COMMONWEALTH OF AUSTRALIA

DEPARTMENT OF NATIONAL DEVELOPMENT
BUREAU OF MINERAL RESOURCES, GEOLOGY AND GEOPHYSICS

BULLETIN No. 30

GEOPHYSICAL INVESTIGATIONS
OF
WATER DEPOSITS, WESTERN AUSTRALIA

by

W. A. WIEBENGA

Issued under the authority of Senator the Hon. W. H. Spooner,
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Minister: Senator the Hon. W. H. Spooner, M.M.

Secretary: H. G. Raggatt, C.B.E.

BUREAU OF MINERAL RESOURCES, GEOLOGY AND GEOPHYSICS

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ILLUSTRATIONS

ABSTRACT

At the request of the Geological Survey of Western Australia, the Bureau of Mineral Resources, Geology and Geophysics provided geophysical staff and equipment to assist in the search for underground water supplies in certain areas of Western Australia where additional supplies are required for further development of the farming industry. The main objects of the survey were to test several types of resistivity equipment and to determine their limitations and optimum working conditions, to estimate the accuracy of depth determinations to formation discontinuities, to determine the nature of the discontinuities, and to estimate the degree of salinity of the ground water.

Results show that in 75 per cent. of the measurements made, errors in depth determinations were within $\pm$ 20 per cent. Although limited control data were available, it was often possible to recognize limestones, cementation zones in limestone, sands and ground-water levels, and in granite areas the transition from weathered to fresh granite was readily recognized. Where conditions were favourable, a satisfactory correlation was obtained between resistivity values and the salt content of solutions in a formation, provided the porosity of the formation was known.

Although the main object of the survey was not the finding of new underground water supplies, this was one of the aims in the Cue area, and a location was found where conditions for a large supply of good-quality water appeared to be favourable.

The resistivity meter which was used in the tests was developed by the Bureau of Mineral Resources, and operated very satisfactorily. The "Megger" earth tester was reliable up to electrode spacings of 100 feet.

The value of future test surveys for underground water would be greatly enhanced if more comprehensive bore information were available for correlation and combination with geophysical and geological observations. Such information should include the porosity and permeability of formations, screen analyses of samples, and salt content and resistivity of bore water.

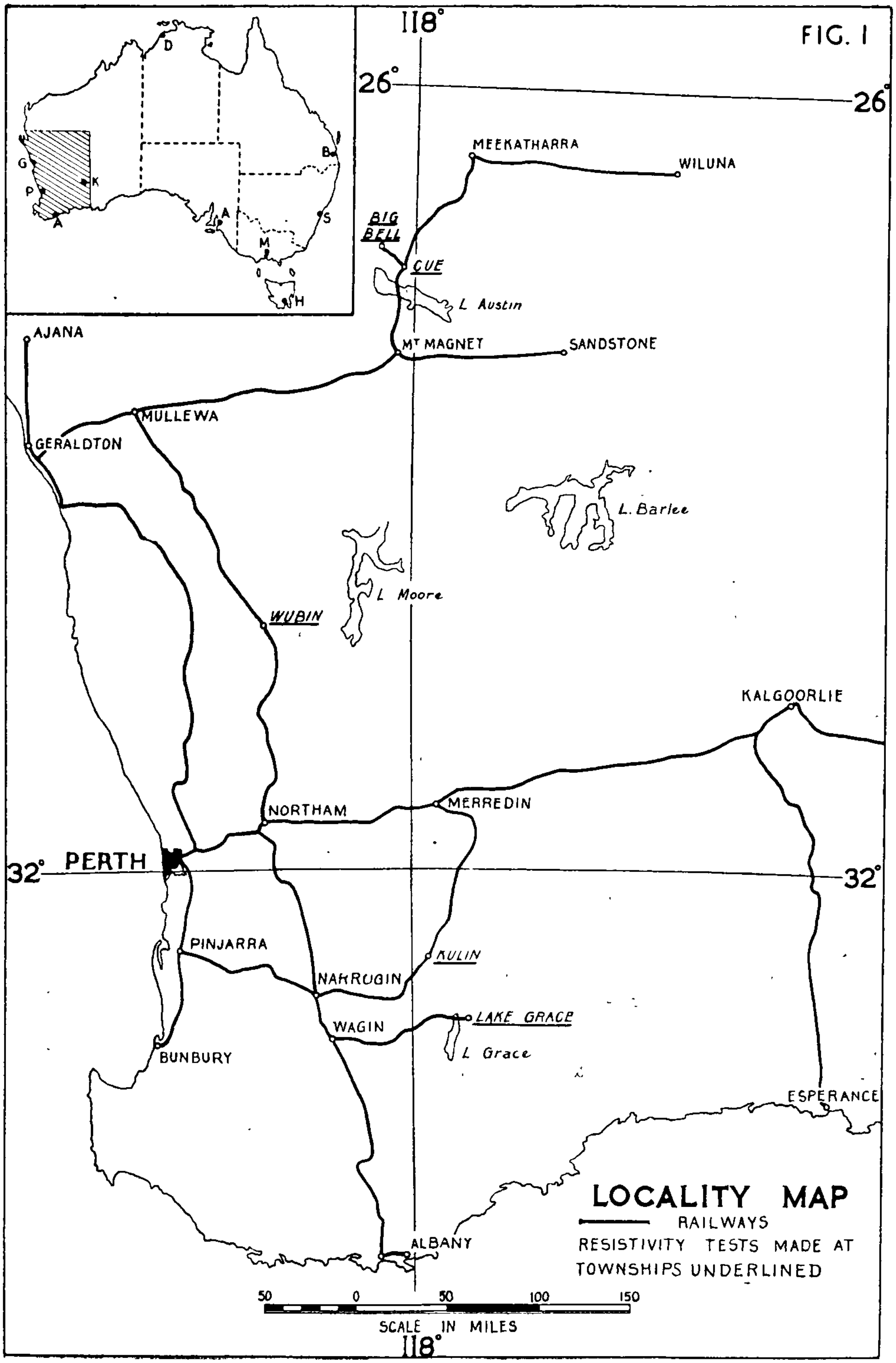
FIG. I
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GERALDTON
L. Barlee
L Moore
WUBIN
KALGOORLIE
NORTHAM
MERREDIN
PERTH
PINJARRA
KULIN
NARROGIN
WAGIN
LAKE GRACE
L Grace
BUNBURY
ESPERANCE
ALBANY
LOCALITY MAP
RAILWAYS
RESISTIVITY TESTS MADE AT TOWNSHIPS UNDERLINED
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SCALE IN MILES

GEOPHYSICAL INVESTIGATIONS OF WATER DEPOSITS, WESTERN AUSTRALIA

By W. A. WIEBENGA

INTRODUCTION

In the development of Australia's rural industries the rainfall and surface and underground water resources are factors of major importance. Thirty-four per cent. of Australia has a rainfall of less than 10 inches and this area is mainly desert and carries little stock. However, the livestock carrying capacity of areas with low and erratic rainfall can be considerably increased if potable water from underground resources is available.

In Western Australia the difficulties encountered in finding water for farming purposes prevent rational development of many rural areas. Also, in some places town water supplies are insufficient or the water is too saline.

Water resources may be classified as follows:—

1. Rain water from tanks or dams.
2. Water from bores or wells.
3. Water from old mine shafts (in mining districts).
4. Water from springs.
5. Water from rivers.

The present investigations are not concerned with the last two types of water supply. Water from tanks or dams is salt free and provides good drinking water, but dams are costly to construct, are subject to high evaporation losses and require a large catchment area. To make the catchment area effective it has to be cleared of vegetation and water gullies have to be ploughed at a cost of about £25 per acre (June, 1951).

To illustrate the extent to which the Government will go to provide adequate water supplies, a concrete dam was constructed across a valley in granite between Lake Grace and Newdegate. This dam, known as the Dingo Reservoir, has a capacity of 10,000,000 gallons and the cost of construction was approximately £30,000. The reservoir is connected with the railroad by a pipeline, about 5 miles long. During dry seasons water is tapped from the pipeline into rail water-tank waggons, transported to various distribution centres, transferred to tank trucks and eventually reaches the farm.

Water from bores is generally preferred because of the low cost of boring compared with the construction of dams. The cost of a shallow boring is approximately £1 per foot (1951). Furthermore, evaporation losses of underground deposits are low. However, in many localities sub-surface conditions are difficult to evaluate from surface topography and geology, and a fairly extensive drilling programme may be required before an underground deposit of potable water is found. Such a drilling programme is time-consuming and a heavy financial burden for the farmer. If modern geophysical methods could be applied to determine the underground conditions and locate deposits of water, a real advance would be made towards solving the problem. For this reason the Geological Survey of Western Australia asked for the co-operation of the Commonwealth Bureau of Mineral Resources, Geology and Geophysics in testing the resistivity method of survey. It was evident that if useful results were obtained these would be important not only for Western Australia but also for most arid areas of Australia. The resistivity method has been used successfully in Europe, U.S.A. and Africa during the past twenty years, but it is stressed that these successes were not easily obtained. They followed long periods of trial and error and were the result of many years of experience.

The work in Western Australia was done by a geophysicist from the Bureau in co-operation with the State Geological Survey. A geologist from the Survey worked as a member of the geophysical party to learn the field practice and to assist in the operations.

The following aims were set:—

1. To test several types of instruments, to determine their limitations and ranges and the optimum conditions for their operation.
2. To estimate the accuracy of depth determination to discontinuities which might be related to the geology.
3. To investigate the possibility of distinguishing the nature of the discontinuities, for example, decomposed granite, fresh granite, ground water level, &c., and the possibility of estimating whether ground water is fresh, brackish or saline.

The test areas were selected in the belief that sufficient bore data would be available to serve as controls. However, except at Austin Downs near Cue, and at Big Bell, the bore information was generally insufficient, vague and unreliable. With the exceptions mentioned above, adequate records had not been kept.

The Western Australia Geological Survey requested that special attention should be given to the water in decomposed granites in areas where the normal water in valleys appears to be saline. Potable water is usually found on the sides of the valleys in perched basins in the top boundary of the fresh granite. The depth to fresh granite is difficult to estimate from surface evidence and gross errors have been made by choosing bore sites in places where the depth was estimated at, say, 50–150 feet, whereas drilling proved it to be only a few feet. Such errors may be avoided by the use of geophysical methods, as will be shown in this report. The purpose of the geophysical survey was not primarily to search for areas with favourable ground water occurrences but to test the resistivity method in areas where information on the occurrence of ground water was available from existing wells and bores.

The following list indicates the areas selected and the number of test stations in each area:—

1. Wubin, 150 miles north-north-east of Perth	10 stations
2. Cue, 345 miles north-north-east of Perth	16 stations
3. Big Bell, 350 miles north-north-east of Perth ..	3 stations
4. Lake Grace, 180 miles south-east of Perth	20 stations
5. Kulin, 150 miles east-south-east of Perth	3 stations

The field work was done over a period of about three months.

METHODS

Although the tests were confined to the resistivity method and a small amount of magnetic work, it is appropriate to review other methods that might be used for underground water investigation.

Several geophysical methods other than the resistivity one can be used to locate underground water supplies and the relative merits of these are discussed below. To be successful, the method should not only solve the geological problems but must also be economical. The cost of the method should compare favourably with the relatively low drilling cost of £1 per foot. A substantial saving in the cost of finding water can be achieved if unsuccessful bores can be eliminated.

SEISMIC METHOD.

The seismic method depends on the degree of contrast in the elastic properties of the different strata. The method is particularly well adapted to depth determinations of horizontal or nearly horizontal strata. The principal objective is depth determination of elastic discontinuities. The physical laws involved resemble those of optical phenomena.

An explosive charge detonated on the ground produces a train of seismic waves. In the refraction method of survey, detectors are placed along a line and first arrival times of the waves are recorded. From these travel times the depths to different discontinuities are computed. In general, the depth to the water table and the basement can be determined fairly accurately. However, gradual transitions of velocities instead of sharp discontinuities may cause interpretation difficulties and introduce inaccuracy into the estimation of the thickness of the decomposed layers overlying the basement.

The advantage of the seismic method is that depth estimates are generally fairly accurate (accuracy about 10 per cent. of depth) but there are several disadvantages. The capital investment is fairly high, as a complete 6-channel outfit costs about £2,000. The speed of operation is fairly slow, resulting in high operational costs. In the areas investigated in Western Australia, the seismic method could probably not compete with the relatively low cost of shallow drilling. The staff requirements are one geophysicist, one assistant and two workmen.

A further disadvantage compared with the electrical resistivity method is that, though the depth of the water table may be determined accurately, no information is obtained regarding the salinity of the water.

On economic grounds the seismic method is not recommended.

GRAVITY METHOD.

The gravity method depends on the density contrast between formations, and has no great resolving power. If the density contrast between basement and overlying strata is known, the depth to the basement can be estimated accurately. Generally, the interpretation of the results improves in proportion to the amount of bore control available. Modern gravimeters are easy to operate and are very accurate.

A disadvantage of the method is that it requires an accurate topographical survey, and elevation measurements should be accurate within 0·5 foot. In general, the gravity method is suitable for tracing the undulations of a covered basement. One gravimeter costs about £4,000. The speed of operation is generally controlled by the speed of the topographical survey. A further disadvantage is that the only information which can be obtained is the depth to basement.

The advantage of the gravity method is low operational cost, generally 10-30 per cent. of that of a seismic survey.

Staff requirements are one geophysicist, one surveyor and one surveyor's assistant.

Because of its limitations and the extra work required for topographical survey the gravity method is not recommended.

MAGNETIC METHOD.

The magnetic method depends on the susceptibility contrast between formations and should therefore provide a means of determining the discontinuity between basement carrying magnetite and overlying strata. Magnetic anomalies indicate undulations of the basement (especially of shallow basement) and the sharpness of the anomalies is usually an indication of depth. The method has no great resolving power, and interpretation is often difficult. The field operation is extremely simple and fast. The capital investment is low—one vertical magnetometer costs about £400. The staff requirements are one magnetometer operator and assistant.

Used alone, the magnetic method is rarely adequate, but in combination with other geophysical methods it will often render additional and valuable information. For this reason and because of the low cost of operation, the magnetic method is recommended for use in combination with other geophysical methods (e.g. electrical) whenever the geological conditions appear favourable.

RESISTIVITY METHOD.

Outline of the Method and its Interpretation.

Several electrical methods are known and of these the resistivity method was thought to be the most suitable for the problems encountered in the search for shallow water deposits. The method depends on the fact that the different formations may be characterized by different electrical resistivities.

In the resistivity method, current is supplied to the ground at two points and the potential is measured between two additional points. The ratio of potential to current, multiplied by a spacing factor, gives what is known as apparent resistivity as a function of spacing and, hence, as a function of depth penetration. This application makes it possible to determine the depth to basement or bedrock, to water level and to beds of stratigraphic importance in general, as long as the formation boundaries are marked by changes of resistivity or resistivity discontinuities. The procedure is often called " electrical drilling ".

If the spacing (and therefore the depth penetration) is kept constant and the arrangement is moved as a whole, horizontal variations in character or variations in depth of a given formation may be determined. In " electrical drilling " the normal Wenner configuration is usually used. The four electrodes are equally spaced in line, the two inner electrodes being potential electrodes. For a homogeneous medium, the following equation holds:—

$$\rho = 2 \pi a \frac{V}{I} \quad \text{— — — — — — — — — — —} \quad (1)$$

where ρ = resistivity in ohm–centimetres
V = measured potential
I = current
a = electrode spacing in feet

If horizontal discontinuities in the sub-surface are present, the same expression is used, but the ordinary resistivity is replaced by the apparent resistivity, ρ_a, i.e.

$$\rho_a = 2 \pi a \frac{V}{I} \qquad \text{(1a)}$$

In the Wenner method, the electrode separation "a" is gradually increased from 1 ft 6 in (log a = 0·2) to say 400 ft. (log a = 2·6) by amounts which give equal increments of 0·1 in log a. For convenient interpretation, log ρ_a is plotted against log a on a scale of 1 unit in the logarithm = 2 inches. Theoretical two-layer type curves have been calculated and plotted on the same logarithmic scale. The shape of the two-layer curves is controlled by the parameter K, in which

$$K = \frac{\rho_2 - \rho_1}{\rho_2 + \rho_1} \qquad \text{(2)}$$

where ρ_2 = the resistivity in ohm–centimetres of the lower layer and ρ_1 = the resistivity of the top layer.

The use of logarithmic plotting enables a standard curve to be applied to any section of an observed resistivity curve. For a two-layer problem one of the type curves is fitted to the resistivity curve and the depth of the discontinuity and the resistivity of the lower layer can be estimated. The two-layer type curves may also be used in the interpretation of three-layer curves by making use of Hummel's relation, which states that the apparent resistances follow Kirchhoff's Law. For two infinite horizontal layers of resistivity ρ_1 and ρ_2 and respective thickness h_1 and h_2, the average resistivity for the two layers is given by:—

$$\frac{h_1 + h_2}{\rho_{av}} = \frac{h_1}{\rho_1} + \frac{h_2}{\rho_2} \qquad \text{(3)}$$

Curves with different K values, in which ρ_{av} is plotted against h_2 on a log scale, have been constructed. Using these curves the three-layer problem is reduced to a two-layer problem. Continuing this process an n–layer problem is reduced to a series of two-layer problems.

In this manner it is possible to estimate the depths to the different layers and their resistivities. It should be borne in mind that in a three-layer problem, the accuracy obtained by the application of Hummel's relation depends on the thickness of the middle layer. Further, the fitting of curves is somewhat ambiguous and consequently depth estimates sometimes ranges between wide limits.

The greater the number of layers present, the less accurate are the depth estimates. Generally, the interpretation can be improved considerably if it is known from previous measurements and experiences what resistivities are to be expected in the sub-surface formations. In the present work it was difficult to establish characteristic resistivities for the different sub-surface formations. A limited number of standard three-layer curves have been computed. A comparison of two-layer curve interpretation with three-layer interpretation shows that generally the tendency exists in using two-layer curves to make depth estimates too large. Therefore it is advisable to test the method first against known control data.

The theoretical curves prove that even for large differences in resistivity there is no abrupt change in apparent resistivity as the electrode separation " a " is increased. If irregular curves or breaks are obtained in the field, they are due to local conditions, usually in the surface layer, and must be eliminated before any interpretation can be attempted.

The resistivity method has been used with success in many countries to solve water supply problems. Generally, long periods of trial and error precede success which, to a large extent, depends on the interpreter's knowledge of the local geology. Advantages of the method are:—

1. Simplicity of equipment and operation.
2. Low capital investment.
3. With approximately horizontal formations the depths to discontinuities can be estimated with reasonable accuracy.
4. Resistivities of different formations can often be estimated with sufficient accuracy to enable the relative salinity of ground water to be deduced.

The staff requirements are one geophysicist, one assistant, and two workmen.

Equipment and Instruments.

The major items of equipment used in the resistivity survey comprised two Utilities, milliameter with current control panel (0–1 amp), D.C. potentiometer (Cambridge pH meter), multimeter, " Megger " earth tester, resistivity meter (designed by the Bureau), and twelve 45–volt B batteries. Miscellaneous items of equipment included insulated wire, porous pots, copper sulphate, cable reels, steel spikes, sledge hammers, tool kit, measuring tapes, survey compass, and wooden pegs.

In areas where the resistivity of the surface layer was very high, the maximum available voltage of 540 volts was applied.

A maximum electrode separation of 500 feet was used at first, but this did not appear necessary, and was subsequently reduced to 400 feet.

While measuring the potential between the two centre electrodes, the current through the two outer electrodes is maintained at a constant value by adjusting resistances in the current circuit on the control panel. Nevertheless, errors may be introduced as a result of—

1. Rapid decline of the energizing current due to polarization and electrolytic phenomena near the current electrodes (common during this survey).
2. Failure to read the current value simultaneously with the potentiometer.
3. Erratic and unpredictable variations of ground potentials in the potential measuring circuit.

To eliminate the first two of the above causes the Geophysical Section of the Bureau developed a new type resistivity meter, specially suitable for measuring low resistances. A field test of the instrument proved to be a success. Not only were the above-mentioned errors eliminated, but the speed of operation was considerably increased. The meter was used in the Cue and Wubin areas.

The " Megger " earth tester is a resistance meter in which the energizing current is generated by turning the crank of a small generator. To investigate the range of the " Megger," its performance was compared with the more reliable D.C. method, in which batteries are used. In the early part of the survey, seventeen " Megger " tests were made for comparison. The resistivity curves agreed for electrodes spacings up to 40 feet. During a later period another ten " Megger " tests were made. Better precautions were taken to establish good ground contacts. When necessary the number of spikes was doubled, and the spikes were driven deeper into the ground. In the later series of tests, agreement between resistivity curves was obtained with electrode spacings up to 100 feet. It can be said that with necessary precautions the " Megger " will be fairly reliable with electrode spacings of up to 100 feet, or for the determination of discontinuities not more than about 60 feet deep. The " Megger " is a small, handy instrument, and can be used as an engineering tool to replace auger drilling for investigating shallow bedrock.

Operational Difficulties.

Several difficulties were encountered during the survey, and in finding the causes of these and means of eliminating them, experience was gained which should be useful in future resistivity surveys:—

1. High resistance of the surface layers prevented sufficient current from entering into the ground. This was partly overcome by doubling the number of spikes used as current electrodes, and by driving the spikes as deep as possible into the ground, preferably to reach the moist level. Furthermore, it was realized that the voltage of the current supply should be increased, and that sufficient heavy-duty, dry batteries should be available to give up to 600 volts if necessary.
2. Rapid decline of the energizing current occurred due to polarization and electrolytic phenomena. Nothing much could be done to remedy this, except to wait until the current levelled off. Sometimes five minutes elapsed before an observation could be made.
3. High surface resistance often resulted in irregular and erratic potential measurements. It was found that this was caused by the moist level being one or more feet below the surface of the ground. This difficulty was solved by digging holes one to three feet deep for the porous pots. Sufficient water was used before the measurements started, to give a good " contact bowl " round the potential electrodes.
4. Self-potentials were sometimes as high as 100 millivolts. These high values were caused by putting the potential electrodes in different types of ground (different laterization zones). These self-potentials did not change appreciably during the observation time and were easily eliminated by making observations with reversed current.

WUBIN AREA (Fig. 2).

Geology and Water Occurrence.

Wubin is in the wheat belt, about 150 miles north-north-east of Perth. The topography, which is gently undulating, with flat-topped, rounded hills, separated by depressions, suggests a mature phase in the erosion cycle. The rainfall is about 12 inches per year, and the drainage is internal towards the salt lakes north-east of Wubin, which form the local erosion base. A typical geological section from surface shows sandy soil, some eluvial and/or alluvial deposits of small thickness, and a thick layer of decomposed (kaolinized) granite overlying fresh granite. The lower valleys are wide and are usually filled with alluvial deposits. The sub-surface water in the lower valleys is usually too saline to be used for irrigation or as drinking water for cattle and

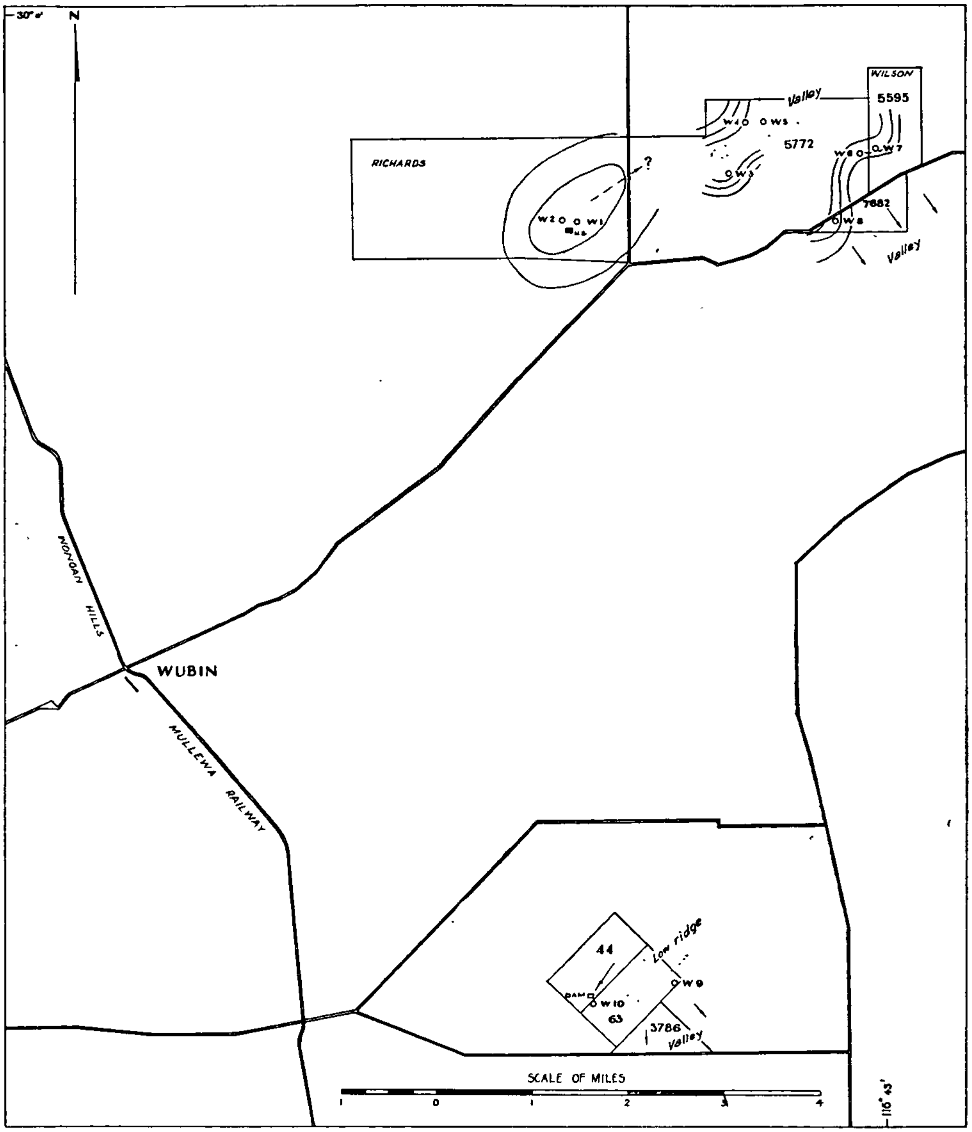

Fig. 2. Wubin Area: Location of Resistivity Stations.

sheep. The search for potable water in the Wubin area is therefore restricted to the higher valleys and depressions, which contain a negligible amount of valley filling of alluvial or eluvial material. The only potable water is within the kaolinized or decomposed granite, the existence of which has been clearly proved. Near test site W2, the rocks from a well still show the original granite structure. Kaolinized feldspar, with different graduations of kaolinization can also be distinguished. Near site W10 the rocks from a dam are entirely kaolinized gneiss, and the dump at the bore near site W3 shows kaolinized granite.

Decomposed granites have a low effective porosity and low permeability, and the yield of a bore in decomposed granite is therefore correspondingly low. Yields above 2,000 gallons of potable water per day are rare and are generally well below this figure. The yield is dependent on the thickness of the decomposed section and the level of the location of the bore in relation to the deeper valleys. The nearer the bore to the deeper valleys the higher is the yield but the greater is the chance of water of high salinity.

It may be questioned whether there is justification for investigating water deposits in weathered granite when bores can be expected to give only low yields (300–1,000 gallons per day) of potable water. However, the local farmers consider that bores of this type are a valuable source of stock water during dry periods, and that the considerable effort required to sink the bores is justified.

The resistivity observations were made near existing bores because the latter provide the only available control data. The data, however, were by no means complete, and consisted generally of the depth of the bore, sometimes the yield, the salinity of the water, and perhaps the water level in the bore, before pumping started. It could be assumed that boring was finished within the decomposed granite section or when the fresh granite was reached.

Results of the Individual Resistivity Tests (Plate 1).

Fig. 2 shows the locations of bores and wells near which resistivity tests were made. Each resistivity test will be referred to by the same number as the corresponding nearby bore or well.

Bore W1 and well W2 are about 100 yards apart and are near the centre of a bowl-shaped basin.

W1—Bore data.

Depth of bore .. .	51 feet.
Salinity	328 grains per gallon.
Yield	1,500 ± gallons per day.

The resistivity curve shows a high resistivity layer near the surface. Between 3 feet and 35 feet is a layer of log resistivity (hereafter called L.R.) 3·2 (1,600 ohm–cm.); between 35 and 50 feet is a low resistivity layer of L.R. = 2·6 ± (400 ± ohm–cm.).

Interpretation: Moist level or top of ground water level within decomposed granite at about 3 feet; relatively fresh water in decomposed granite between 3 and 35 feet; saline water between 35 and 50 feet and fresh granite at 50 feet.

The bottom of the bore at 51 feet probably indicates the depth to fresh granite. This figure agrees closely with the depth deduced from the resistivity curve.

W2—Well data.

Depth of well	40 feet.
Salinity	510 grains per gallon.
Yield	2,000 ± gallons per day.

The resistivity curve shows the complicated pattern of a five-layer curve. Between 1·5 and 7·5–12·5 feet is a fairly low resistivity layer; between 7·5–12·5 and 30 feet the resistivity is somewhat higher; between 30 and 52 feet is a very low resistivity layer of L.R. = 2·4 ± (250 ± ohm–cm.).

Interpretation: Moist level or top of ground water level at about 1·5 feet. Between 1·5 and 7·5–12·5 feet is a layer, which, from geological considerations, is probably alluvial material; between 7·5–12·5 and 30 feet is decomposed granite with fresh water; between 30 and 52 feet a layer of decomposed granite with saline water is indicated on top of the fresh granite. Note the similarity between the lower parts of the resistivity curves of W1 and W2.

W3 is on the hillside, fairly high above the valley floor. It is not certain that the bore is in decomposed granite; it might be in granite wash and kaolin.

Bore data.

Depth of bore ..	..	74 feet (fresh granite not reached).
Salinity	.. ..	151 grains per gallon.
Yield ..	.. ..	2,000 gallons per day.

The resistivity curve is a typical four-layer curve with discontinuities at 12 and 80 feet, and a thin, high resistivity layer near the surface. The L.R. of the layer between 12 and 80 feet is 2·85 ± (700 ± ohm–cm.).

Interpretation: A moist layer between surface and 12 feet; ground water level at about 12 feet; a layer with brackish water between 12 and 80 feet, and fresh granite at 80 feet.

W4 and *W5* are close to each other, W4 on the hillside and W5 in the middle of a valley.

W4—Bore data.

Depth of bore ..	..	49 feet.
Salinity	.. ..	570 grains per gallon.
Yield ..	.. ..	700 gallons per day.

At 20 feet a fresh water supply of about 200 gallons per day was obtained. The bore is in decomposed granite.

The resistivity curve indicates a steady lowering of the resistivity towards the top of the granite. Discontinuities are found at approximately 3, 9, 56, and 80–100 feet. The layer between 56 and 80–100 feet has a L.R. of 2·2 ± (160 ± ohm–cm.).

Interpretation: A moist layer between 3 and 9 feet; a layer with relatively fresh water between 9 and 56 feet; a layer with water of high salinity between 56 and 80–100 feet, and fresh granite at 80–100 feet. The transition between fresh and saline water is probably fairly gradual. The interpretation shows fair agreement with the available control.

W5 is in the centre of a valley containing fluviatile deposits and probably does not reach decomposed granite.

Bore data.

Depth of bore ..	..	40 feet.
Salinity	.. ..	Higher than 700 grains per gallon.

The resistivity curve indicates discontinuities at 1, 4·5, 45, and about 180 feet, but it is doubtful whether the discontinuity at 4·5 feet is a real one. The resistivity tends to decrease from the surface to the top of the fresh granite. The L.R. of the layer between 45 and 180 feet is about 2·7 (500 ohm–cm.).

Interpretation: The moist level is at about 4·5 feet. The valley floor is probably at about 45 feet and a layer of decomposed granite between 45 and 180 feet with saline water.

W6 is located on the hillside.

Bore data.

Depth of bore	70 feet.
Salinity	410 grains per gallon.
Total Soluble Salt (hereinafter called T.S.S.) ..	460 grains per gallon.

The resistivity curve shows main discontinuities near the surface, and at 2·5, 15, and 125–160 feet. The L.R. of the layer between 15 and 125–160 feet is about 3·15 (1,400 ohm–cm.).

Interpretation: Top of moist level at 2·5 feet; ground water level at 15 feet and the top of the fresh granite at 125–160 feet.

W7 is a few hundred yards east of W6 on the hillside.

Bore data.

Depth of bore	110 feet, bottom probably in fresh granite.
Water level at 70 feet ..	(?)
T.S.S.	821 grains per gallon.

The resistivity curve indicates discontinuities at 7, 32, and 85–110 feet. The L.R. of the layer between 32 and 85–110 feet is 2·5 ± (320 ± ohm–cm.).

Interpretation: Top of moist level at 7 feet; ground water level within decomposed granite at about 32 feet; water of high salinity between 32 and 85–110 feet, and the top of the fresh granite at 85–110 feet.

The bore is too deep. Relatively fresh seepage water would probably have been obtained if the bore had been stopped at 60–70 feet.

W8 is on the hillside, about three-quarters of a mile south of W6.

Bore data.

Depth of bore	78 feet, bottom in fresh granite.
T.S.S.	374 grains per gallon.

The resistivity curve indicates discontinuities at 3, 22, and 86 feet, and the L.R. of the lower layer is about 3·15 (1,400 ohm–cm.).

Interpretation: Top of moist level at 3 feet; top of ground water level within decomposed granite at 22 feet; top of fresh granite at 86 feet or slightly deeper. The fairly high resistivity of the layer above the granite indicates brackish or relatively fresh water.

W9 is situated near the summit of a low hill.

Bore data.

Depth of bore	110 feet, bottom in fresh granite, but amount of seepage water very small. It is clear from the topography that this is an unfavourable location for a bore.

The resistivity curve indicates discontinuities at 1·5, 7, and 50–90 feet.

Interpretation: Soil at the surface; sand (alluvial deposit) between 1·5 and 7 feet, and decomposed granite between 7 and 50–90 feet. From the resistivity interpretation it is concluded that drilling continued for about 40 feet in fresh granite. The resistivity curve does not indicate any ground water level within the decomposed granite.

W10 is in a bowl-shaped depression, about 1 mile west of W9.

Bore data.

Depth of bore	.. 120 feet.
Salinity	.. 450 grains per gallon.
Yield	.. 300 ± gallons per day.

A nearby dam shows that the decomposed granite is close to the surface.

The resistivity curve shows main discontinuities at 3 and 112 feet and a possible discontinuity at 14 feet. The L.R. of the layer above 112 feet is 3·05 ± (1,100 ± ohm–cm.).

Interpretation: Soil and sand at the surface; decomposed granite between 3 and 112 feet; fresh granite at 112 feet.

The ground water level within the decomposed granite is probably at about 14 feet. The low yield of 300 ± gallons per day indicates a low effective porosity.

Discussion of Resistivity Results.

The resistivity curves all have a similar pattern, namely high resistivity near the surface, low to moderate resistivity in the decomposed granite, often accompanied by a sharp decline in resistivity near the bottom, and high resistivity in the fresh granite.

The following table shows the accuracy of depth determinations of the fresh granite:—

Station No.	Depth to Fresh Granite.		Approximate Percentage Error.
	Resistivity Data.	Bore Data.	
	ft.	ft.	ft.
W1	50	51	2
W2	52	40	30
W3	80	74 ±	8
W4	80–100	49	82
W5	180	40	..
W6	125–160	70	100
W7	85–110	110	12
W8	86	78	10
W9	50–90	110	36
W10	112	120	7

The following table indicates the high-salinity water levels from resistivity and bore data:—

Station No.	Depth to High Salinity Water Level.	
	Resistivity Data.	Bore Data.
	ft.	ft.
W1	35	..
W2	30	..
W4	56	49 ±
W5	45	40 ±
W7	32	..

From the results it appears that depth estimates from resistivity tests in the Wubin area are reasonably accurate—probably within 15 per cent. of depth.

Ground water levels and saline water levels can be recognized in some tests. The more saline the water, the more marked its effect on the resistivity curves. Where a gradual transition exists from moist to saturated conditions or from fresh water to saline water, the boundaries are not well-defined and consequently cannot be expected to show up in the resistivity curves.

The results suggest a relation between resistivity and salinity, which may be explained as follows:—

The resistivity is controlled mainly by the amount of pore solution in the rock and the salt content of the pore solution. The higher the salt content, the lower the resistivity, and vice versa. Assuming the porosity of the rock (here decomposed granite) to be more or less uniform, we can express the above relationship by an empirical formula $\rho S =$ constant, i.e.:—

$$\log \rho + \log S = C \text{ — — — — — — — — — — — } (4)$$

in which ρ is the resistivity in ohm-cm. and S the salinity in grains per gallon.

In the following table are listed the station number salinity, log salinity, log ρ_m and log ρ. For W7 and W8 the total soluble salt content (T.S.S.) is given; this is reduced to salinity by multiplication by 0·6 (an empirical factor derived from data in the Cue area). ρ_m is the minimum apparent resistivity from the resistivity curves; ρ is the resistivity of the decomposed granite above the fresh granite. It should be borne in mind that the salinity refers to water in the whole decomposed granite section, while the resistivity refers to the layer just above the fresh granite. In other words, the measured salinities are probably too low. But, as the error introduced will be more or less constant, it should not affect the use of the empirical formula.

Station No.	Salinity (S). (Grains/gallon.)	Log *S*.	Log ρ_m.	Log ρ.
W1	328	2·52	2·95	2·6
W2	510	2·71	2·90	2·4
W3	151	2·18	3·0	2·85
W4	570	2·76	2·8	2·2
W5	700	2·85	3·0	2·7
W6	410	2·61	3·2	3·15
W7	493 ± (821, TSS)	2·69	2·8	2·5
W8	224 ± (374, TSS)	2·35	3·5	3·15
W10	450	2·65	3·3	3·05

The empirical formulae derived from these data are (see Figures 3 and 4):—

$$\log S = 5 \cdot 7 - \log \rho_m \pm 0 \cdot 25 \qquad (4a)$$

$$\text{and } \log S = 5 \cdot 35 - \log \rho \pm 0 \cdot 35 \qquad (4b)$$

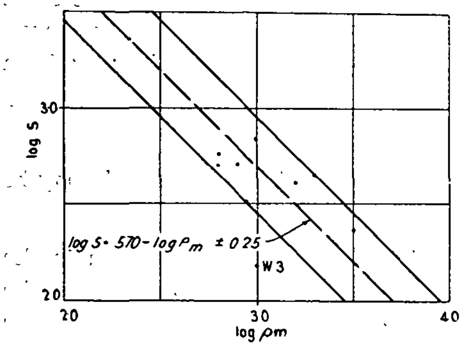

Fig. 3: Relation between apparent resistivity and salinity for decomposed granites at Wubin.

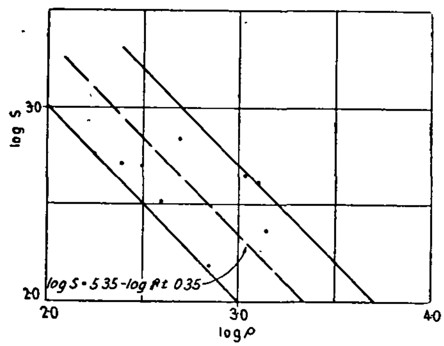

Fig. 4: Relation between resistivity and salinity for decomposed granites at Wubin.

Formula (4*a*) appears to give slightly better results, and the following table shows the errors involved when applying this formula to the above data:—

Station No.	Measured Salinity.	Salinity from Formula 4 (*a*).	Error.	Percentage Error.
W1	330	560	230	70
W2	510	630	120	24
W3	150	500	350	200
W4	570	800	230	41
W5	700	500	− 200	29
W6	410	320	− 90	22
W7	490	800	310	63
W8	220	160	− 60	27
W10	450	250	− 200	44

From the table it appears that in the decomposed granites of the Wubin area the salinity can be estimated from the resistivity by the use of empirical formulae, with an accuracy of about ±50%.

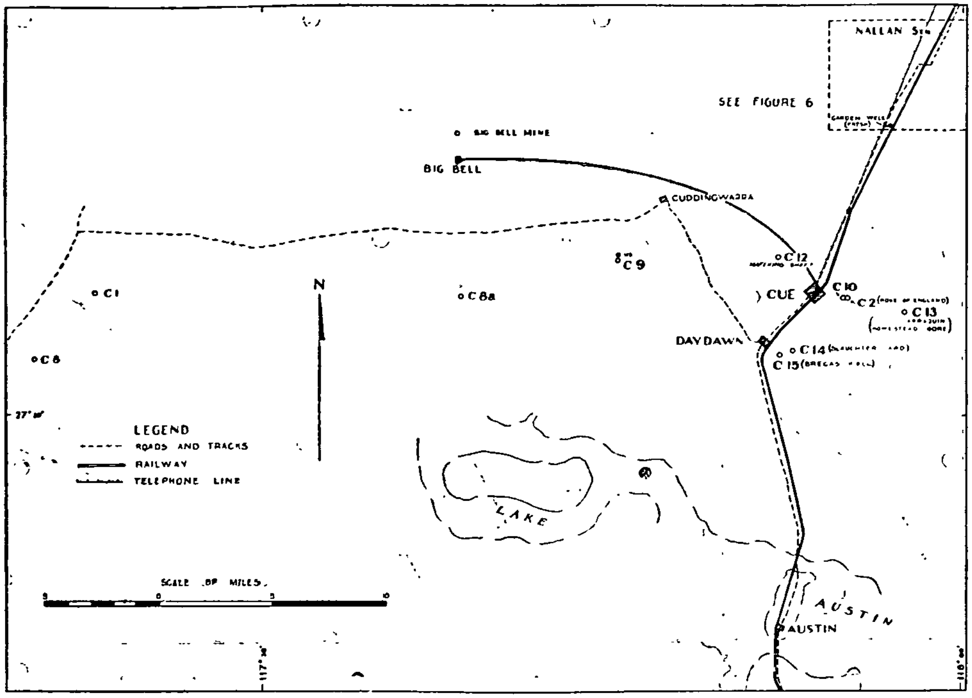

Fig. 5: Cue area: location of resistivity stations.

CUE AREA (Figs. 5 and 6).

GEOLOGY.

The geological observations in the large Cue district have been restricted to certain areas and were made solely in connexion with the investigation for water occurrences. The average rainfall over the last twenty years is about 8 inches per year. The main rock types in the area are:—

1. Pre-Cambrian granites, gneisses and schists (green stones) with pegmatites and quartz reef zones.
2. Sedimentaries of an unknown age, namely, a limestone formation at Nallan and perhaps the limestones at Austin Downs.
3. Fluviatile deposits such as valley flats at Austin Downs and the large flood plain between Cue and Nallan.

The local erosion base of the area is formed by Lake Austin, a shallow salt lake or clay pan at an elevation of about 1,450 feet. All ground water in the area gradually drains towards the lake. Near Cue, there are several flat-topped hills, the tops of which correspond to an old peneplain. These hills, which are about 150 feet above the neighbouring country, consist of gneiss with a laterite cap. In addition, there are many low hills and ridges, the valleys between which are covered with fluviatile deposits.

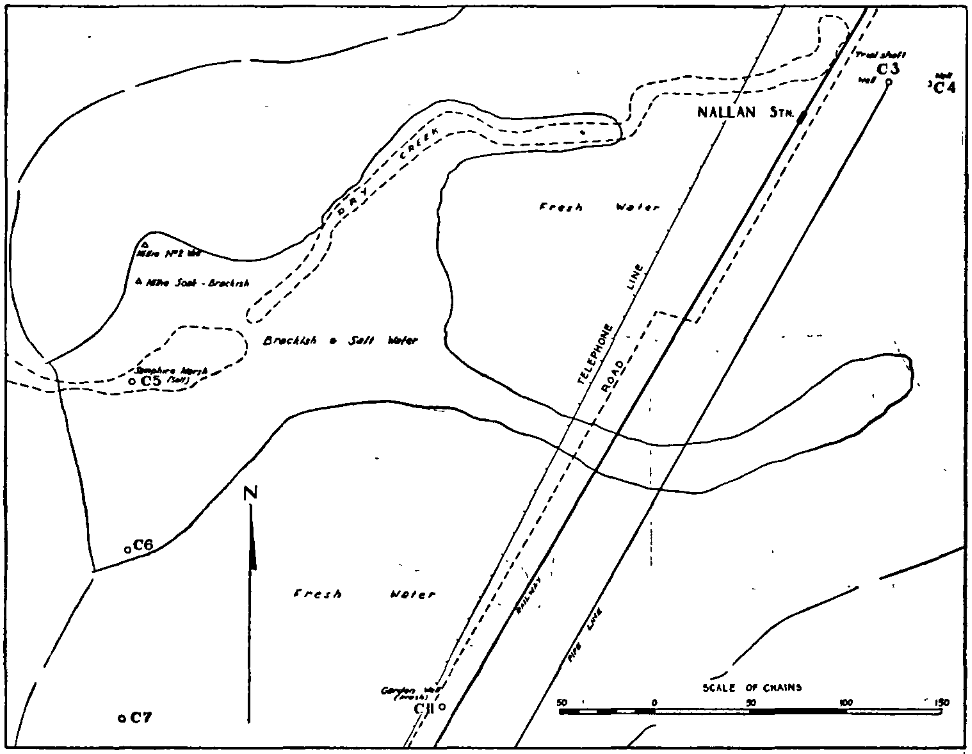

Fig. 6: Cue area: location of wells and quality of water at Nallan.

WATER DEPOSITS IN FRACTURED QUARTZ REEFS OR PEGMATITES.

The Possibility of Water Supplies from Mine Shafts.

The Cue area has been the centre of extensive mining activity, and is dotted with abandoned mine shafts, which gradually fill up with water. Local farmers and gardeners use many of these shafts as wells and find this water supply suitable in quantity and quality for their limited requirements. Cue township receives its water from Nallan, about 12 miles away, but the water is hard and corrosion of the pipes is severe. A new water supply for Cue township is being sought and attention has fallen on these mine shafts. The maximum requirement for the township is about 80,000 gallons per day.

Pumping tests have been made at a few shafts. A test at the Rose of England shaft yielded 1,100 gallons per hour for several days, lowering the water level from 118 to 175 feet. The Mafeking shaft is regarded by the local authorities as a possible source for the town supply. However, the use of these old mine shafts for large water supplies is not recommended. Despite favourable pumping tests it is not possible to see how these water deposits in fractured quartz reefs can keep up a large supply indefinitely. Moreover, the danger of salt encroachment is acute. The Rose of England shaft, for example, is situated near a shallow valley, which was shown by the resistivity test (C10) to carry salt water. Pumping for several months will eventually make this salt water flow towards the shaft. Furthermore, mining experience shows that, in general, the water from mine workings is saline, because it comes from fracture and fault zones. The relatively fresh water at present in the shafts is explained by the drainage of surface water towards these shafts. Heavy pumping during long periods will exhaust this supply and the saline mine water will take its place. As will be mentioned later, a reasonable chance for a good water supply exists in the valley flats near Yarraquin Homestead, where geological conditions are similar to those near the Big Bell water supply.

Results of Individual Resistivity Tests (Plate 2).

C2 is 100 feet from the Rose of England shaft, which is sunk in schists to a depth of 175 feet or more. At the bottom of the shaft are two drives. Near the shaft are some quartz reefs, which are probably intersected by the shaft or the drives.

The salinity of the water is 76 grains per gallon and the T.S.S. 148 grains per gallon. The resistivity curve shows discontinuities at 2, 5, 14 and 50 feet; the layer between 14 and 50 feet has an L.R. value of 2·5 (320 ohm–cm.).

Interpretation: A surface layer of sand down to 2 feet; between 2 and 50 feet a weathered zone; below 50 feet fresh schist; moist level at 5 feet; ground water level perhaps at 14 feet. The water level in the shaft bears no apparent relation to the weathered zone or any possible water table in this zone. This suggests that the supply of water from the shaft would be limited, and that during pumping tests the water probably flowed towards the shaft through fractures, faults or fractured quartz reefs. The water pumped from the shaft would probably become saline eventually.

C12 is near the Mafeking shaft, which is situated in a north striking shear zone containing pegmatites. The granite walls of the veins are completely kaolinized and the shaft has collapsed. The T.S.S. of the shaft water is 144 grains per gallon and the hardness is 28. The resistivity curve shows discontinuities at 7–8 feet and 50–100 feet.

Interpretation: Weathered zone about 70 feet thick; moist level or ground water level at 7–8 feet.

C14 is near the Slaughter Yard well, within a quartz reef zone. The depth of the shaft is 74 feet, water level 62 feet, T.S.S. 86–117, salinity 70 and hardness 27.

The resistivity curve differs from the usual pattern, in that the surface resistivity is very low. The curve shows discontinuities at 2, 9, 63 and 107 feet.

Interpretation: The weathered section is about 107 feet thick, with surface material to 2 feet, moist level probably at 9 feet and ground water level at 63 feet. The abnormal shape of the curve can be entirely attributed to the extremely low resistivity of the surface layer, the L.R. for which is 2·2 (160 ohm–cm.), compared with the normal value for the Cue area of about 4·0 (10,000 ohm–cm.). The layers between 2 feet and 107 feet have L.R. values which are respectively 3·5 (3,200 ohm–cm.), 3·3 (2,000 ohm–cm.), and 3·0 (1,000 ohm–cm.), showing the normal decreasing trend in the weathered zone. The discontinuity at 63 feet correlates with the water level in the shaft at 62 feet.

C15 is near Brega's well, which, like the Slaughter Yard well, is within a quartz reef zone. The depth to the water level is 69 feet, T.S.S. 195, and salinity 130.

The resistivity curve shows discontinuities at 4, 13 and 59 feet. The discontinuity at 13 feet is somewhat uncertain.

Interpretation: The shape of the curve between 4 and 59 feet could be explained by a gradual decrease in resistivity to 59 feet due to increase of moisture with depth. The water level in the shaft is below the bottom of the weathered zone. It is possible that the quartz reef is fractured and water from the weathered zone drains into the fractures, resulting in the effective ground water level being below the weathered zone.

Summary of Resistivity Results.

The resistivity curves show similar patterns, except C14 (Slaughter Yard well), where the shape of the curve is influenced by the exceptionally low resistivity of the surface layer.

The resistivity curves suggest that the thickness of the weathered layer of a reef zone can be estimated but no control is available to check this opinion. The average thickness of the weathered zone calculated from the resistivity curves is about 70 feet.

Except at C14 the water levels in the shafts do *not* agree with the ground water level indications of the resistivity curves. At C2 (Rose of England) and C15 (Brega's well) the shaft water levels are below the weathered zone and probably represent the water level in the fractures of the reef or country rock while water of the weathered zone slowly drains into these fractures. It should be noted that a period of heavy rainfall preceded the measurements and this may have influenced the resistivity curves.

WATER DEPOSITS IN LIMESTONES OR IN RELATION WITH LIMESTONES.

Occurrence of Limestone in the Cue Area.

The Cue water supply is obtained from Nallan, where wells are sunk in a limestone formation. This limestone is an important aquifer in the area and therefore the following notes will be of interest.

It is generally believed that limestones in this district are chemical or lacustrine deposits. However, there is reason to believe that the limestone at Nallan is either a normal marine or lake sediment. West of the Cue-Nallan road, between mileposts 273 and 274, the limestone can be observed in an opencut. The observed part consists of two layers, a reddish limestone of 1·5–2 feet, on top of a white limestone. The limestone shows roughly horizontal stratification, and small drag-folds are developed. Part of the limestone is brecciated, and the breccia vugs are silicified. In several places leached out limestone was observed. Leaching and redeposition are normal occurrences in limestone but there is no evidence that the primary deposit is chemical or lacustrine. At Nallan, the limestone is present over an extensive area. At the pump station the minimum thickness, as shown by the pump shaft, is 20 feet. The resistivity profiles indicate a much larger thickness, up to 100 feet.

Limestone is also found in varying thickness in the Austin Downs area, where drilling shows that it is generally bedded between a fluviatile conglomerate and decomposed granite. The thickness of the Austin Downs limestone probably does not exceed 25 feet. No opencuts were available to observe the limestone clearly and it would be difficult to state with certainty whether the Austin Downs limestone is a lacustrine deposit or a sediment.

Results of Resistivity Tests (Plate 2).

C3 is near the pumping stations. The depth of the well (Trial shaft) is 20 feet, and the water level is at 15 feet. Changes in water level during dry and wet seasons are not more than 1 foot, thus indicating a large sub-surface water reservoir. The salinity is 100, hardness 37 and T.S.S. 140. The resistivity curve shows a curious pattern of 2 maxima; below log $a = 2{\cdot}0$ the curve tends towards a minimum. Discontinuities are indicated at 2, 10, 22 and 120 feet with layers of high resistivity between 2 and 10 feet and between 22 and 120 feet.

Interpretation: Recent heavy rainfall probably made the surface resistivity slightly lower than usual. The discontinuity at 10 feet indicates the top of the moist level or the water level and therefore the limestone is probably leached out down to this depth.

From 22 to 120 feet a higher resistivity layer can probably be interpreted as a massive limestone in which most of the fractures and pores have been recemented. The discontinuity at 120 feet probably represents the top of the decomposed granite. The low resistivity below 120 feet indicates salt water in the decomposed granite. The above interpretation cannot be checked against bore control, but it is a sound geological probability.

C4 is near a well, approximately 800 feet east of C3. The depth to the water level is about 15 feet.

The resistivity curve shows the same curious pattern as at C3, but the maximum and minimum are at a lower level, discontinuities being at 13, 50, 70 and 180 feet. The curve shows two maxima and a decrease in resistivity below $\log a = 2{\cdot}2$ (160 ohm–cm.).

Interpretation: The curve shows that the top of the decomposed granite is at about 180 feet and that the decomposed granite probably contains saline water. Without additional control interpretation of the layers above 180 feet is speculative, but it is suggested that the two high resistivity layers at 13 to 50 feet and 70 to 180 feet, are cementation zones, and that water is present in an aquifer between them. The measured level of water at 15 feet may be due to drainage of surface water towards the well. Alternatively, water may have been struck at a lower level under slight pressure, which would cause the water to rise in the well.

C9 is located near Austin Downs Homestead. The bore is 25 feet deep and is entirely in limestone. Fresh water was struck at about 20 feet.

The resistivity curve shows discontinuities at 32 and 90 feet.

Interpretation: Bearing in mind that limestone is found at the surface, the high resistivity layer between 32 and 90 feet can be interpreted as a cementation zone. The ground water level will probably be found above this cementation zone. The top of the decomposed granite is at about 90 feet, and water in the decomposed granite is probably brackish.

C8 is located at Austin Downs.

The depth of the bore is 66 feet and fresh water is met at 24 feet. The yield is 130 gallons per hour. The bore log shows:—

0– 2 ft.	:	surface sand
2– 7 ,,	:	conglomerate
7–22 ,,	:	limestone
22–66 ,,	:	decomposed granite.

A three-layer curve fit to the resistivity curve shows a lower resistivity layer between 10 and 26 feet. L.R. of the layers from top to bottom is 3·93 (8,500 ohm–cm.), 3·45 (2,800 ohm–cm.), and 4·41 (26,000 ohm–cm.).

Interpretation: To be consistent with the bore log, the layer between 10 and 26 feet must represent limestone. From the fairly high resistivity of the layer fresh water could have been predicted. The decomposed granite shows a higher resistivity than normal, and it is not known whether this can be entirely explained by low salinity or whether it indicates an unusual type of decomposed granite. It appears that the limestone formation is too thin to develop a well defined cementation zone which would show up as a maximum.

C8a is also located at Austin Downs. The depth of the bore is 80 feet and fresh water is met at 41 feet. The yield is 120 gallons per hour. The bore log shows:—

0– 1 ft.	:	soil
1–28 ,,	:	conglomerate
28–47 ,,	:	limestone
47–68 ,,	:	kaolin
68–80 ,,	:	decomposed granite.

The layer referred to as kaolin may be decomposed granite. The resistivity curve shows a discontinuity at 8–10 feet and a three-layer curve fit shows a low resistivity layer between 80 and 104 ± feet. The resistivity probably decreases gradually from the surface down to 8–10 feet.

Interpretation: The discontinuity at 8–10 feet suggests ground water level at that depth. The layer between 80 and 104 feet is interpreted as decomposed granite with saline or brackish water. The top of the fresh granite is suggested at 104 feet. The interpretation does not show much agreement with the bore log. But it should be borne in mind that the resistivity measurements were taken during a period of heavy rainfall, which probably caused a considerable rise in the ground water level.

Summary of Resistivity Results.

There is a difference in the resistivity-curve pattern between the different stations.

C3 and C4 have two maxima, C9 has one maximum, and C8 and C8*a* have minima. The maxima were tentatively explained by assuming cementation zones within the limestone formation. At C8*a* the conglomerate and the limestone appear to have approximately the same resistivity and the minimum is caused by saline or brackish water in the underlying decomposed granite. At C9 the conglomerate has a higher resistivity than the limestone and the latter formation causes the minimum.

The following table gives an estimate of the resistivity ranges (expressed as logarithms) for limestones carrying fresh water. The higher limits probably correspond to cementation zones:—

Station.	Log Resistivity.
C3	3·7 — 4·45
C4	3·4 — 4·3 (?)
C9	3·75 — 4·75
C8	3·45
Average	3·9 ± 0·4

The log resistivities for conglomerates at Austin Downs are:—

Station.	Log Resistivity.
C8	3·9
C8a	3·45
Average	3·7

It might be asked whether, using the resistivity curves discussed above and a knowledge of the surface geology, one could predict the occurrence of favourable water deposits.

The following table illustrates that the resistivity method will provide a useful guide in the location of favourable water deposits:—

Station.	Fresh Water Predicted.	Brackish or Saline Water Predicted.	Fresh Water in Well or According to Bore Log.
C3	Between 10′ and 22′	Below 120′	At 15′
C4	Between surface and 13′	Brackish between 50′ and 70′ and saline below 180′ ±	At 15′
C9	Between surface and 32′	Probably brackish below 90′	At 20′
C8	Between 10′ and 26′	.. .. ..	At 24′
C8a	Between 8′ and 80′ ..	Saline below 80′ ..	At 41′

WATER IN FLUVIATILE DEPOSITS AND VALLEY FLATS.

Resistivity Tests C5, C6 and C7 (Plate 2).

Resistivity tests C5, C6 and C7 were made in a line, 0·5, 1·5 and 2·5 miles respectively south of Millie Soak, near wells or bores. The bores corresponding to C6 and C7 could not be found on the ground. On Fig. 6 it will be seen that C5 and C6 are in a salt water area and C7 in a fresh water area.

The old data available for control are:—

C5, depth of well 10 feet, salt water at 7 feet,

C6, depth of bore 42 feet, salt water at 6 feet,

C7, depth of bore 68 feet, fresh water at 18 feet.

The wells or bores are all in the flood plain between Cue and Nallan. The resistivity measurements were taken after a long period of heavy rainfall and therefore the ground water levels may have been higher than indicated by the above data.

C5. The resistivity curve shows discontinuities at 1·5, 2, 30 and 108 feet.

Interpretation: The ground water level is indicated at 1·5 feet. The surface sandy soil layer extends down to 2 feet; between 2 and 30 feet the fluviatile deposits contained relatively fresh water during the period of the measurements (heavy rainfall). Between 30 and 108 feet is a layer of very low resistivity, interpreted as decomposed granite containing water of very high salinity. The top of the fresh granite is at about 108 feet.

C6. The resistivity curve shows discontinuities at 3, 35 and 141 feet.

Interpretation: The ground water level is at 3 feet, probably decomposed granite containing very saline water between 35 and 141 feet and the top of the fresh granite at about 141 feet.

C7. The resistivity curve indicates discontinuities at 11, 134 and 215 feet.

Interpretation: The ground water level is at 11 feet, decomposed granite containing very saline water between 134 and 215 feet and the top of the fresh granite at about 215 feet.

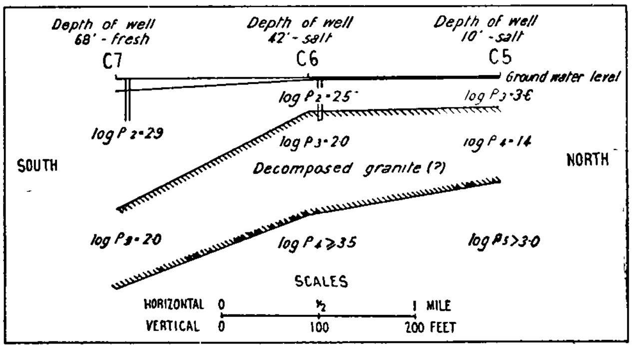

Fig. 7: Cue area: cross-section through C5, C6 and C7.

Summary of Resistivity Tests C5, C6 and C7.

The results of the resistivity tests and their interpretation are shown in the section of Figure 7. It will be seen that to the south of C6 the top of the decomposed granite dips towards the south. At C5 and C6 the salt water layer is shallow and during dry periods saline water will encroach towards the surface, resulting in brackish and salt water in the wells. A well or bore at C7 should always yield fresh water as long as it is not too deep.

Resistivity Tests C11, C13, C1 and C10 (Plate 2).

C11 is situated near the Old Garden Well which is in the alluvial floor plain between Cue and Nallan. The depth of the well is 20 feet, and the water level in the well is 18 feet. T.S.S. is 230 and hardness 57. The resistivity curve shows discontinuities at 2, 8, 32–45 and 120–160 feet.

Interpretation: Top of moist level or ground water level is at 8 feet, relatively fresh water between 8 and 32–45 feet, brackish or saline water within the decomposed granite between 32–45 and 120 feet and the top of the fresh granite at about 120 feet. The L.R. of the decomposed granite layer is 2·8–3·0 (630–1,000 ohm–cm.), which, if comparable with the results at Wubin, would indicate a salinity between 200 and 400.

C13 is situated near the Yarraquin Homestead bore, which is 168 feet deep. The depth to the water level is 140 feet but it is not known whether this water level was measured during or before pumping.

The yield is 7,000–10,000 gallons per day, T.S.S. 53 and salinity 38.

The high yield indicates a high permeability, which is unusual for decomposed granites and suggests fluviatile deposits. The resistivity curve indicates discontinuities at 2, 4–10 and 58–115 feet.

Interpretation: The top of the moist or ground water level is indicated at 4–10 feet and the valley floor at 58–115 feet.

The high permeability and high effective porosity, which are indicated by the high yield, explain the relatively low resistivity of the layer between 4–10 and 58–115 feet, despite the low salinity. The fluviatile deposits at Yarraquin probably consist of clay with gravel layers but the electricial method of survey does not possess sufficient resolving power to detect these gravel layers at depth.

The locality near Yarraquin should be closely investigated as a source of fresh water for Cue township.

C1 is situated near bore No. 7 at Austin Downs. The depth of the bore is 82 feet, the fresh water level in the bore is 61 feet and the yield is 126 gallons per hour.

The bore log shows:—

0	–	1	ft.	:	soil
1	–	5	,,	:	conglomerate
5	–	46	,,	:	kaolin
46	–	57	,,	:	yellow clay
57	–	82	,,	:	decomposed granite.

The layer referred to as kaolin may be decomposed granite. The resistivity curve shows discontinuities at 2, 4 and 45 feet; the L.R. of the layer between 4 and 45 feet is 3·5 (3,200 ohm–cm.).

Interpretation: The layer between 4 and 45 feet can be interpreted as clay (valley filling) and/or decomposed granite, while the fresh granite starts at about 45 feet. Water may be expected between 4 and 45 feet, and the high resistivity of this layer (3,200 ohm–cm.) indicates fresh water. Comparison with the available control shows that the range for the predicted water level is higher than the reported water level in the bore. Also, the top of the fresh granite is lower than predicted by the resistivity curve.

C10 is in a shallow valley and is 700 feet west of the Rose of England shaft (C2). The resistivity curve indicates discontinuities at 16 and 20–30 feet. The L.R. of the layer between 16 and 20–30 feet has the very low value of 1·65± (45 ohm–cm.), indicating a layer of high salinity.

Interpretation: No control data are available. The resistivity data indicate normal valley filling from the surface to 16 feet, probably a weathered zone with highly saline water between 16 and 20–30 feet and fresh rock at 20–30 feet. The saline water layer makes it risky to use the Rose of England shaft as a water supply source.

Summary of Resistivity Tests C11, C13, C1 and C10.

In the following table, predictions are compared with findings or reported data:—

Station.	Prediction.	Control.
C11	Fresh water between 8 and 32–45 feet, saline below 32–45 feet	Fresh to brackish water at 18 feet
C13	Brackish water between 4–10 and 58–115 feet	Reported water level at 140 feet, but this level was probably measured after pumping. Fresh water in bore
C1	Fresh water between 4 and 45 feet within decomposed granite	Reported water level at 61 feet, but during a wet season the level may be considerably higher
C10	Saline water between 16 and 20–30 feet	

BIG BELL AREA (Fig. 8).

The Big Bell Mine is supplied with water by a line of wells across a valley flat. A fairly extensive boring campaign was carried out to investigate sub-surface conditions and to avoid sinking wells into salt water. This is one of the few areas where fair control was available for the resistivity tests. Three resistivity tests were made near bores 5, 8 and 10, which show a section with a considerable range in the depth to bedrock.

The average salinity of the water from all bores in the area is about 119. The yields at bores 5, 8 and 10, near stations BB1, BB2 and BB3 respectively, were about 1,440, 780 and 1,120 gallons per hour. The water in bore 10 is saline or brackish.

The resistivity curves for BB1, BB2 and BB3 are shown in Plate 2. BB1 indicates discontinuities at 63 feet and 118 feet which are interpreted as the water table and the upper surface of the fresh granite respectively. The upper part of BB2 is too regular to permit satisfactory two-layer curve fitting, but the lower part of the curve shows discontinuities which are interpreted as water table at 65 feet and fresh granite at 250 feet. On curve BB3, the water table appears to be indicated at 64 feet. The electrode separations were not large enough to obtain an indication of the granite.

The interpretation of the resistivity tests is shown by the full lines in the section in Figure 9. The depth estimates appear to be about 10 per cent. too large. If the relationship between resistivity and salinity, derived for the Wubin area, is applied to the Big Bell results, the salinity is estimated at between 250 and 500. This is too high and indicates a higher porosity for the water-bearing formation at Big Bell.

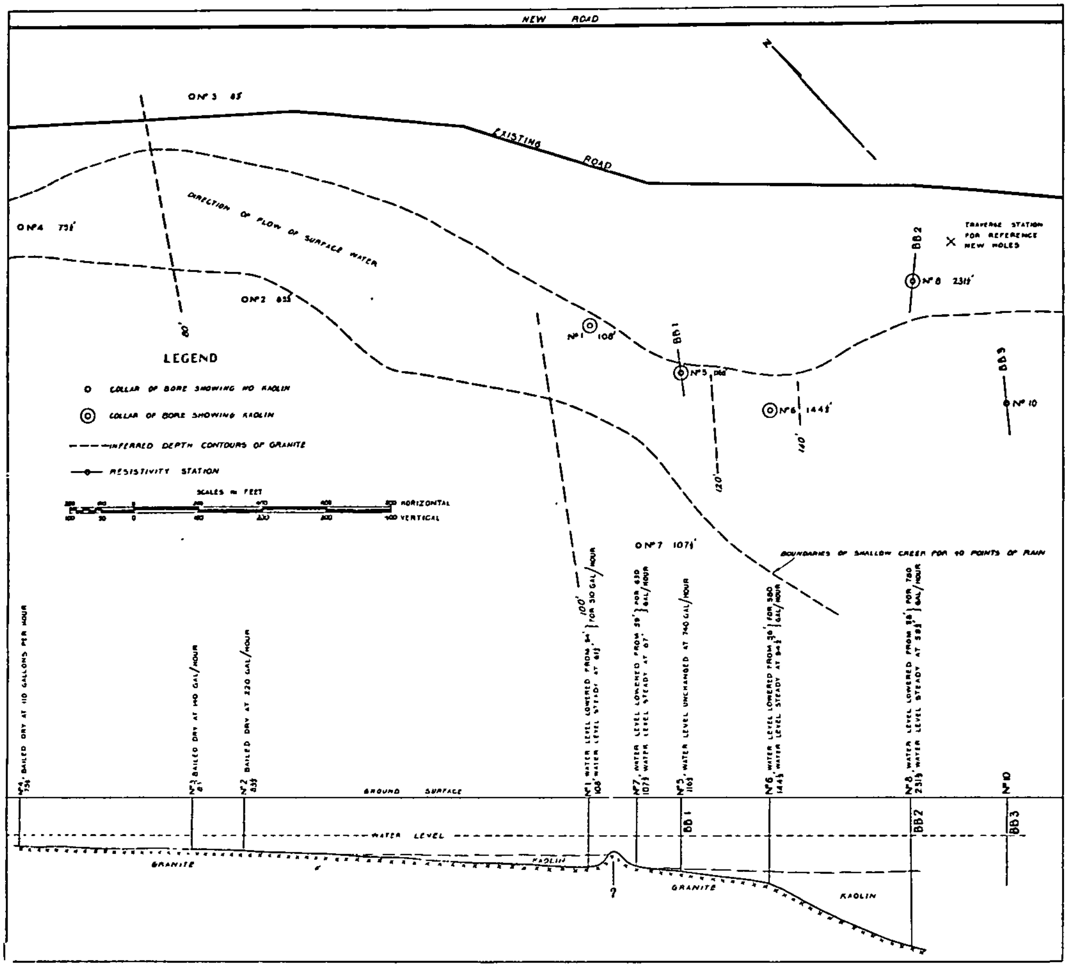

Fig. 8: Big Bell area: location of resistivity stations and geological cross-section.

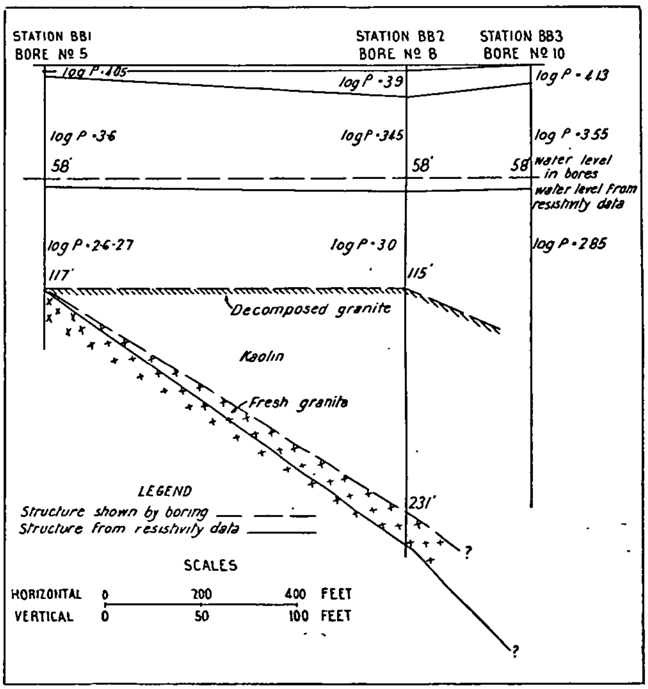

Fig. 9: Big Bell area: cross-section through BB1, BB2 and BB3.

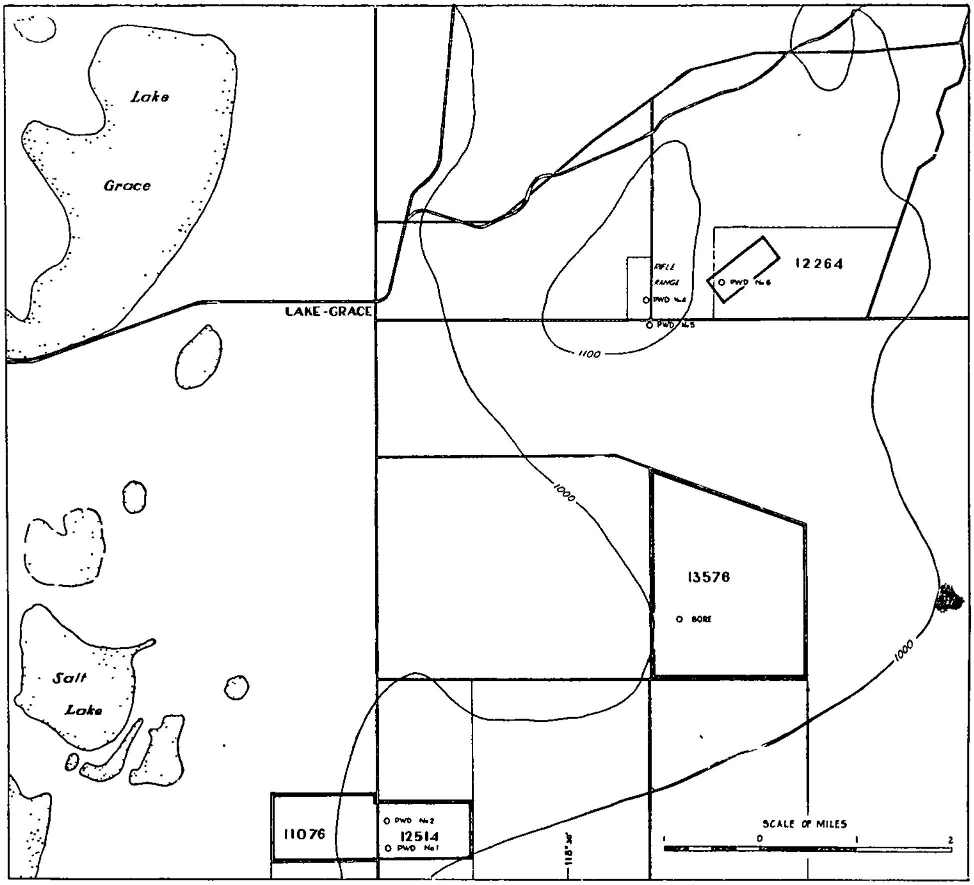

Fig. 10: Lake Grace area: plan of locations.

LAKE GRACE AREA (Fig. 10).

GEOLOGY.

Lake Grace township is in a plain between a north-striking ridge to the east and the shallow salt lakes to the west. The level of the lake is about 900 feet above M.S.L. and rainfall is about 13·5 inches.

The area represents a mature state in the erosion cycle. The top levels of the hills probably represent the remnants of an old peneplain, while the lake level can be considered as the local erosion base. The lakes and the connecting valleys have no drainage to the sea and consequently the lake water and the ground water of the lower valleys is gradually becoming more saline. The rocks are the old igneous and metamorphic rocks of the Australian shield such as granites, gneisses and related rock types. The top section of these rocks is generally transformed, partly or completely, into rocks commonly known as decomposed granites. In this area they consist mainly of kaolinized minerals or kaolin with unaltered quartz crystals. In some places it is difficult to distinguish between the decomposed granites and granite wash; the distinction is almost impossible in bores. The decomposed granite which will yield small quantities of seepage water, can be called an aquiclude. As most of the water in the lower valleys is highly saline, the search for potable water should be limited to the higher levels. In general, this area is comparable with the Wubin area. In some places the granites or decomposed granites are overlain by limestone. The limestone is found between 940 and 1,040 feet above M.S.L. and its thickness does not seem to be more than 20–25 feet. Near L.G. 8 (Fig. 16) it forms the cap of a hill and contains rounded lateritic pebbles. The origin of this limestone is still somewhat vague. The restriction of the limestone to certain levels (940–1,040 feet) indicates it to be the remnants of an old peneplain surface. It can probably be classed as a chemical deposit and could be termed "*caliche.*" This type of deposit is only formed in regions of limited rainfall and often forms the cap rock of buttes and mesas (Pettijohn, 1949, 308). The shallow valleys are probably filled with gravel, sand and clay.

Modern lateritic weathering is an important feature of this area and because it causes both earth currents and large changes in resistivity of the near-surface layers, a short discussion is justified. The main characteristics of lateritic weathering noted during the survey are shown in Fig. 11.

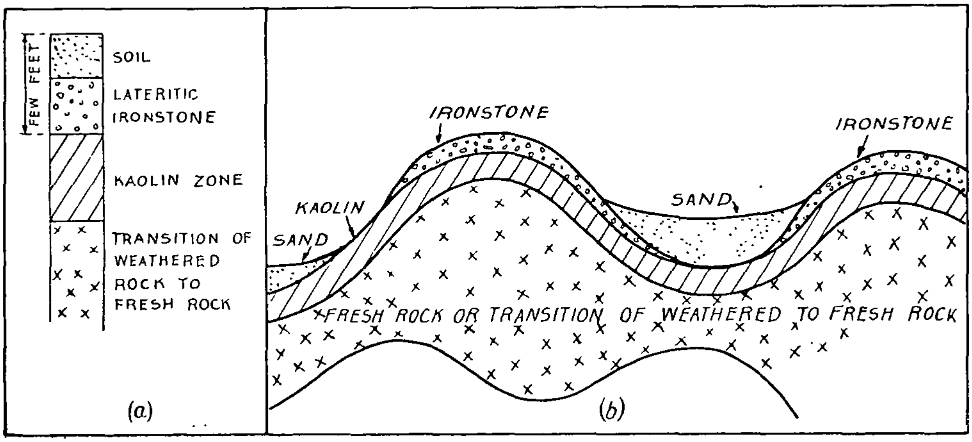

Fig. 11: Cross-section illustrating lateritic weathering.

The zones shown in Fig. 11 (*a*) normally follow the terrain topography, but, where the normal process of erosion has been disturbed, for example by removal of the vegetation or by sudden changes in the erosion base, different rock types may appear at the surface as shown in Fig. 11 (*b*).

These rock types contain different salt solutions, and potential differences which are set up at the boundaries are at least partly responsible for the high natural earth currents observed when the porous pots are placed in the different rock types. These currents sometimes fall off rapidly, probably owing to the building up of counter potentials. This effect is often a disturbing factor in resistivity measurements.

GEOPHYSICAL RESULTS.

The resistivity survey in Western Australia was started at Lake Grace, and the work in this area was therefore largely concerned with the testing of equipment and development of a suitable field technique. Many difficulties were met, some of them instrumental, others due to high natural earth currents or to the high surface resistance of some sand deposits. Most of the difficulties were eventually overcome but they are the cause of the resistivity data in this area being seldom of a high standard and as a result some of the resistivity curves must be considered merely as trend lines. There was also a lack of bore control and of general geological information. Although the quality of the resistivity data is not as high as at Cue, Big Bell or Wubin, interpretation is generally possible and the results are useful in illustrating the application of the resistivity technique.

Resistivity Tests LG6, LG19 and LG20.

These tests were made near PWD Bore No. 6 in a valley situated in the higher part of the area (Figs. 10 and 12):—

Log of PWD Bore No. 6.

0 – 9	ft.	:	dark brown clay.
9 – 15	,,	:	brown, sandy clay.
15 – 19·5	,,	:	hard ironstone.
19·5– 27	,,	:	limestone.
27 – 39	,,	:	limestone and white, sandy clay.
39 – 50	,,	:	dark red, sandy clay.
50 – 72	,,	:	brown, sandy clay.
72 – 82	,,	:	quartz and sandy clay.
82 – 96	,,	:	brown, sandy clay.
96 –105	,,	:	limestone and sandy clay.
105 –127·5	,,	:	white, quartz sand and limey clay.

Water at 85 feet, yield 7,000–9,000 gallons per day, salinity 500.

The bore log is not considered to be very reliable. Kaolin is certainly present but is not mentioned. Limestone and limey clay are mentioned several times and it is possible that normal kaolin has been called limestone. A large part of the section can probably be called decomposed granite and granite wash.

The resistivity curves of LG6 and LG20 (Plate 3) show irregularities which are probably due to lateral variations in resistivity and it has been necessary to smooth the curves to obtain an interpretation by the two-layer curve fitting method.

Interpretation: The discontinuities indicated by the resistivity curves are shown in section in Figure 12. The lowest discontinuity can safely be interpreted as the top of the fresh granite. The first layer above the fresh granite with L.R. = 2·45–2·7 (280–500 ohm–cm.) is probably decomposed granite. If it is assumed that the decomposed granite has approximately the same porosity as that at Wubin, the relationship between resistivity and salinity can be applied. Salinities estimated this way are 500–800 grains per gallon, which agrees fairly well with the measured salinity of the bore water.

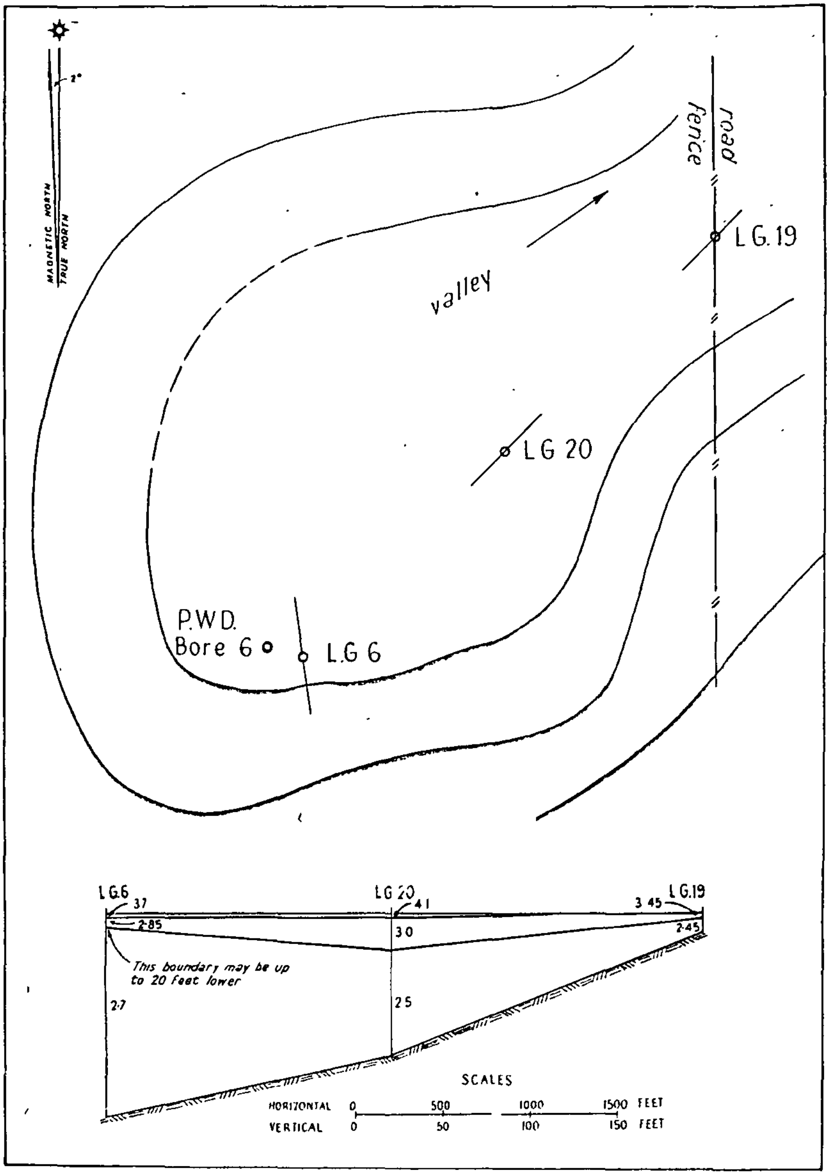

Fig. 12: Lake Grace area: form lines and cross-section through LG6, LG20 and LG19.

*Resistivity Tests. LG*14, *LG*15, *LG*11, *LG*13, *LG*18, *and LG*17 *on Location* 13576 (*Elliot's Property*).

The only control data are from the bore near LG11 (Fig. 13). The bore log is:—

0– 3 ft.	:	sand	This whole section probably represents decomposed granite and perhaps granite wash.
3– 27 ,,	:	conglomerate	
27–110 ,,	:	kaolin	
110–115 ,,	:	quartz	
115–139 ,,	:	kaolin	
139–141 ,,	:	decomposed granite	

141–142 „ : fresh granite
Yield of bore : 300 gallons per day
Salinity : 500±

The yield of the bore is small and the salinity high but nevertheless the water is valuable for sheep. The layers indicated by the resistivity curve for LG11 (Plate 3) can be closely correlated with the layers of sand, conglomerate, decomposed granite and fresh granite, as recorded in the bore log. The water from the bore is seepage water and the L.R. of the decomposed granite is 2·9 (800 ohm–cm.), which corresponds to a salinity of approximately 500. If, in the other resistivity profiles, the L.R. of decomposed granite is much lower than 2·9, the seepage water is likely to be too saline to be used for sheep.

The interpretation of the resistivity tests is shown by the sections in Figures 14 and 15. These show that the salinity increases rapidly from LG11 towards LG17 and from LG14 towards LG18. South of LG13 and also west of the line LG13–LG15 the ground water will be very saline.

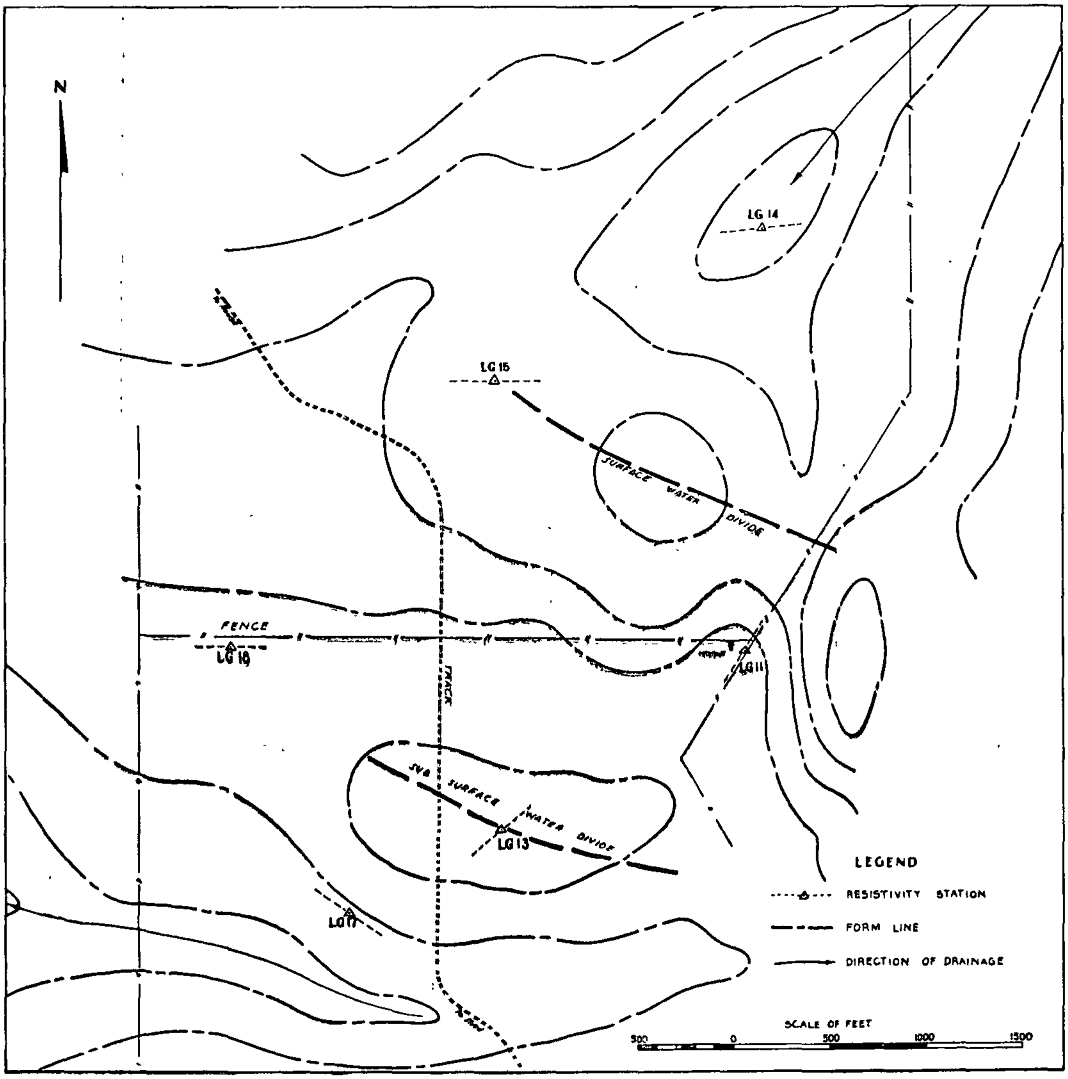

Fig. 13: Lake Grace area: plan of location 13,576.

The most favourable part of the area is to the north-east of a line joining LG11 and LG15, and the best location for a bore would be near LG14. It should be borne in mind that the shallower the bore, the fresher the water. During boring operations regular testing for quality and quantity is recommended.

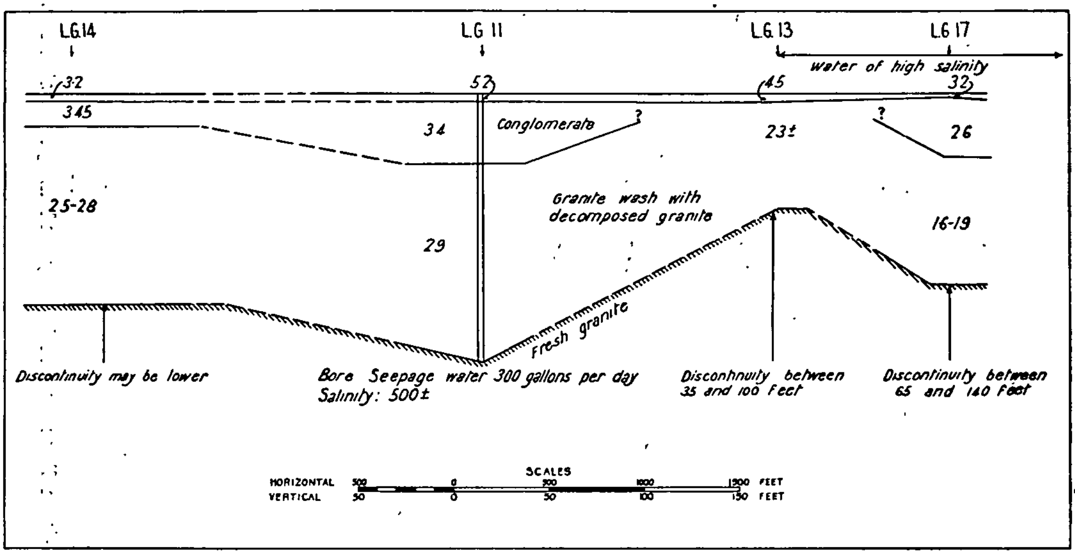

Fig. 14: Lake Grace area: cross-section through LG14, LG11, LG13 and LG17.

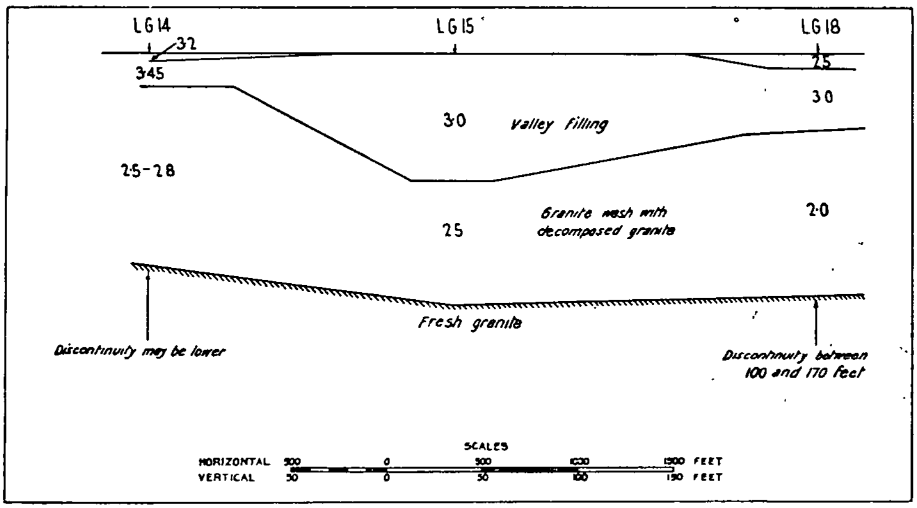

Fig. 15: Lake Grace area: cross-section through LG14, LG15 and LG18.

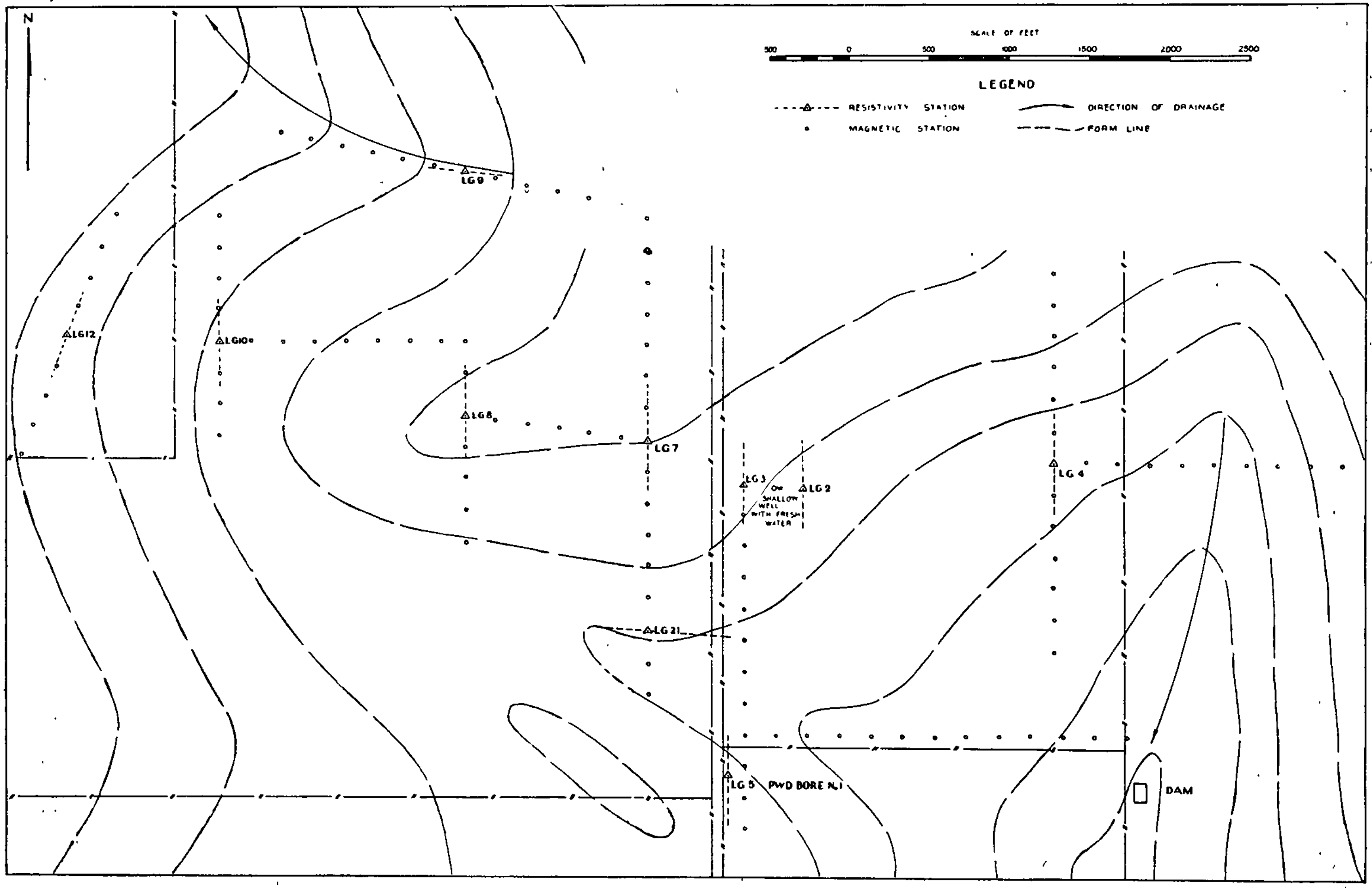

Fig. 16: Lake Grace area: Locations 11076 and 12514—form lines and resistivity and magnetic stations.

Resistivity Tests LG2, LG3, LG4, LG5, LG7, LG8, LG9, LG10, LG12 and LG21 on Locations 11076 *and* 12514.

Fig. 16 shows the general layout of the resistivity stations. Form lines show the main features of the surface topography. The only bore in this area is PWD Bore No. 1, near LG5. The log of the bore is as follows:—

0– 1 ft.	:	sand	
1– 15 „	:	gravelly clay, probably granite wash	
15– 77 „	:	limey clay (probably kaolin)	Probably decomposed granite.
77– 78 „	:	quartz	
78– 84 „	:	limey clay (probably kaolin)	
84– 97 „	:	brown, sandy clay	
97–126 „	:	clay with biotite mica	
126–133 „	:	green clay	
133–137 „	:	sand	

Yield 8,000 gallons per day, salinity 500. The large water yield is surprising and indicates some unusual condition in the decomposed granite.

The resistivity curve LG5 (Plate 3) is interpreted as showing sand from the surface to 5 feet, decomposed granite from 5 feet to 250 feet and fresh granite at 250 feet. The low resistivity of the decomposed granite (320 ohm–cm.) is consistent with the high salinity of the bore water, combined with relatively high porosity.

The interpretation of LG8 and LG9 is shown in Figure 17. The section on Figure 18 shows the interpretation of the resistivity curves LG12, LG10, LG8, LG7, LG3, LG2 and LG4.

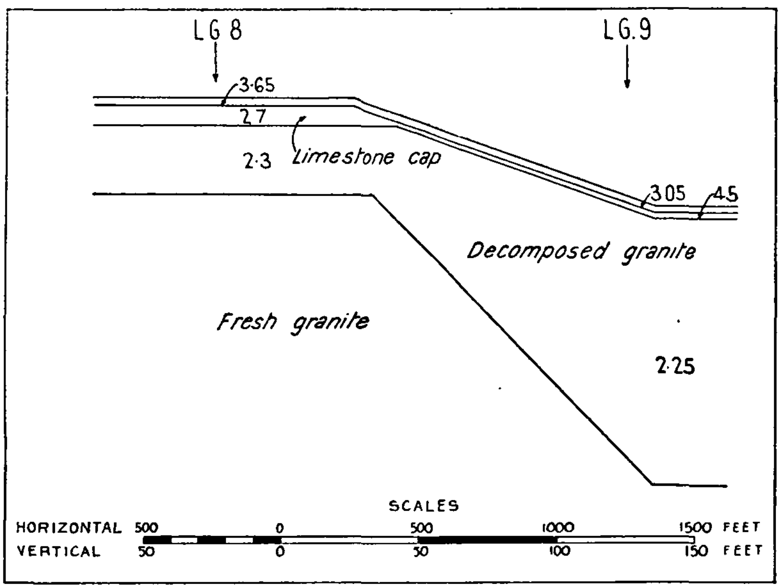

Fig. 17: Lake Grace area: cross-section through LG8 and LG9.

At LG8 the resistivity curve indicates a layer of L.R. = 2·7 (500 ohm–cm.) between 2 and 10 feet, which corresponds to a limestone found at the surface. The boundary between the decomposed and fresh granite is shown to be shallow (not more than 30–40 feet). General geological considerations show that the limestone is a remnant of an old peneplain surface and apparently the limestone acts as a protection against weathering. The boundary between decomposed and fresh granite dips steeply to the north, east and west of LG8.

A sand formation, probably a wind-blown deposit, fills the valley to the south-east of LG7. A shallow fresh water well between LG3 and LG2 indicates that fresh water or good stock water should be obtained from the sand formation between LG7 and LG4. The depth of the bores should not exceed 35 feet. Within the decomposed granite, seepage water of moderate salinity can be expected between LG8 and LG10, and between LG3 and LG7.

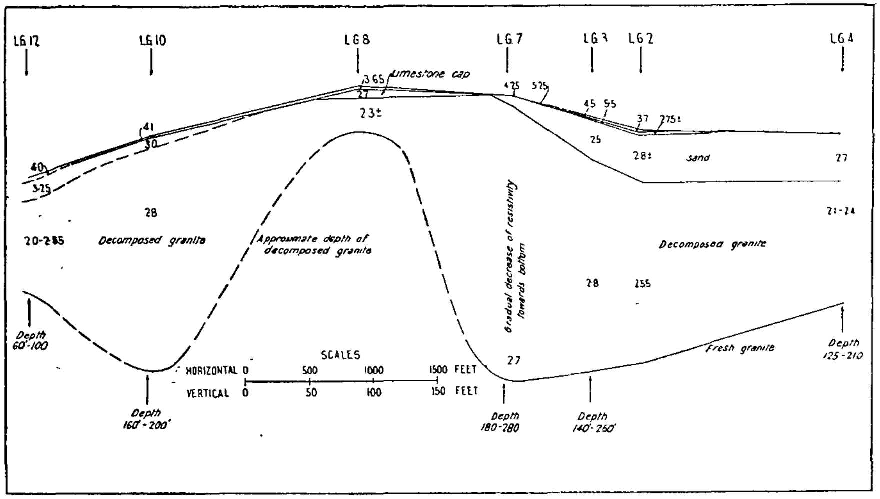

Fig. 18: Lake Grace area: cross-section through LG12, LG10, LG8, LG7, LG3, LG2 and LG4

The resistivity curve of LG21 (Plate 3) shows the sand layer down to about 18 feet, and below this, decomposed granite. The irregularity of the readings makes a reliable determination of the depth to fresh granite difficult, but the smoothed curve indicates a very shallow depth of about 45–70 feet. However, as will be shown in the discussion of the magnetic results, LG21 is situated over the centre of a narrow valley in the granite and the resistivity readings have probably been modified by the influence of the sides of the valley. The effect would be to give an apparent depth much smaller than the true depth.

Magnetic Survey on Locations 11076 *and* 12514.

The resistivity investigation of this area was supplemented by a small magnetic survey. The vertical magnetic intensity anomalies are shown on Fig. 19 with a contour interval of 100 gammas. The anomalies are large and can be attributed to the effect of the shallow basement. The anomalies may arise from two causes, namely lateral changes of polarization of the basement rocks and/or topography of the basement. The magnetic contour plan shows a sharp negative anomaly striking east. If the anomaly had been positive, a dyke or a valley with magnetic concentration might have been suspected, but as the anomaly is negative the only fitting interpretation is a narrow valley in granite basement striking east from LG21. This conclusion could not have been drawn from the general topograpy and geology.

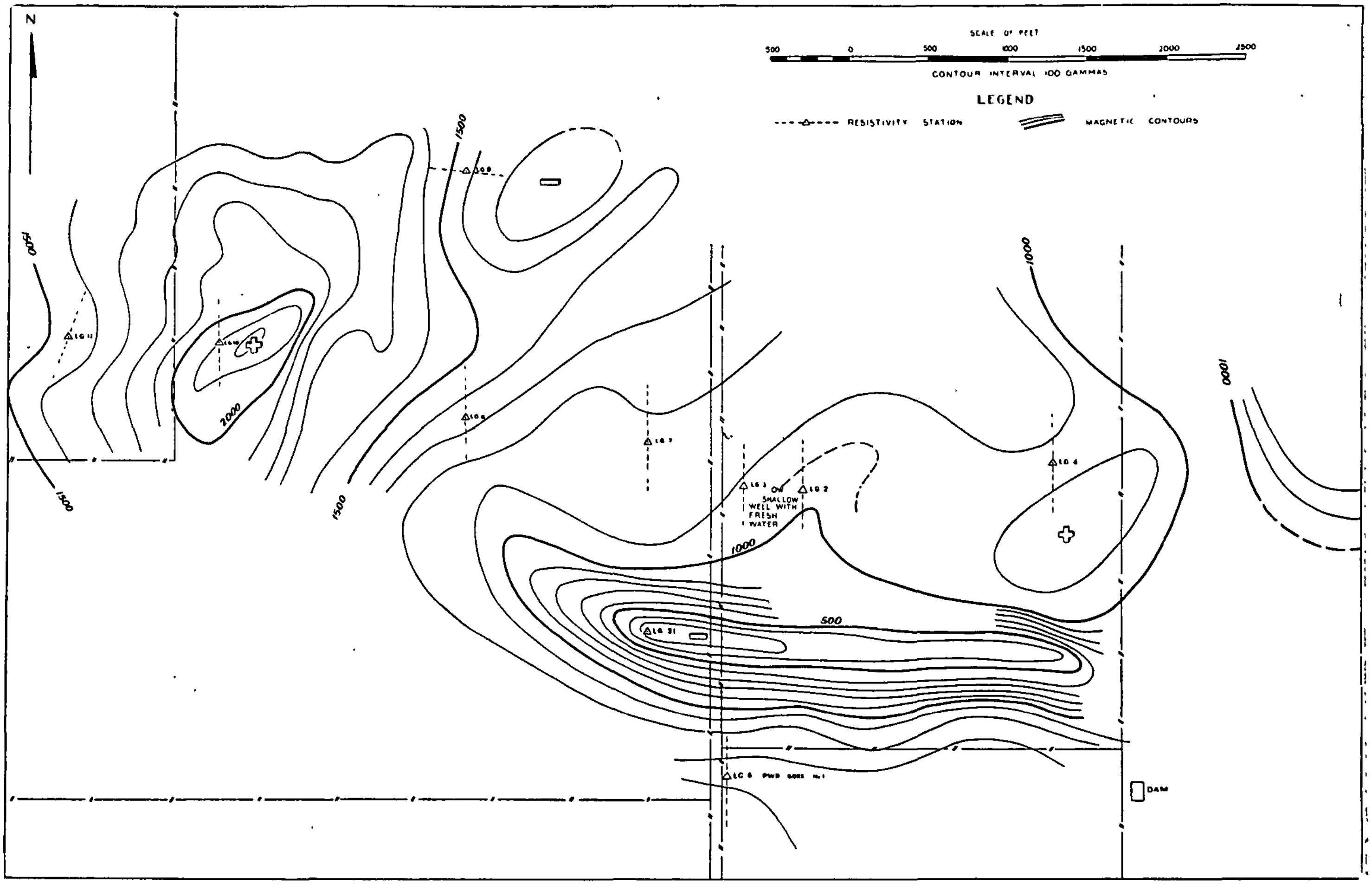

Fig. 19: Lake Grace area: Locations 11076 and 12514—vertical magnetic intensity anomalies.

The vertical magnetic intensity near LG4 is about 900 gammas lower than the intensity near LG10. The cause of the variation is not apparent from such a limited survey, but is probably a regional change in the polarization of the basement.

Resistivity Test LG1.

An isolated resistivity profile was observed near PWD Bore No. 4 at the rifle range (Fig. 10). The bore is dry and is 5 feet deep, mainly in eluvial detrital. The resistivity profile (Plate 3) shows discontinuities at 3 feet and 25 feet, the layer between these two depths representing decomposed granite.

The bottom of the decomposed granite is too shallow, the catchment area too small and the location too near to the summit of a hill for any appreciable quantity of seepage water to be expected.

KULIN AREA.

Three resistivity tests were made in the Kulin area (Fig. 20).

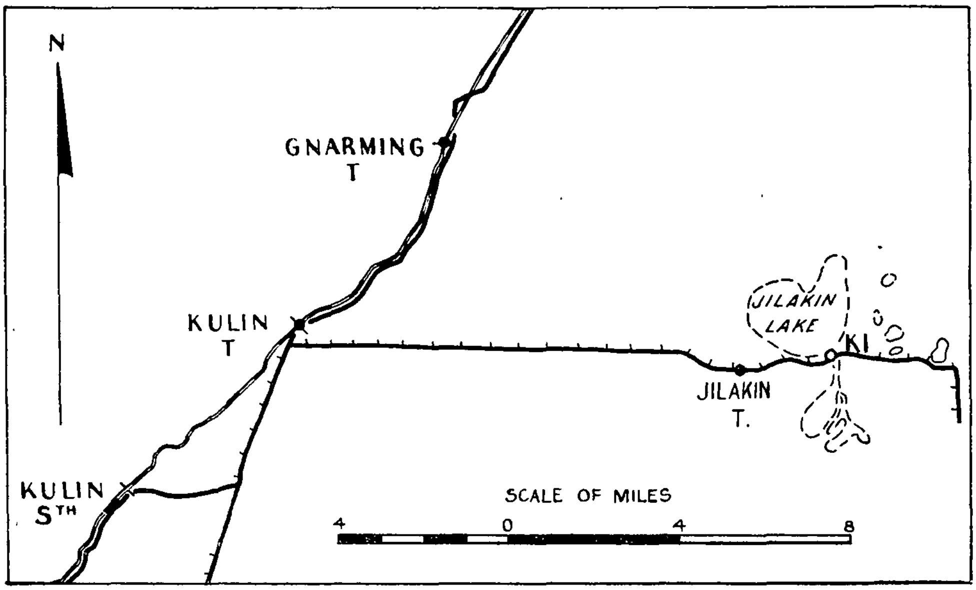

Fig. 20: Kulin area: location of resistivity station K1.

K1 is situated near Jilikin well, in a narrow valley filled with fluviatile deposits. Steep granite hills outcrop at about 500 feet distance.

The depth of the well is 34 feet; presumably the well was stopped on reaching granite. The water level is at about 20 feet, and the salinity is 20 (very low).

The resistivity curve (Plate 3) indicates discontinuities at 2·5 and 24–32 feet; the L.R. of the layer between 2·5 and 24–32 feet is 3·15 to 3·3 (1,400 to 2,000 ohm–cm.).

Interpretation: The top of the moist level is at 2·5 feet, the valley floor at 24–32 feet and there is probably fresh water between 2·5 feet and the valley floor. The interpretation is in fair agreement with the control data.

K2 is situated near a bore in a valley a few hundred feet north-east of Warrawoona farm (in the south-west corner of Location 2592). The depth of the bore is 103 feet, water level is at 11 feet, the yield is about 1,500 gallons per day, and the salinity 450.

The resistivity curve indicates discontinuities at 1·5, 19 and 52 feet; the L.R. of the layer between 19 and 52 feet is 2·7 (500 ohm–cm.).

Interpretation: The discontinuity at 1·5 feet represents the transition between surface layer and valley filling; the discontinuity at 19 feet probably represents the bottom of the valley and the top of the decomposed granite; the discontinuity at 52 feet is the approximate top of the fresh granite. The resistivity of the decomposed granite indicates brackish or saline water. The ground water level is near the surface, a fact which is adequately explained by recent high rainfall. The resistivity curve indicates that the bore is too deep; a depth of 30–40 feet would probably have been sufficient.

K3 is situated near a bore approximately 2,000 feet south-east of Warrawoona farm. The depth of the bore is 115 feet, the water level is at 100 feet, the yield is 3,000 gallons per day and the salinity 190. The bore is favourably placed in a basin-shaped valley, well above the lower valley level. Though the resistivity curve is smooth, ordinary two or three-layer curves do not fit. Comparison with two-layer curves, in which the resistivity of the top layer gradually changes, makes it clear that the resistivity gradually decreases. An approximation with two-layer curves can be made only by assuming an intermediate discontinuity. Hence the discontinuity shown at 14–16 feet does not really exist, there being a gradual change of resistivity between 4 and 100 feet. Discontinuities are indicated at 2, 4 and 85–140 feet.

Interpretation: Probably decomposed granite between 4 and 85–140 feet; top of the fresh granite at 85–140 feet. No water level is indicated but the thick section of decomposed granite with the relatively high L.R. of 3·0–3·25 (1,000–1,800 ohm–cm.) makes it probable that an ample supply of brackish seepage water will be available. This agrees well with the available control.

ACCURACY OF DEPTH DETERMINATION.

One of the principal aims of this experimental survey was to test the accuracy of depth determination of discontinuities. To obtain an estimate of such an accuracy, reliable bore logs are needed. Unfortunately, bore information was difficult to obtain and was generally unreliable. Exceptions were the logs for bores on the Austin Downs property and in the Big Bell area.

Despite these difficulties, an attempt was made to use all the available information in preparing the following table, which shows the depth to discontinuities from both resistivity and control data, and the type of discontinuity. Those stations for which fairly reliable bore information was available are marked with an asterisk, and data from them have been used in a statistical analysis to compute a correlation factor between depth determination from resistivity data and bore data. Where the resistivity curve gives only a possible range in depth, the centre value of the range was used.

Station.	Depth to Discontinuity (feet). Resistivity Data.	Control Data.	Type of Discontinuity.
* W1	50	51	Top of fresh granite
W2	52	> 40	,, ,, ,,
* W3	80	> 74	,, ,, ,,
W4	80–100	> 49	,, ,, ,,
W5	180	> 40	,, ,, ,,
W6	125–160	> 70	,, ,, ,,
* W7	85–110	110	,, ,, ,,
* W8	86	78	,, ,, ,,
W9	50–90	< 110	,, ,, ,,
W10	112	< 120	,, ,, ,,
* W4	56	49 ±	Saline water level
,, ...	9	< 20	Fresh water level
* W5	45	40 ±	Saline water level
* C3	10–22	15	Fresh water in limestone
* C4	Surface–13	15	Fresh water above cementation zone in limestone
,, ...	50–70	..	Brackish water on a lower level
* C9	Surface–32	20	Fresh water above cementation zone in limestone
* C8	10–26	24	Fresh water in limestone
C8a	8–80	41	Fresh water in limestone
C5	1·5	7	Ground water level (discrepancy caused by recent rainfall)
C6	3	6	,, ,, ,, ,,
C7	11	18	,, ,, ,, ,,
C5	30	shallow	Top of decomposed granite
C6	35	,,	,, ,, ,,
C7	134	> 68	,, ,, ,,
* C11	8–40	18	Fresh water in decomposed granite
	40–140	> 20	Saline water in decomposed granite
C13	58–115	..	Valley floor
* C1	4–45	61	Fresh water, in decomposed granite
* BB1	63	58	Water level
* BB1	118	117	Top of fresh granite
* BB2	65	58	Water level
* BB2	250	231	Top of fresh granite
* BB3	64	58	Water level
LG6	8–115	85	Brackish or saline water
* ,, ...	8	9	Top of decomposed granite
* ,, ...	115	128 ±	Top of fresh granite
LG11..	36–140	125	Water in decomposed granite
* ,, ...	36	27	Top of decomposed granite
* ,, ...	140	141	Top of fresh granite
* LG1	3	5 ±	Top of decomposed granite
* K1	24–32	34 ±	Valley floor
K3	15 to 85–140	100	Brackish water in decomposed granite
* ,, ...	85–140	115 ±	Top of fresh granite

In Figure 21 the depths of discontinuities from resistivity curves are plotted against the depths obtained from bore or well data. If the two sets agree completely, the points coincide with a line through the origin of the diagram at an angle of 45°. The line which best fits the data is expressed by the equation—

$y = 0{\cdot}95x - 6$, in which

y = depth to discontinuity in feet and

x = depth to discontinuity computed from resistivity data.

Standard error in y is 14 feet.

Average $x = 62$.

Average $y = 64$.

The correlation coefficient is 0·965, with a standard error of 0·015. As a close approximation we may say that the resistivity data indicate the depth of a discontinuity correctly, with the standard error of 14 feet in the range from surface to 150 feet depth. From consideration of instrumental and interpretation

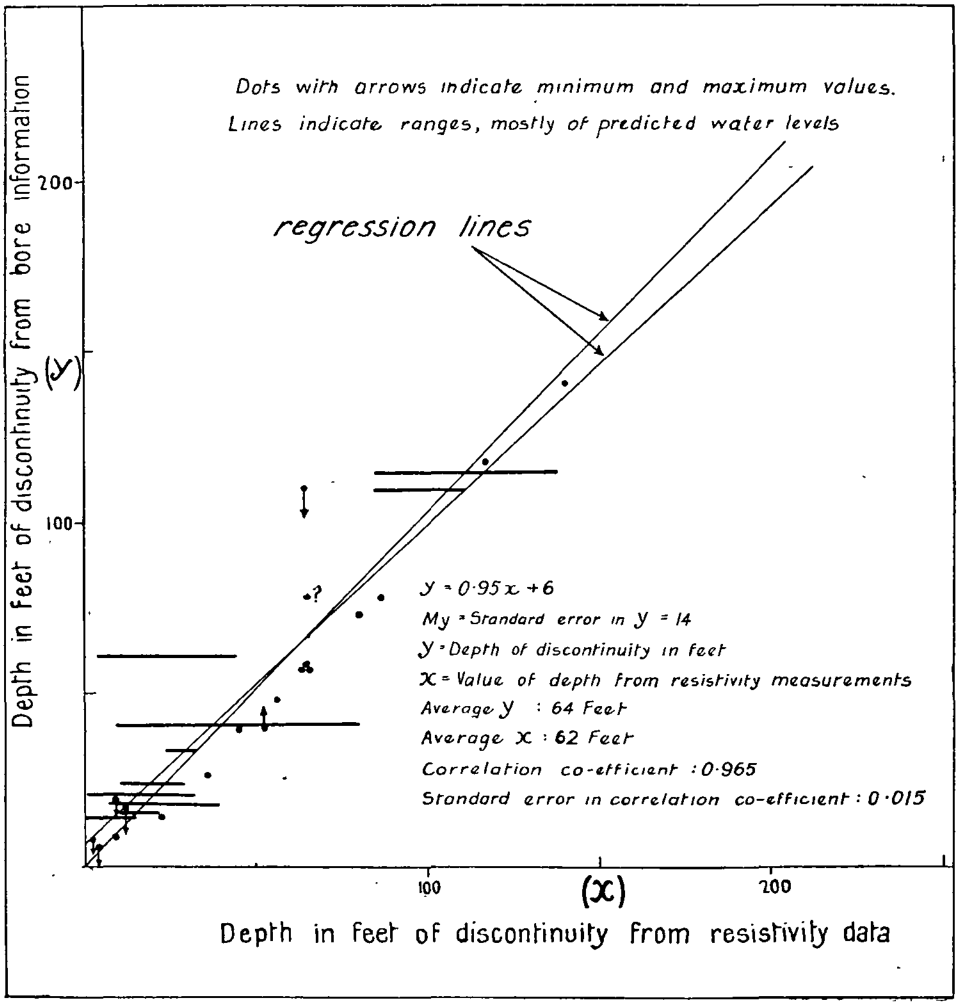

Fig. 21: Statistical analysis of depth determinations.

errors it might be expected that errors in depth determination would increase with increasing depth to the discontinuity. To investigate this, the ratio $100\frac{x - y}{y}$, indicating a percentage error per unit of depth, was computed and plotted against the depth (Fig. 22).

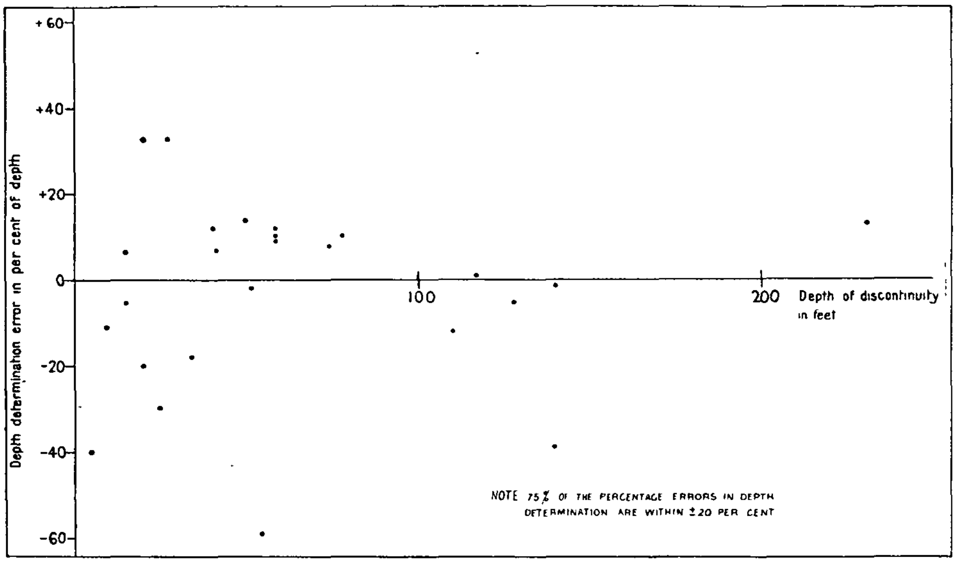

Fig. 22: Depth determination error as a function of depth.

It will be seen that—

(1) Percentage errors are largest near the surface and decrease appreciably for discontinuities below 30 feet. Although at first sight this might seem to indicate that the reliability of the interpretation improves with depth, this is not so. The true explanation lies in the relative reliability of the shallow and deep bore data with which the resistivity interpretations have been compared. Ground water levels and the water content of near-surface formations are largely influenced by the rainfall shortly preceding the tests, and this accounts for the relatively large differences between the depths determined from the resistivity curves and those shown in the bore logs which were taken in most cases many years before. Apparently, this source of error completely overshadows the normal instrumental and interpretation errors.

(2) Seventy-five per cent. of the errors in depth determination are within ± 20 per cent. of depth.

The depths of the lowest discontinuities determined were all less than 150 feet, except for one which was 250 feet, and were less than 40 per cent. of the maximum electrode separation used.

ORGANIZATION OF RESISTIVITY SURVEY.

A field party for resistivity work should consist of at least four men, namely, one party leader, one observer and computer, and two assistants.

The party leader should be a geophysicist with a good understanding of geological problems or a geologist with geophysical knowledge and experience.

The party leader decides on the layout of the survey. The instrument observations and computations are made by the party leader and the observer. Routine computations and plotting should be done while the observations are being made so as to give an immediate check on the quality of the observations. The two field assistants are required in the general preparations, laying out of lines and handling of cables and electrodes. Usually, two or three profiles can be made per day but the number will depend on terrain, equipment, weather and access roads. The equipment needed is substantially the same as used in these tests and listed earlier in the report.

CONCLUSIONS AND RECOMMENDATIONS.

1. The depth of discontinuities can be determined by the electrical resistivity method. Seventy-five per cent. of the errors in depth determination are within $\pm$ 20 per cent. of depth.

2. With one exception the maximum depths determined were less than 150 feet. The maximum electrode separation was 400 feet.

3. In granite areas the transition from weathered granite to fresh granite can be readily recognized. Even with limited geological control it is sometimes possible to recognize sands, limestone, cementation zones in limestone, ground water levels, &c.

4. The more saline the ground water the greater the reduction in resistivity and consequently the easier it is recognized. Gradual downward increase of water content in rock pores makes it impossible to recognize ground water levels; the effect is a gradual decrease in resistivity and not a sharp discontinuity. This condition is common in decomposed granites.

5. After establishing a few test bores in an area to test the salinity (or salt content) of solutions in a formation, it is possible to estimate the salinity of that type of formation from resistivity data. The assumption made is that the porosity of such a formation varies only within narrow limits or remains practically constant. The method can be improved by resistivity determination of bore water samples. At Wubin the salinity of seepage water within decomposed granites could be estimated from resistivity measurements by the use of an empirical formula with an accuracy of about 50 per cent.

6. If the porosity of a formation is known, the salt content of its solutions can be deduced from resistivity data and vice versa *after* establishing an empirical relation between resistivity and salt content of a solution.

7. A new type of resistivity meter developed by the Bureau of Mineral Resources was tested and proved successful.

8. The Megger earth tester is reliable up to electrode spacings of 100 feet, if necessary precautions are observed. It is a useful engineering instrument which could replace shallow auger drilling. It can also be used for constant separation traverses with electrode separations less than 100 feet.

9. Small scale magnetic surveys will disclose the topography of shallow granite basement.

10. Accurate bore data are essential for test or experimental surveys by geophysical (or other) methods. The present tests were handicapped by lack of accurate bore data.

11. During the survey, the geophysical party was asked to look for a new water supply for the Cue township. Conditions for a large supply of good quality water are favourable near Yarraquin homestead. This area is recommended for a detailed survey by resistivity and possibly magnetic methods.

12. It is concluded that the resistivity method is a valuable tool in solving water supply problems. Depth to discontinuities, and, under favourable conditions, type of formation and water can be estimated. But it cannot be sufficiently stressed that these methods can only be successful if the interpreter of the geophysical data has a thorough understanding of the geological setting in such problems. This can best be achieved by working in close co-operation with geologists who have a wide background of experience in those areas in which water investigations are to be carried out.

13. It is stressed that in other countries where resistivity methods of water search have met with considerable success, this success has only been achieved by years of systematic work. It is believed that in Western Australia this would also apply and that further tests under known conditions, combined with investigations in virgin areas to be followed by test bores, would lead to a steady improvement in interpretation. The testing of hydrological characteristics of bores might prove of considerable importance. Such hydrological characteristics include the determination of porosity, permeability, screen analysis of bore samples, salt content and resistivity of bore water. These data, correlated and combined with geophysical and geological observations, would add greatly to the chances of finding potable water.

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APPENDIX A.

WATER QUALITY: DEFINITION OF TERMS USED.

Water quality is usually indicated by total soluble salt content, salinity and hardness.

Total soluble salt content (T.S.S.) is the amount of salt in solution in grains per gallon. It is determined by slow evaporation of water.

Salinity is the amount of sodium chloride (NaCl) in grains per gallon. Usually the chloride content is determined and all chloride is assumed to be sodium chloride (common salt).

Hardness (strictly speaking "temporary hardness") is caused by $CaCO_3$ and $MgCO_3$ in solution. It is generally expressed as grains of calcium carbonate ($CaCO_3$) per gallon.

To be usable the salinity of water should be within the following ranges:—

Human consumption—less than 120 grains per gallon,
Irrigation water—less than 120 grains per gallon,
Cattle water—less than 400 grains per gallon,
Sheep water—less than 500 grains per gallon,

although sheep can become gradually accustomed to water containing as much as 1,000 grains per gallon.

APPENDIX B.

RESISTIVITY AS A HYDROLOGICAL CHARACTERISTIC.

Resistivity can be regarded as a hydrological characteristic because a close relation exists between porosity, salinity and resistivity. Such a relation could be established empirically, for instance during boring operations in the field, and it could be used to estimate the salinity of water from resistivity measurements if the porosity were known (if, for instance, the type of rock and formation were known).

This relation could be a useful tool in resistivity work on water problems, and a theoretical approach to the development of such a relation is therefore justified.

Heiland (1946, 635) has developed equations which show the relation between the resistivity of an aggregate (ρ_x), the resistivity of the pore solution (ρ_1) and the pore volume (V_1). The equations are an approximation and it is assumed that the pores are completely filled with pore solution.

$$\log \rho_x/\rho_1 = \log (3 - V_1)/2V_1 \text{ for high porosity} \qquad (5a)$$
$$\log \rho_x/\rho_1 = \log 3/V_1 \text{ for porosity lower than } 25\% \qquad (5b)$$

From these expressions an approximate equation can be derived which will be applicable to both high and low porosity ranges, viz.:—

$$\log \rho_x/\rho_1 = -1{\cdot}25 \log V_1 \qquad (6)$$

An equation of the same type could probably be established empirically if sufficient data were available.

The resistivity of the pore solution could be determined in a laboratory by tests on bore water. Theoretically, an estimate can be made because the resistivity of a solution can be represented by:

$$\rho = \frac{10^6}{C\ (1_a + 1_c)}, \text{ in which}$$

ρ = resistivity in ohm–cm.

C = concentration of salt in mg. equivalent per litre.

1_a and 1_c = ion mobilities

For NaCl (common salt):

$$\rho_s = \frac{38000}{S},$$

$$\text{i.e. } \log \rho_s + \log S = 4{\cdot}58 \qquad (7)$$

where ρ_s is resistivity of salt solution and

S the concentration in grains per gallon.

For $CaCO_3$ ($Ca(H_2CO_3)_2$ in solution),

after estimating 1_a and 1_c:

$$\rho_c = \frac{40000}{S'}$$

$$\text{i.e., } \log \rho_c + \log S' = 4{\cdot}60 \qquad (7a)$$

Equations 7 and 7*a* are practically identical and no large error will be made if total soluble salt content is substituted for NaCl content in equation 7.

Equation 7 could be derived from resistivity determinations of bore water samples in a laboratory, together with determinations of total soluble salt content.

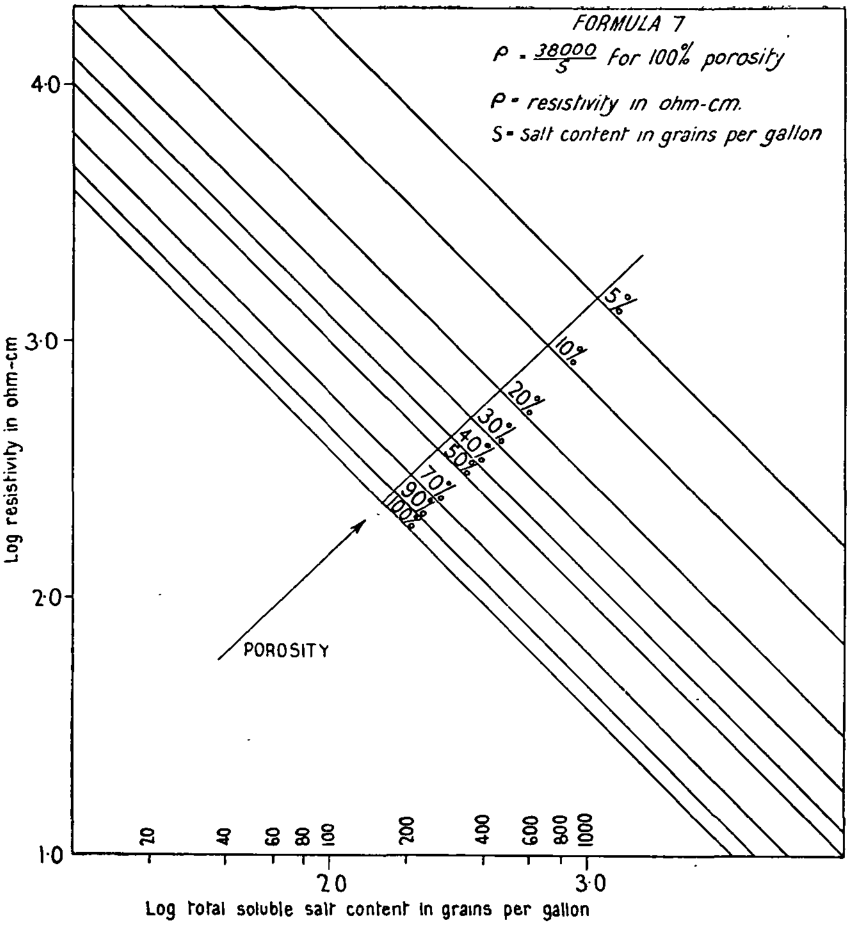

Fig. B1: Relation between resistivity, porosity and salt content.

Equation 7 is plotted on Fig. B1 and is represented by the line for 100% porosity. With the help of equation 6 similar lines were drawn for other porosity values. It will not be difficult to recognize that equation 4 (see Wubin area) can be represented by one of these lines.

For the Wubin area, the relation between salinity and resistivity is represented by the empirical equation 4*b*:—

$$\log S \doteq 5{\cdot}35 - \log \rho.$$

If it is assumed that the total soluble salt content (T) is 1·5 times the salinity (see Appendix C), then equation (4*b*) becomes:—

$$\log T = 5{\cdot}5 - \log \rho.$$

Plotting this on Figure B1, it is noted that this corresponds to a porosity of about 20–25%. In other words, the chart indicates that the average porosity of decomposed granites at Wubin is about 20–25%.

APPENDIX C.

CORRELATION BETWEEN TOTAL SOLUBLE SALT CONTENT, SALINITY AND HARDNESS.

From scattered data in water supply files of Cue township it was found that the total soluble salt content (T) shows a high correlation of 0·77 with salinity (S) and 0·71 with hardness (H).

Further:—

$T/S = 1{\cdot}5$, standard deviation $= 0{\cdot}25$.

$T/H = 3{\cdot}6$, standard deviation $= 0{\cdot}82$.

These relations, when established for certain areas, are an aid in comparing different sets of data which would not otherwise be comparable.

APPENDIX D.

THE INFLUENCE OF GRADUAL RESISTIVITY CHANGES.

In the interpretation of resistivity data the constancy of resistivity within a formation and sharp discontinuities are generally assumed. The reason is that mathematical treatment of variable resistivity within a formation is so complicated and difficult that until recently no useful formulae have been developed. Gradual changes of resistivity must be a fairly common phenomenon in nature.

For example, the water content of rock pores increases gradually with depth through zones of pellicular water and capillary or fringe water to the zone of saturation.

Huber (1951) discusses this problem in an article in an Austrian periodical. The following is a summary of the article:—

> "Observations concerning the obvious influence of varying water content upon the specific resistance of the soil led to the construction of a new type of double-layer curve, assuming that the specific resistance of the uppermost layer obeys an exponential law. These resistance curves are compared with the double and triple layer curves calculated by assuming layers of constant resistivity. By means of several examples, the errors in depth measurement caused by applying the latter curves are indicated.
>
> For the classification of the new curves the position of their asymptotes is the determining factor. In many cases the divergencies between geoelectric measurements and results of boring may be eliminated by making use of these new resistance curves."

Families of such curves are shown in Figs. D1, D2 and D3 in which the following notation is used:—

ρa = apparent resistivity.

l = electrode separation in the Wenner configuration.

h = thickness of upper layer.

z = depth.

ρ_o = resistivity at the surface.

ρ_z = resistivity within the upper layer = $\rho_o e^{\propto Z}$

ρ_I = resistivity at bottom of the upper layer = $\rho_o e^{\propto}$ (when h = 1).

ρ_{II} = resistivity in the lower layer.

q = $\frac{\rho_{II}}{\rho_{I's}}$

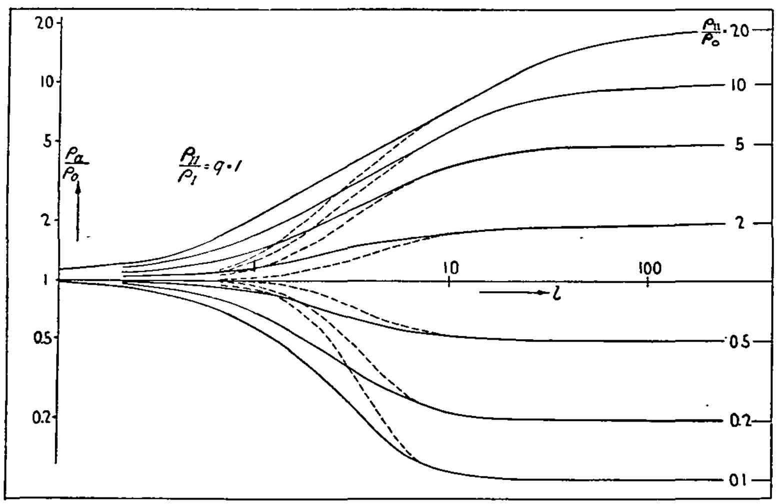

Fig. D1: Two-layer resistivity curves with exponential change in top layer, without discontinuity.

In Fig. D1 the curves shown are for $\rho_{II} = \rho_{I}$ (i.e., q = 1), h = 1 and for values of ρ_{II}/ρ_o ranging from 0·1 to 20. The condition $\rho_{II} = \rho_{I}$ implies that the resistivity of the upper layer is assumed to change from its value of ρ_o at the surface to a value at the interface equal to the uniform resistivity of the lower layer. Hence there is no actual discontinuity at the bottom of the upper layer. The dashed lines represent the corresponding curves for two layers with uniform resistivities ρ_o and ρ_{II}. It is observed that when the resistivity of the upper layer follows an exponential law the use of the ordinary two-layer curves will result in depth estimates that will be too small.

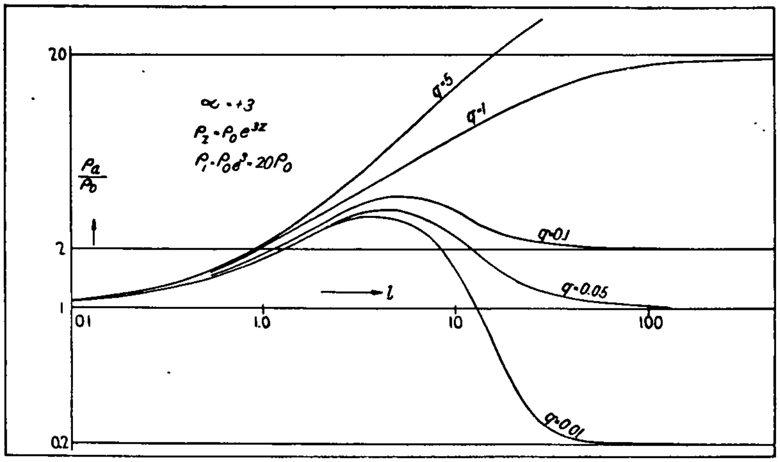

Fig. D2: Two-layer resistivity curves with exponential increase in top layer.

Fig. D2 shows a family of curves for $\alpha = 3$, h = 1, with q as parameter ranging from 0·01 to 5. With $\alpha = 3$, the resistivity at the bottom of the upper layer is given by $\rho_I = 20\,\rho_o$. The different values of q correspond to different values of resistivity of the lower layer. It will be noticed that for q = 0·01 to 0·1 the curves are of the three-layer type.

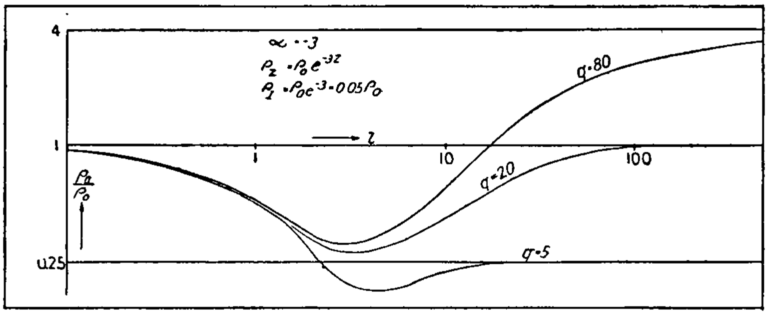

Fig. D3: Two-layer resistivity curves with exponential decrease in top layer.

Fig. D3 shows a similar set of curves but with $\alpha = -3$ and q values of 5, 20 and 80.

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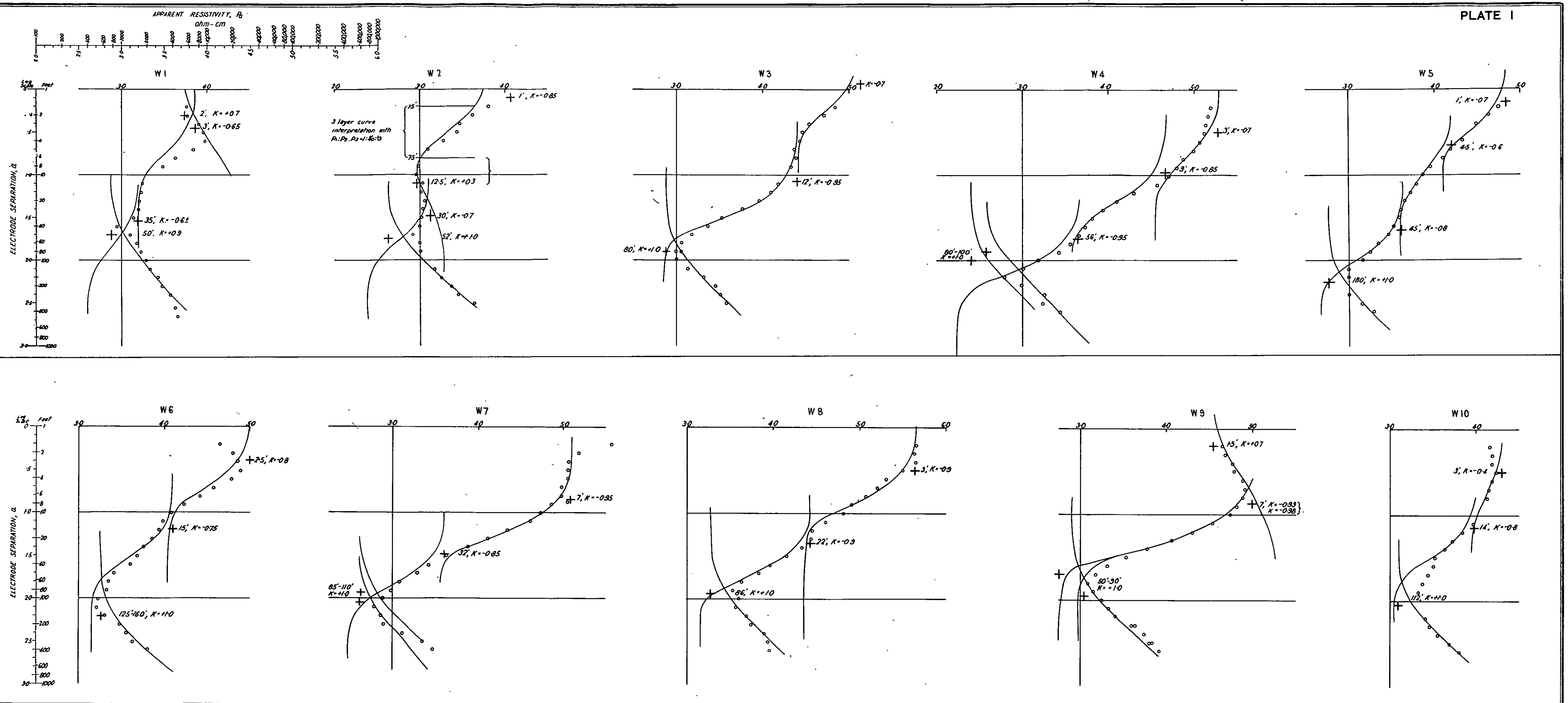
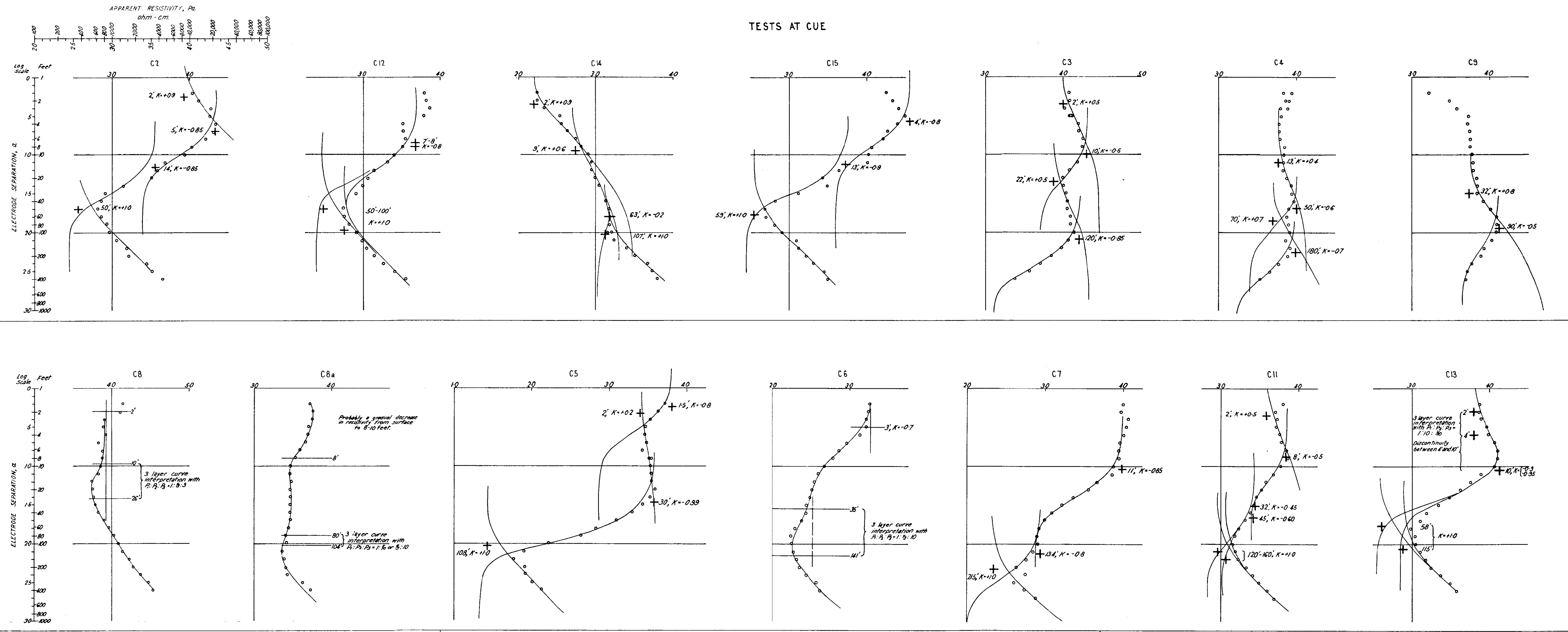


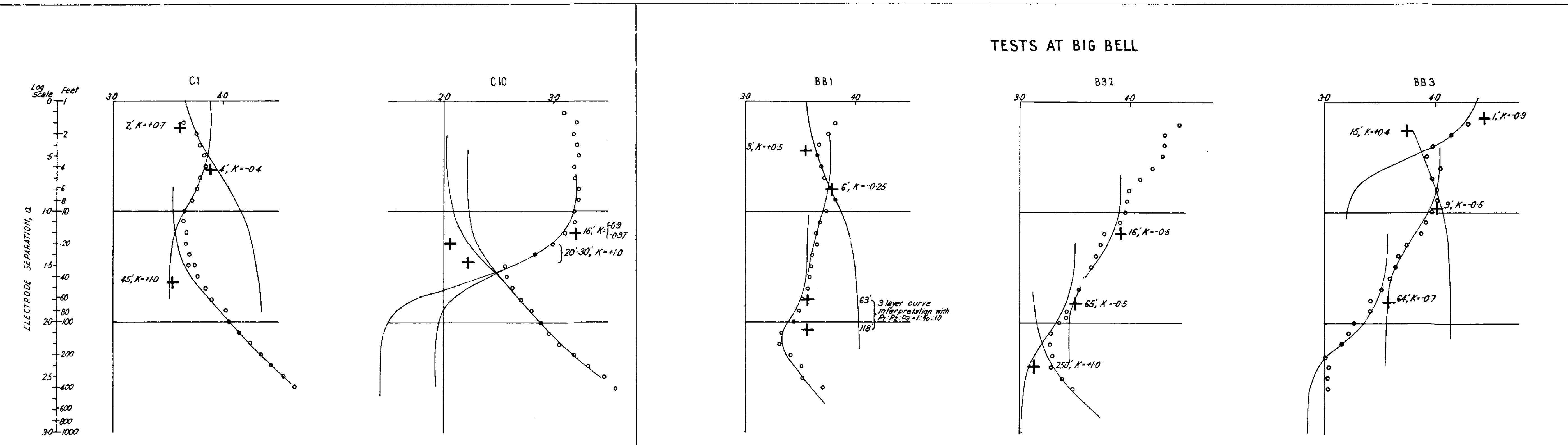
GEOPHYSICAL INVESTIGATION OF WATER DEPOSITS, WESTERN AUSTRALIA

WUBIN AREA

RESULTS OF RESISTIVITY TESTS

Geophysicist William A. Wiebenga





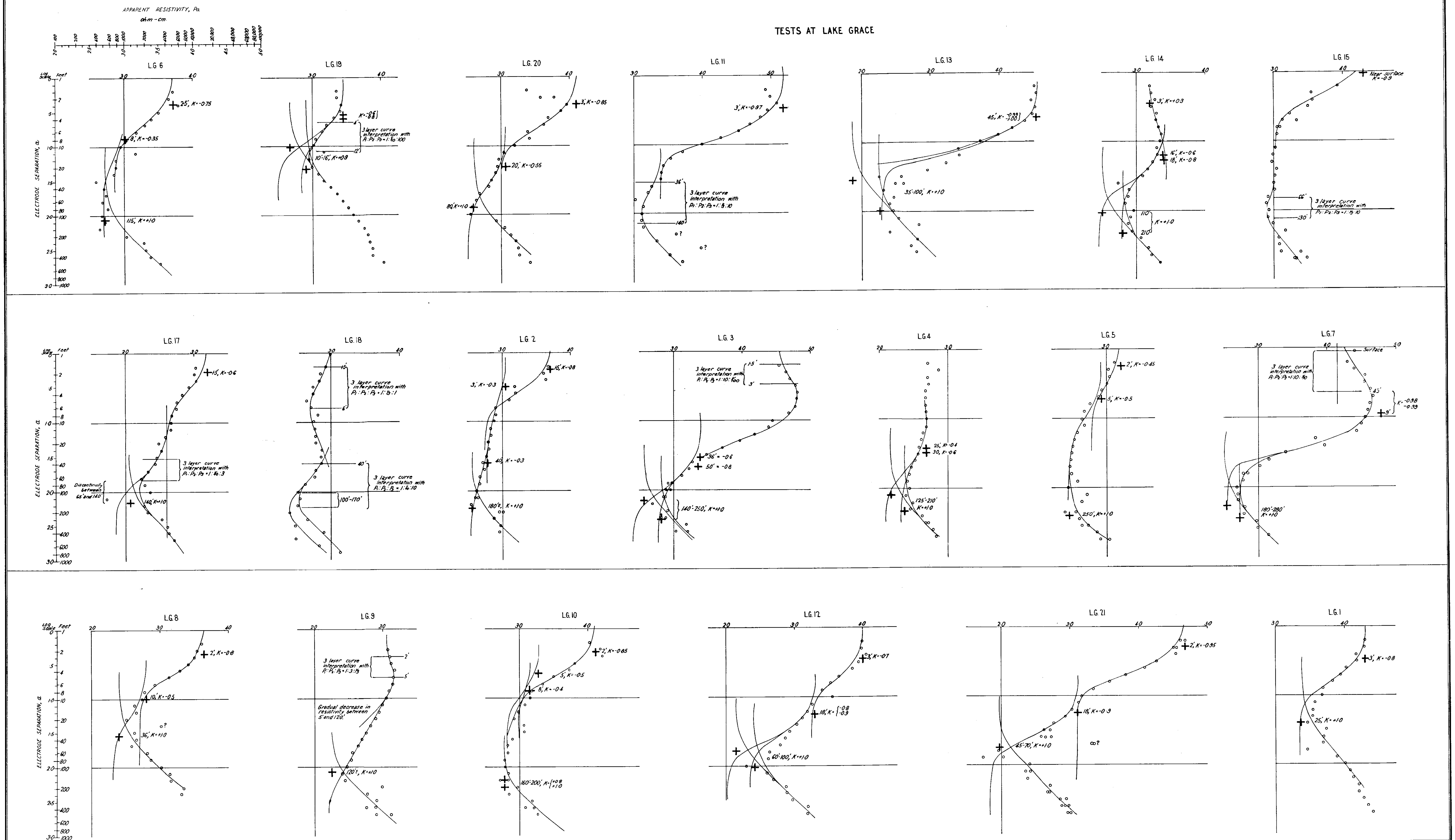
GEOPHYSICAL INVESTIGATION OF WATER DEPOSITS, WESTERN AUSTRALIA

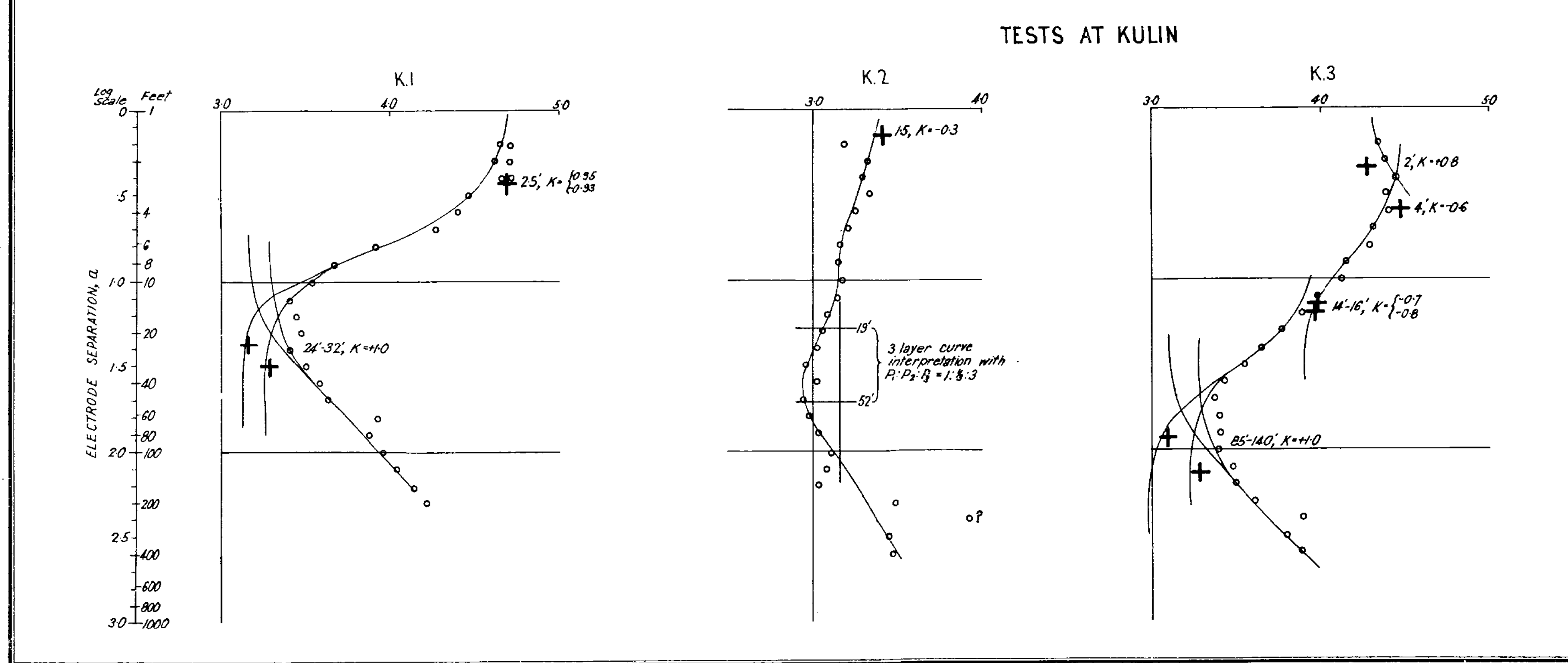
CUE AND BIG BELL AREAS

RESULTS OF RESISTIVITY TESTS

William A Wiebenga

Geophysicist





GEOPHYSICAL INVESTIGATION OF WATER DEPOSITS, WESTERN AUSTRALIA

LAKE GRACE AND KULIN AREAS

RESULTS OF RESISTIVITY TESTS

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