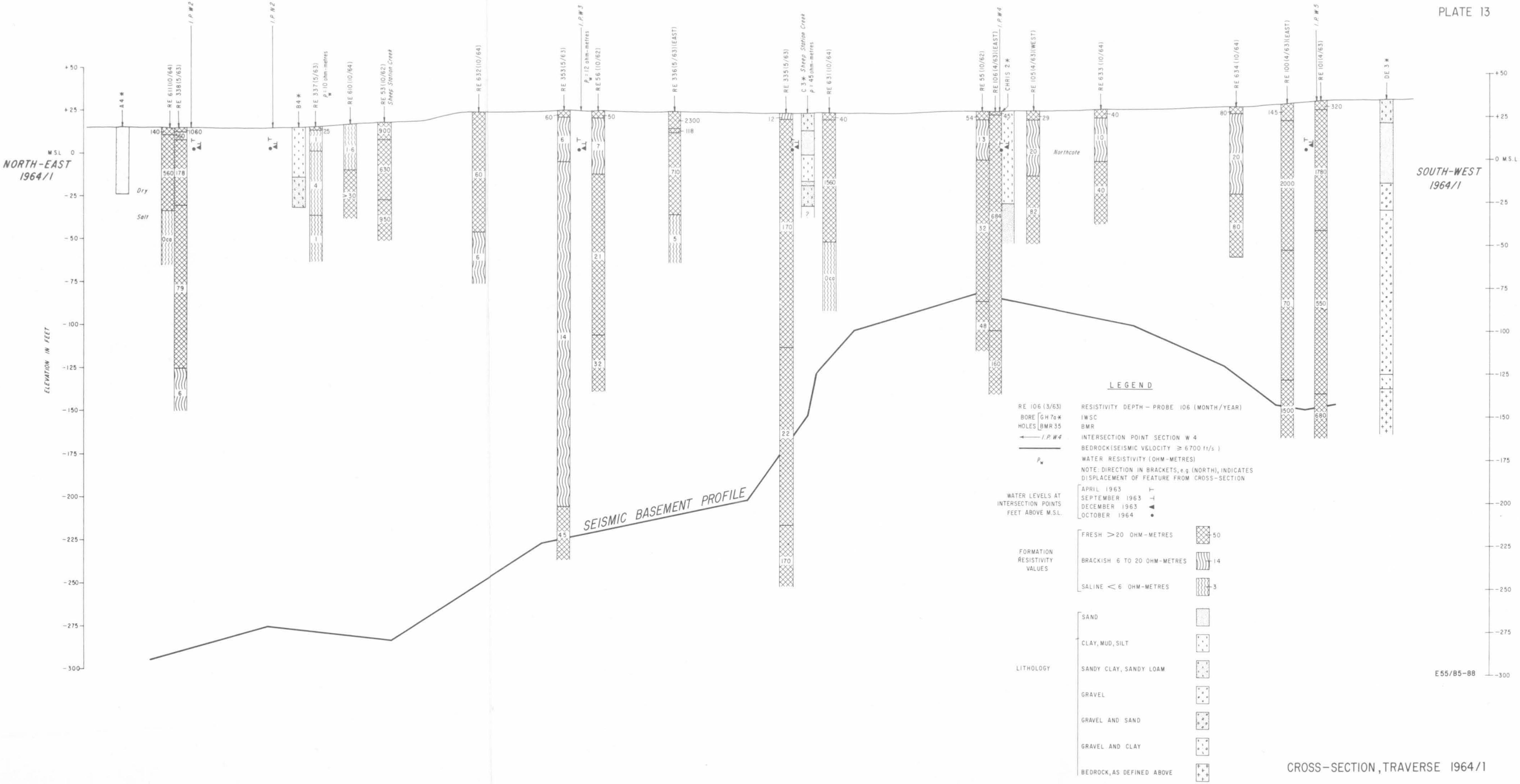
PLATE 11
BOWLING GREEN BAY
LEGEND
SECTION
RAILWAY
HIGHWAY
ELEVATION CONTOUR (AMSL)
CONTROL POINT (USUALLY ON EXISTING ROAD)
PACIFIC OCEAN
BRANDON
AYR
HOME HILL
KELLYS MT
CHARLIES HILL
MT ALMA
MT INKERMAN
STOKES RANGE
BEACH HILL
PETERS ISLAND
RITA ISLAND
ANABRANCH OF BURDEKIN RIVER
BURDEKIN RIVER
NORTH COAST RAILWAY
BRUCE HIGHWAY
1 0 1 2 MILES
SURFACE ELEVATION CONTOUR MAP
E55/B5-64

PLATE 12



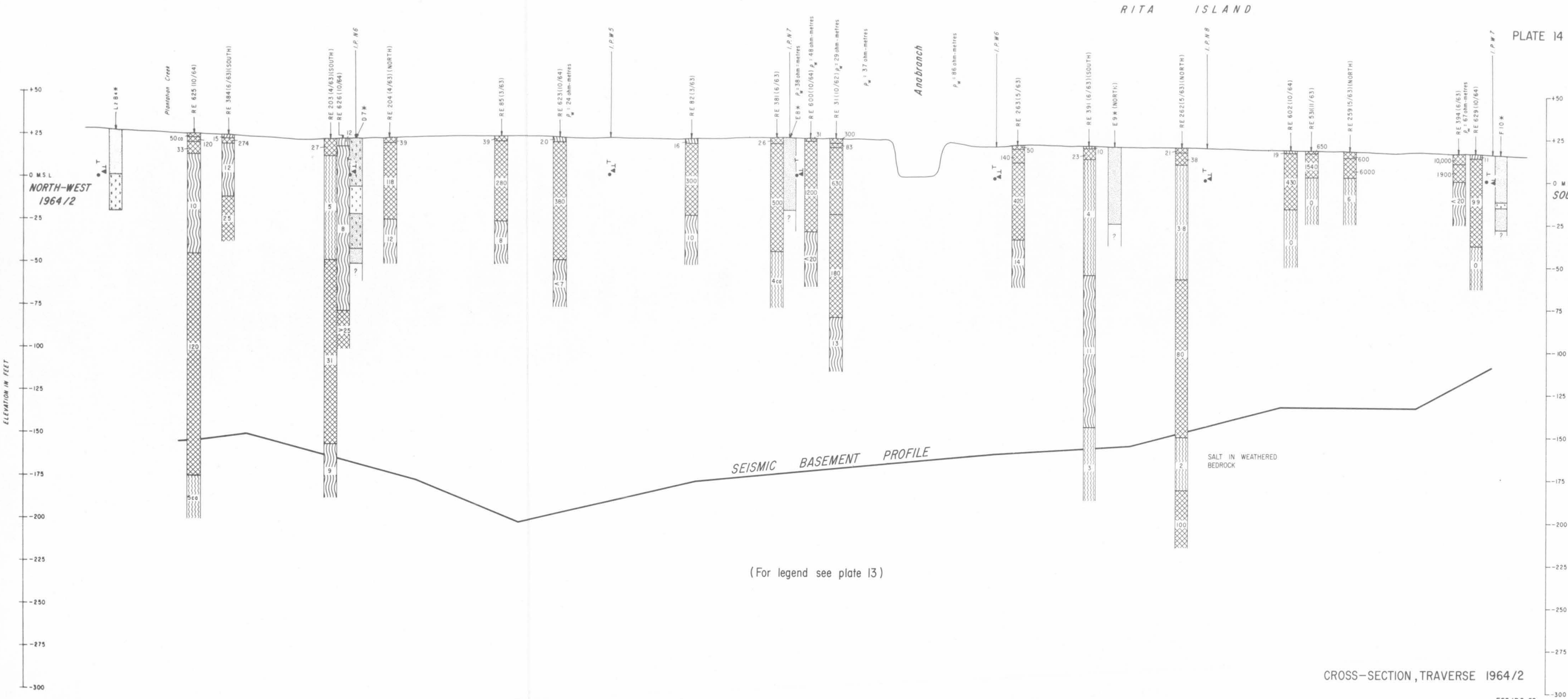
MAP SHOWING DISTRIBUTION OF PERMEABLE SUBSURFACE FORMATIONS

PLATE 13



CROSS-SECTION, TRAVERSE 1964/1

PLATE 14

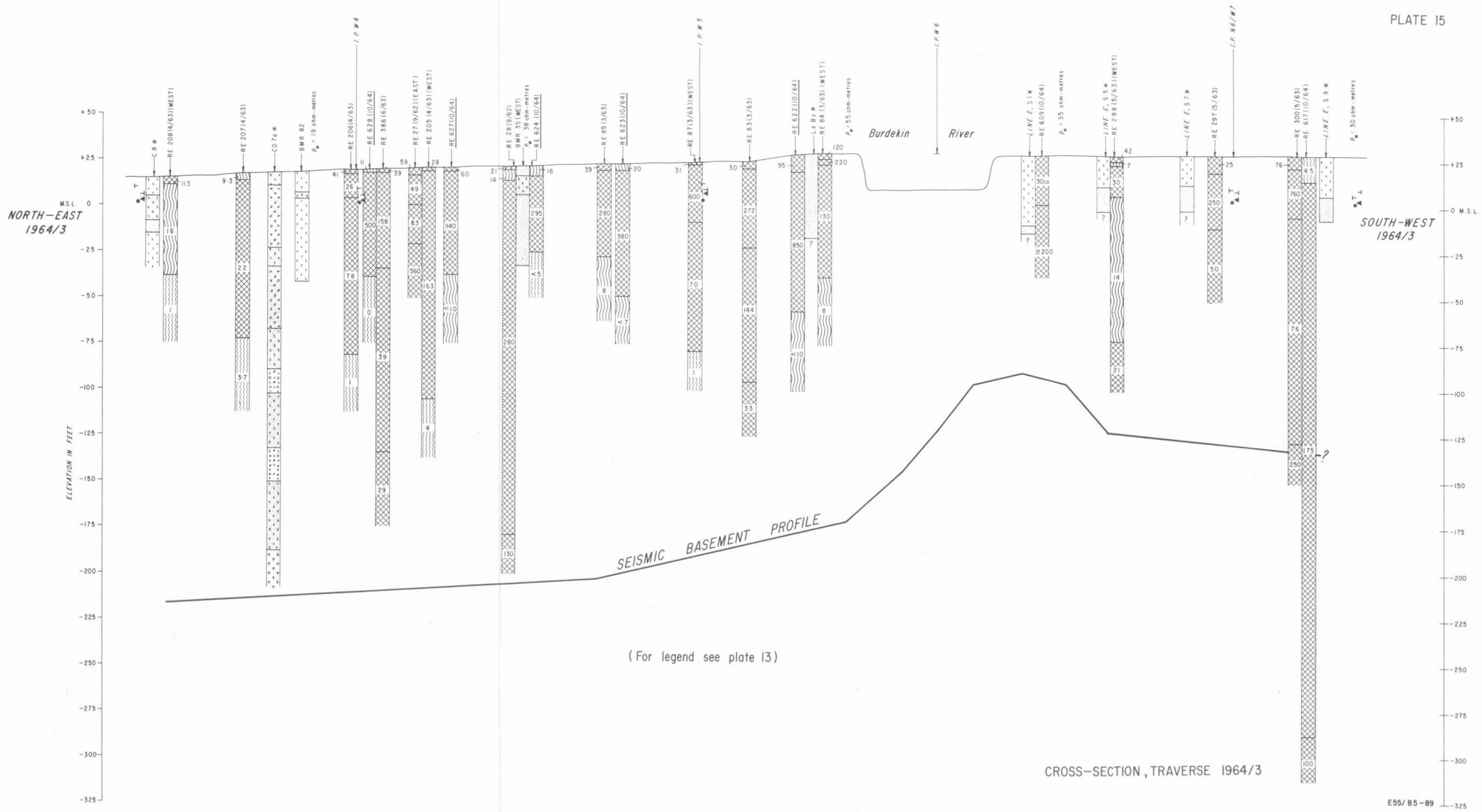


(For legend see plate 13)

CROSS-SECTION, TRAVERSE 1964/2

E55/B5-88

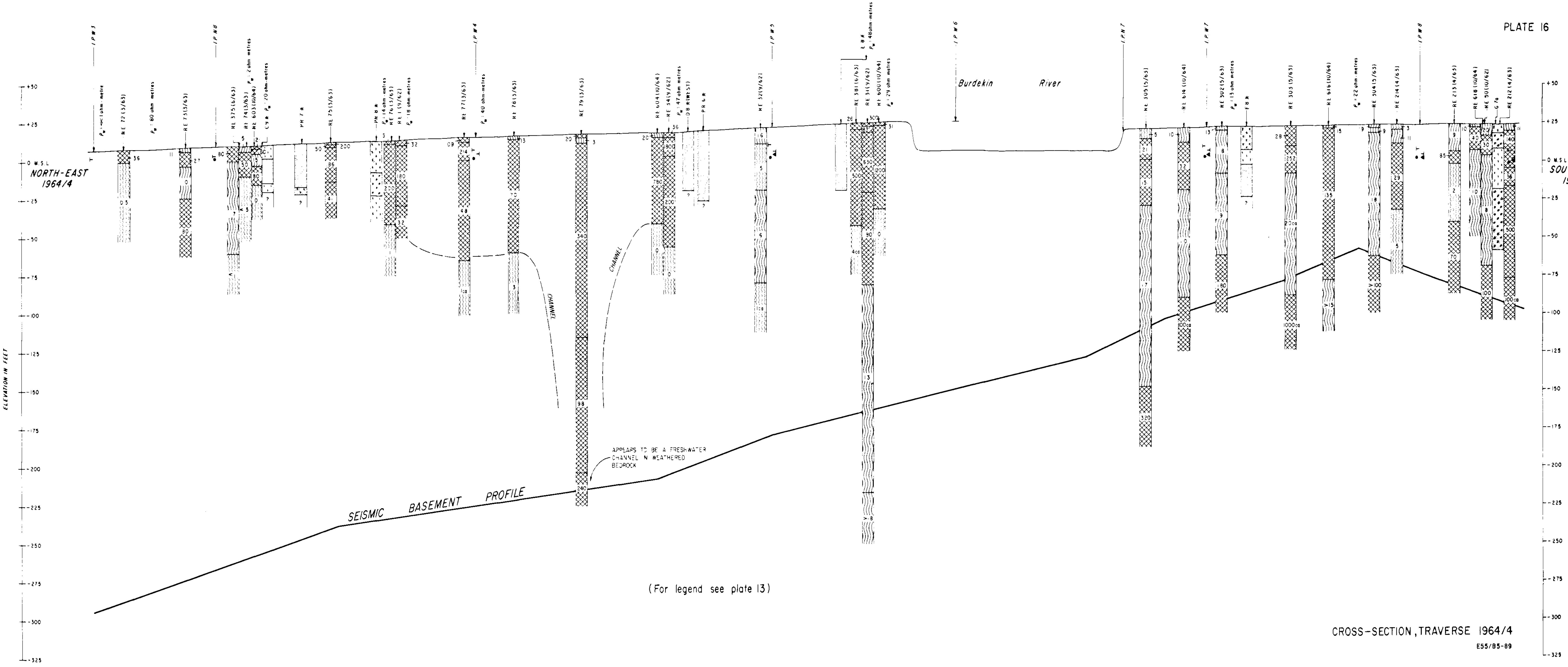
PLATE 15



CROSS-SECTION, TRAVERSE 1964/3

E55/B5-89

PLATE 16



CROSS-SECTION, TRAVERSE 1964/4

E55/B5-89